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Untangling the drivers of energy reduction in the UK productive sectors: Efficiency or offshoring?

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HIGHLIGHTS

- Novel decomposition using results using exergy analysis and input-output model.
- Thermodynamic efficiency is not the main driver of energy intensity improvements.
- Majority of energy savings from structural change are due to offshoring.
- Significant slow-down in energy savings from all factors after 2009.

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ABSTRACT

The UK has been one of the few countries that has successfully decoupled final energy consumption from economic growth over the past 15 years. This study investigates the drivers of final energy consumption in the UK productive sectors between 1997 and 2013 using a decomposition analysis that incorporates two novel features. Firstly, it investigates to what extent changes in thermodynamic efficiency have contributed to overall changes in sectoral energy intensities. Secondly, it analyses how much of the structural change in the UK economy is driven by the offshoring of energy-intensive production overseas. The results show that energy intensity reductions are the strongest factor reducing energy consumption. However, only a third of the energy savings from energy intensity reductions can be attributed to reductions in thermodynamic efficiency with reductions in the exergy intensity of production making up the reminder. In addition the majority of energy savings from structural change are a result of offshoring, which constitutes the second biggest factor reducing energy consumption. In recent years the contributions of all decomposition factors have been declining with very little change in energy consumption after 2009. This suggests that a return to the strong reductions in energy consumption observed between 2001 and 2009 in the UK productive sectors should not be taken for granted. Given that further reductions in UK final energy consumption are needed to achieve global targets for climate change mitigation, additional policy interventions are needed. Such policies should adopt a holistic approach, taking into account all sectors in the UK economy as well as the relationship between the structural change in the UK and in the global supply chains delivering the goods and service for consumption and investment in the UK.

1. Introduction

Most of the IPCC scenarios aiming to limit global warming to 2 °C result in a stabilisation of energy consumption at the global level [1]. This requirement for stabilisation should be considered as an optimistic requirement as most of the scenarios also rely on large quantities of unproven negative emission technologies [2,3]. If such technologies do not materialise at sufficient scale, stabilisation of global energy

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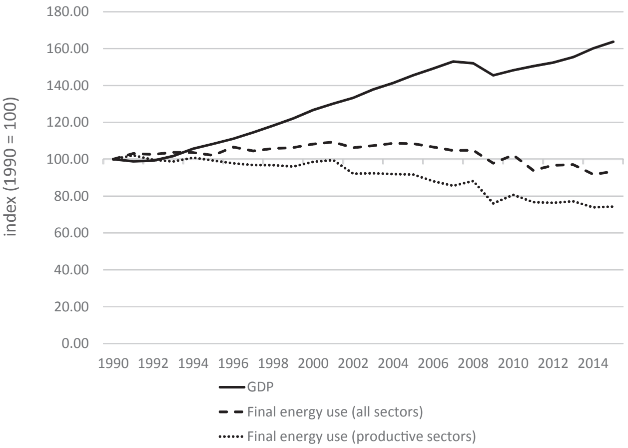

Fig. 1. UK GDP and final energy consumption (exluding non-energy use) between 1990 and 2015. Values are indexed with 1990 = 100. Productive sectors include the industry and non-industrial sectors but excludes energy consumption for domestic and transport purposes. GDP and energy data were obtained from the UK Office for National Statistics [7] and the Energy Consumption in the UK data collection [8] respectively.

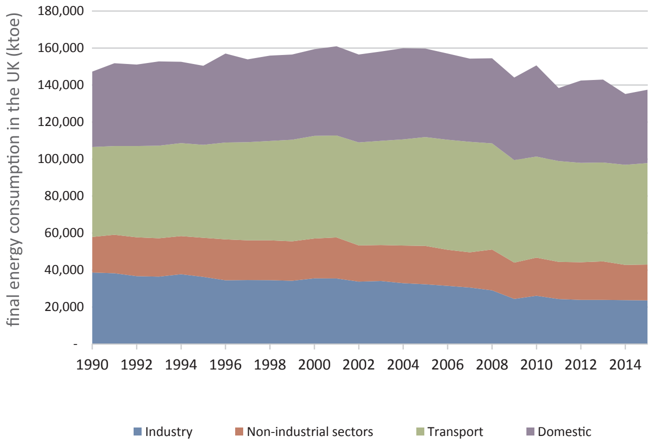

Fig. 2. Final energy consumption in the UK by sector. This article only investigates energy use in the productive sectors which represent the industry and non-industrial sectors shown here. Energy data were obtained from the Energy Consumption in the UK data collection [8].

consumption might not be sufficient and absolute reductions might be needed to avoid dangerous climate change. At the same time global population is predicted to increase over the period to 2050 by about 30% compared to current levels in the UN's medium variant [4] and many less-developed countries will need to increase their energy consumption to reduce poverty and social hardships, especially given that 16% of the global population currently do not have access to energy [5]. Increasing energy consumption in developing countries combined with a need to stabilise (let alone reduce) global energy use therefore implies the need for absolute reductions in energy consumption in developed countries, potentially exceeding 50% for per capita energy-use.

However, only very few developed countries have so far achieved an absolute decoupling of final energy consumption and economic growth over extended periods of time [6]. One of the few examples where this has happened is the UK. Despite a 19% growth in real GDP, final energy consumption (excluding non-energy use) declined by 11% between 2001 and 2013 (Fig. 1). However, to meet climate change targets energy consumption will most probably need to be reduced even further. To assess the need for further policy interventions and to see whether lessons from the UK can be applied in other countries, it is important to understand what has been driving the reduction in energy consumption in the UK and whether the trends are likely to continue into the future.

This study will contribute to this understanding by providing an analysis of the final energy consumption in the UK 'productive' sectors between 1997 and 2013, meaning the industrial and non-industrial sectors producing economic output. While final energy consumption in the productive sectors only accounted for 31% of all final energy consumption in the UK in 2013 (Fig. 2), the reductions in final energy consumption in these sectors accounts for about two thirds of the overall reductions in UK final energy consumption since 2001. To investigate the drivers of energy consumption in the productive sectors this study employs an index decomposition analysis with two novel features. Firstly, it draws on energy conversion chain (ECC) analysis that allows the estimation of the conversion efficiencies from final energy to useful exergy [9]. In this way energy intensity reductions can be broken down into a component representing thermodynamic conversion efficiency and a component representing the changing monetary output per unit of useful exergy. Secondly, it employs data from a multi-regional input-output (MRIO) model to investigate how much of the energy savings resulting from structural change can be attributed to offshoring. The results of this decomposition analysis are also compared to the results of a conventional approach featuring only energy intensity and structural change factors.

Index decomposition analysis is a widely-used tool to identify the drivers of change in energy use and carbon emissions [10,11]. It has been applied to study aggregate energy consumption in countries [12,13], as well as energy consumption in particular sectors, such as the residential [14,15] and transport sectors [16,17]. Index decomposition analysis of economic sectors commonly decomposes energy use according to three factors, namely energy intensity, structural change and output [18]. In such an approach energy intensity describes the energy used per unit of monetary output in each sector, structural change describes the sectoral composition of the economy and economic output describes the change in the aggregate output of the economy. Such decomposition analyses for the UK generally conclude that energy intensity reductions have been the major driver of reductions in UK final energy consumption over the last two decades, even though structural change has also been important [13,18–24]. However, most of these studies only pay brief attention to the UK as part of a multi-country study and there has not been a comprehensive analysis of the drivers of final energy consumption in the UK productive sectors in the past two decades. Hammond & Norman [21] decompose trends in energy and CO_2 emissions in the UK, but focus exclusively on the manufacturing sectors between 1990 and 2006. Reports from the ODYSEE-MURE project present detailed analyses of the ODEX efficiency indicator, but pay less attention to structural change [25].

The conventional decomposition approach focusing on energy intensity, structure and output provides important insights, but it leaves important questions unanswered about the underlying drivers of changes in energy intensity and economic structure. Firstly, the measure of energy intensity does not answer the question of whether changes have been driven by increasing thermodynamic efficiency of energy conversion processes or by other effects influencing monetary output. Secondly, looking at structural change within a country does not indicate whether this structural change is a reflection of offshoring, (i.e. a shift of energy-intensive production to other countries) or whether it is due to changed economic needs and the production structure that satisfies them. Whether structural change is due to offshoring is important, because it determines in how far energy savings from structural change have contributed to global climate change mitigation efforts. There are studies that have used input-output models to investigate changes in the energy-footprint of countries, including the UK [26,27]. However, these studies do not link the changes in the footprint to the changes in domestic structure to assess in how far domestic structural change has been a result of offshoring. Other studies specifically study the economic impacts of environmental improvements along the whole supply chain of products, focussing on specific companies or sectors [28,29]. The two novel features employed in this study provide new insights into the underlying drivers of energy intensity reductions and structural change across the whole of the UK productive sectors.

2. Data and methods

2.1. The decomposition factors

This study investigates the drivers of the change in final energy consumption (excluding non-energy use) in the UK productive sectors between 1997 and 2013. Final energy excludes energy consumed by those economic sectors that produce primary energy carriers (e.g. the extraction of oil & gas) or transform primary energy into final energy carriers for sale (e.g. oil refineries). For brevity the word energy always refers to final energy in this article. The productive sectors include only those economic sectors that use final energy consumption in the production of economic value. The energy used for personal transport and domestic uses is not investigated. The commercial transport sector is also not analysed in this study, because it is difficult to disentangle the energy consumption for private and commercial transport and transport energy use is a complex issue that would not be well served by the approach applied here to the other sectors (for a good analysis of UK road freight energy use see [17]). The productive sectors analysed are subdivided into fifteen sectors including twelve industrial and three non-industrial sectors (Table 1). This is the lowest level of disaggregation for which energy data are available from 1997. These sectors cover all sectors in the national accounts excluding the transport and energy producing sectors. For ease of presentation many of the results will be aggregated as 'industrial' and 'non-industrial' sectors, in which the latter contains the public and commercials services and agriculture sectors.

To analyse the change in final energy consumption in the UK productive sectors two decomposition analyses are presented. The first decomposition analysis follows the conventional approach to estimate the role that changes in the energy intensity and structure of the economy have contributed to the observed change in final energy consumption in the UK productive sectors. The main purpose of this conventional decomposition is to serve as a comparison to the new and extended approach. Specifically, this comparison was used to verify that the treatment of structural change in the newly developed extended approach is comparable to the conventional approach, because the extended approach uses slightly different decomposition factors to describe structural change. For the purpose of the conventional decomposition analysis final energy consumption in the productive sectors (E) is expressed as the combination of an intensity effect (I), a structural change effect (S), an output effect (O) and a population effect (P) (Table 2):

$$E = \sum_i I_i S_i O P = \sum_i \frac{E_i}{X_i}\frac{X_i}{X}\frac{X}{P}P \tag{1}$$

where E_i is sectoral energy consumption in the UK, X_i is sector output in the UK, X is total output of the UK economy and P is UK population. The subscript i denotes the economic sectors studied, which are presented in table 1.

The extended analysis introduces two novel features that further investigate the intensity and structural change effects. While the final energy use (E) is the same as in the conventional approach, the extended approach includes more factors in the identity used to decompose final energy consumption. These six factors are a conversion efficiency effect (CE), an exergy intensity effect (EI) an offshoring effect (OS), a changed need effect (CN), a final demand effect (DM) and a population effect (P) (Table 2):

$$E = \sum_i CE_i EI_i OS_i CN_i DMP = \sum_i \frac{E_i}{UE_i}\frac{UE_i}{X_i}\frac{X_i}{XG_i}\frac{XG_i}{Y}\frac{Y}{P}P \tag{2}$$

where E_i is sectoral energy consumption in the UK, UE_i is the useful exergy consumed in each sector, X_i is sector output in the UK, XG_i is the global output of the sector embodied in UK final demand, Y is UK final demand and P is UK population.

The first two factors subdivide the energy intensity effect in the conventional decomposition into two separate effects, namely the conversion efficiency effect and the exergy intensity effect. These two factors sum exactly to the energy intensity effect in the conventional decomposition. The conversion efficiency effect describes the efficiency with which final energy is transformed into useful exergy in each sector as obtained from ECC analysis [9]. Useful exergy describes the work that is delivered at the last stage of the energy conversion chain that can still be measured in energy units, for example useful heat, mechanical drive, or light. Useful exergy can therefore be considered to be most closely related to the energy services delivered [31]. The conversion efficiency effect is calculated as final energy per unit of useful exergy used in each sector. This factor presents a thermodynamic measure of energy efficiency that can be consistently applied across all the sectors. In contrast, the exergy intensity effect captures the changes in the monetary output that is produced for each unit of useful exergy. These can include changes in the physical efficiency of the production process that are not captured by the conversion efficiency effect, but also changes in the monetary value of production, imperfect deflation and structural change within sectors. For example the conventional approach applied to the steel sector would describe the energy intensity of the sector as the final energy used in the sector divided by the output of steel (in monetary terms). The extended version splits this ratio into a ratio describing the final energy used per unit of useful exergy used (i.e. the mechanical drive, heat and light used) and a ratio describing the useful exergy used divided by the output of steel (in monetary terms). This can provide new insights into whether reductions in energy intensity have come from increases in physical conversion efficiencies or changes in the monetary value of the output produced.

The offshoring and changed need effects allow further examination of the drivers of structural change. The two effects do not exactly sum to the structural change effect in the conventional decomposition because the extended decomposition uses final demand per capita as its fifth decomposition factor, rather than total output per capita, which is used in the conventional decomposition. Final demand describes all the goods and services bought in the UK, whether for the purpose of

Table 1
Sector split used in the conventional and extended decomposition analysis, based on the classification used in the Digest of the United Kingdom energy statistics [30].

Sector name	SIC 2007 code
Industrial Sectors	
Iron & Steel	24.1–24.3
Non-ferrous Metals	24.4–24.5
Mineral Products	08, 23
Chemicals	20–21
Mechanical Engineering and Metal Products	25, 28
Electrical and Instrument Engineering	26–27
Vehicles	29–30
Food, Beverages & Tobacco	10–12
Textiles, Clothing, Leather & Footwear	13–15
Paper, Printing and Publishing	17–18
Other Industries	16, 22, 31–33, 36–39
Construction	41–43
Non-industrial sectors	
Public Administration	84–88
Commercial Services	45–47, 52–53, 55–56, 58–66, 68–75, 77–82, 90–99
Agriculture	01–03

Table 2

Summary of the decomposition factors used in the conventional and extended decomposition analysis. More detailed descriptions are provided in . Data sources used to construct the factors are outlined in Section 2.3.

Decomposition factor		Description	Units
Conventional decomposition			
Intensity	I_i	Final energy used in each UK sector (E_i) divided by the monetary output of the sector (X_i)	ktoe/million £
Structural change	S_i	Monetary output of each UK sector (X_i) divided by the total output of the UK economy (X)	million £/million £
Output	O	Total output of the UK economy (X) divided by the UK population (P)	million £/person
Population	P	UK population (P)	person
Extended decomposition			
Conversion efficiency	CE_i	Final energy used in each UK sector (E_i) divided by the useful exergy used in the sector (UE_i)	ktoe/ktoe
Exergy intensity	EI_i	Useful exergy used in each UK sector (UE_i) divided by the monetary output of the sector (X_i)	ktoe/million £
Offshoring	OS_i	Monetary output of each UK sector (X_i) divided by the sector's global output embodied in UK final demand (XG_i)	million £/million £
Changed need	CN_i	Global sector output embodied in UK final demand (XG_i) divided by the total amount of UK final demand (Y)	million £/million £
Demand	DM	Total amount of UK final demand (Y) divided by UK population (P)	million £/person
Population	P	UK population (P)	person

consumption or investment. The use of final demand in the analysis is required to incorporate the global supply chains that are associated with final demand in the UK. Since total final demand and total output generally develop in a similar fashion, the results of the conventional and extended decomposition analysis remain comparable.

The offshoring effect describes the ratio of domestic sector output divided by the global sector output embodied in UK demand. The global output embodied in UK final demand is obtained from the UKMRIO model [26] and describes the total monetary output (in each sector) that is used globally to satisfy the final demand of goods and services in the UK, taking into account intermediate consumption along the whole supply chain. For the steel sector this includes all steel used at some point in the supply chain of the products bought in the UK. For example this could be steel that is produced in China, if it is then made into a car in Germany and sold in the UK. The changed need effect in turn describes the global sector output embodied in each unit of final demand in the UK, for instance how much steel has been used in the world for each £ of goods bought for UK final demand. The terms offshoring and changed need are used here as a convenient shorthand. The offshoring effect does not exclusively capture the deliberate movement of industry from the UK to other countries. Instead it can be interpreted as an indicator of the potential sectoral capacity that the UK economy possesses to satisfy the final demand for goods and services in the UK. For example it compares the amount of steel embodied in UK final demand to the steel produced in the UK, even if the latter is not necessarily used for products sold in the UK. Similarly the changed need effect captures a variety of potential changes both in the composition of UK final demand as well as in the structure of the global supply chains satisfying this demand. In effect, the offshoring and changed need effects determine whether structural changes in the UK have been matched by structural changes in the economic output embodied in UK final demand. If the structural change in the UK (e.g. a relative decline of manufacturing) is not matched by changes in the embodied output it is considered to constitute a type of offshoring. In contrast, if the structural change in the UK is a reflection of broader changes in the economic output embodied in UK final demand, it can be considered a case of changed need.

2.2. *The decomposition index*

This study employs the Logarithmic Mean Divisia Index (LMDI). The LMDI method has been identified as one of the most suitable methods for energy decomposition because it gives complete decomposition without residuals, it has a sound theoretical foundation, it passes the test of time reversal and factor reversal and is easy to implement [10,32,33]. It is also well suited to multidimensional and multilevel energy data, as used for this study, because it gives perfect decomposition at the sub-category level and is consistent in aggregation [34]. The LMDI index can be used in two different ways, either in an additive or in multiplicative form. This choice does not affect the conclusions from the study because the results from either method can be transformed into the other by a simple formula [10]. In this study the additive version of the LMDI index is used as it was considered that its results are easier to interpret.

The subject of this study is the decomposition of the total final energy consumption in the UK productive sectors (E) which is subdivided into the energy consumption of economic sub-sectors, denoted by subscript *i*. For the purpose of the decomposition analysis E is expressed as a product of *n* factors, $E = \sum_i E_i = \sum_i x_{1,i}*x_{2,i}*x_{3,i}*\cdots*x_{n,i}$. The factors used in this analysis are described in Section 2.1.

The additive LMDI method is then used to allocate the overall difference in energy consumption between a time period 0 and a time period T (ΔE) to the respective factors:

$$\Delta E = E^T - E^0 = \Delta E_{x_1} + \Delta E_{x_2} + \Delta E_{x_3} + \ldots + \Delta E_{x_n} \tag{3}$$

Drawing on Ang [10] the following LMDI formula was used to determine the contribution of the kth factor to the change in energy consumption (version LMDI-I):

$$\Delta E_{x_k} = \sum_i \frac{E_i^T - E_i^0}{\ln(E_i^T) - \ln(E_i^0)} * ln\left(\frac{x_{k,i}^T}{x_{k,i}^0}\right) \tag{4}$$

This study uses decomposition analysis to investigate the change in energy consumption over a multi-year time period. As annual data is available this study employs a chained decomposition methodology. This means that the change of energy consumption is always decomposed for two consecutive years rather than comparing each year to a common base-year. The chaining method should be preferred when annual data is available as it better represents the true change and the results are independent from a choice of base year [35].

2.3. *Data*

Data describing the final energy consumption of UK industry, services and agricultural sectors was obtained from the Digest of UK Energy Statistics and the Energy Consumption in the UK data collection [8]. The Digest of UK Energy Statistics [30] contains a category of 'unclassified industrial energy use' which introduces an element of uncertainty into the analysis. For this article the 'unclassified industrial energy use' was allocated to the Other Industries sector. The data showed that significant decreases in one of the two categories was often accompanied by significant increases in the other category. This suggests that the data in both categories are strongly influenced by statistical re-classifications of different energy uses between the two sectors. Therefore it was considered most consistent to add the unclassified energy use to the energy use in the Other Industries sector, although this is likely to overestimate the energy use in the latter. While results for the Other Industries sector should therefore be interpreted with caution, this treatment does not affect the results for the industrial sector as a whole.

There has been some discussion in the literature about the measure of economic output that is best used to measure the energy intensity of the productive sectors [36]. This literature is mainly concerned with the question whether it is better to use physical or monetary values, and, if the latter are used, which kind of monetary value to use (for a good summary see [21]). In this study only monetary output measures are used, as this allows a comparable and consistent treatment of all sectors. There are different monetary output measures that can be used, including value added and total value of production. While value added is most frequently used, Hammond & Norman [21] concluded that there is no evidence that one measure is superior. In this study the total value of production is used to measure output, as given in the national supply and use tables. This measure was chosen because it fits better into the input-output framework used in the extended decomposition.

All the economic data was obtained from the UKMRIO model, which is based on the national accounts produced by the UK Office for National Statistics [26]. The economic data obtained include figures for the annual production of the fifteen investigated sectors, production of the UK economy as a whole, levels of final demand in the UK as well as the global output of each sector embodied in UK demand. Monetary variables in the UKMRIO model were converted into constant prices by applying the double deflation method [27]. As is conventional in input-output analysis, the sector output embodied in UK final demand was obtained by multiplying the Leontief inverse of the input-output table with the vector of UK final demand for each year. A more detailed description is available in Owen et al. [26]. This method implies that the boundary for calculating embodied sector outputs includes only the intermediate demand of goods and services in each year, but not capital expenditures.

The analysis in this article is restricted to the time period from 1997 to 2013, because the input data obtained from the UK MRIO model is only available for this time period. However, the time period is adequate as it captures the change in trend from stagnating to decreasing final energy consumption in the UK productive sectors observed around 2001 (Fig. 1).

Data on the useful exergy used in each sector was produced by the authors. The useful exergy data is calculated in three steps. First the final energy used in each sector is mapped to the main useful work categories (heat, mechanical drive, electricity and muscle work) and then to individual task levels within these categories (e.g. work done by cars, light bulbs, etc.). Second, for each individual task level conversion efficiencies (final energy to useful exergy) are estimated based on the literature or new calculations. Third, the task-level final energy values and final-to-useful conversion efficiencies are then multiplied together, and summed to obtain the useful exergy used in each sector. A more detailed description of the methodology can be found in Brockway et al. [37,38].

3. Results

The conventional decomposition shows that reductions in final energy consumption in the UK productive sectors between 1997 and 2013 were achieved despite significant upward pressures on energy consumption from increased output per capita and population growth (Fig. 3a). Energy consumption declined because these upward pressures were more than offset by reductions from the energy intensity and structural change effects, with the reductions allocated to the energy intensity effect being significantly bigger than the reductions allocated to the structural change effect.

Despite using more and slightly different factors the extended decomposition analysis produces very similar results (Fig. 3b). There are no differences in the qualitative patterns and the quantitative differences between the output and demand effects as well as between the structural change effect and the combined offshoring and changed need effects are small. This gives confidence that the results are comparable. A number of interesting observations stand out.

Firstly, the exergy intensity effect is larger than the conversion efficiency effect, when the whole time period is considered (Fig. 3b). However, up to 2005 the conversion efficiency effect contributes more reductions in energy consumption. The relationship between the exergy intensity effect and the conversion efficiency differs between the sectors. While the two are of equal magnitude in the industrial sectors the exergy intensity effect is significantly larger in the non-industrial sectors (Fig. 4). Within the industrial sectors the bulk of reductions in energy consumption is very much concentrated in two sectors, namely Iron & Steel and Chemicals. These two sectors account for over 60% of reductions in energy use in the industrial sectors and 60% of the reductions assigned to the energy intensity effect in industry, even though they only used 32% of all industrial energy in 1997. An important contributor to this concentration is the exergy intensity effect. Almost 75% of the energy savings allocated to this effect in the industrial sectors occur in the Iron & Steel and the Chemicals sectors (detailed sectoral results are provided in Table A.1 in the Appendix).

Secondly, the energy savings attributed to the offshoring effect are much bigger than the energy savings attributed to the changed need effect, with virtually no reductions in energy consumption due to the changed need effect at the aggregate level (Fig. 3b). This pattern is the result of energy savings attributed to the changed need effect in the industrial sectors (Fig. 4a) being cancelled out by increases in energy consumption attributed to the changed need effect in the non-industrial sectors (Fig. 4b). All the energy savings from the offshoring effect occur in the industrial sector with no changes in energy consumption in the non-industrial sectors attributed to the offshoring effect. While the Agriculture sector shows a significant reduction in energy use due to the offshoring effect, the size of the sector is so small that it hardly shows up in the aggregate total for the non-industrial sectors.

Lastly, the importance of the different effects varies significantly over time (Table 3). Both the conversion efficiency and the offshoring effect contribute to energy savings but at declining rates, with very low contributions after 2009. The exergy intensity effect contributes strongly to reductions in energy consumption between 2001 and 2009 and also at a more moderate rate thereafter. The demand effect increases energy use except for the time of the crises. However, even after 2009 contributions from the demand effect remain subdued. This means that after 2009 the contributions from all factors are significantly smaller than they were in the time before the crisis (Table 3).

4. Discussion

4.1. The role of thermodynamic efficiency in energy intensity

The significant reductions in energy intensity identified in this study present an encouraging trend and have been the key driver in reducing final energy consumption in the UK despite significant increases in output. Energy intensity reductions have been happening across the whole time period studied and across virtually all sectors, with the Textiles, Clothing, Leather & Footwear sector presenting the only exception. However, when interpreting the results it needs to be considered that a decomposition analysis cannot determine whether the trends in the different factors are independent from each other. For example the analysis cannot indicate whether energy intensity reductions (or structural changes) would have been similar without growth in output leading to even larger reductions in energy use. For example there is some evidence that output growth and reductions in energy efficiency are interlinked [39].

The novel features employed in this article have produced more detailed in insights into the underlying drivers of improved energy intensity. Unexpectedly, the reductions in thermodynamic conversion efficiency have contributed much less to energy savings than reductions in the exergy intensity of production. This finding suggests that energy intensity is not necessarily a good proxy for thermodynamic energy efficiency.

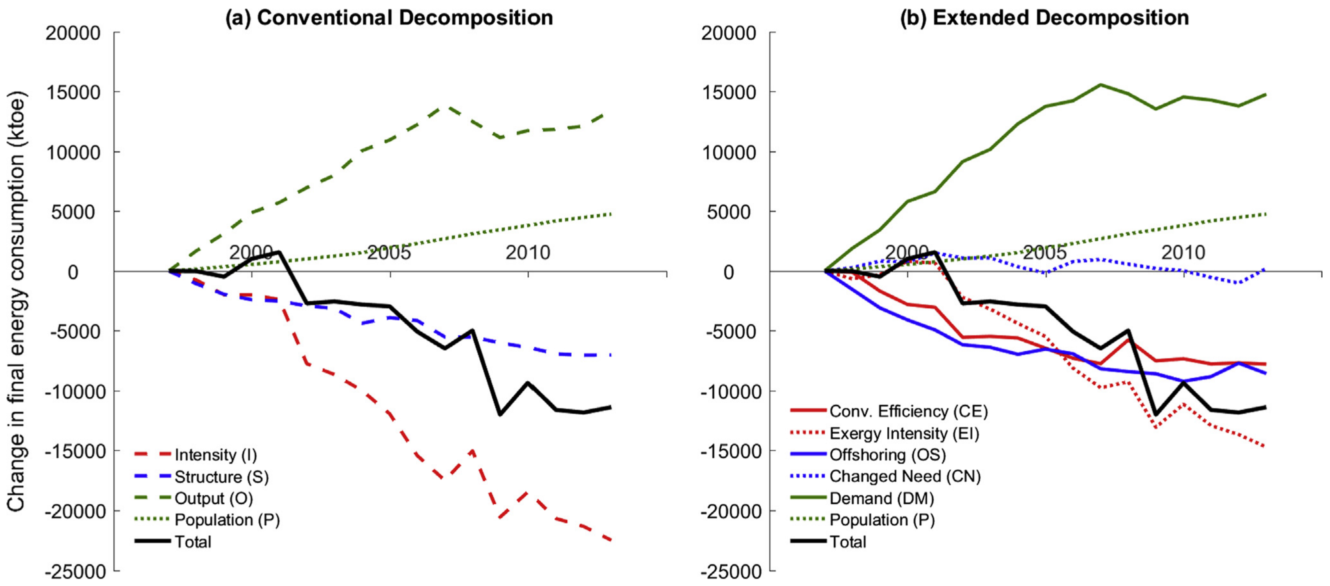

Fig. 3. Aggregate results showing the allocation of change in final energy consumption in the productive sectors to the decomposition factors in (a) the conventional decomposition analysis and (b) the extended decomposition analysis. For each year the cumulative change since 1997 is shown.

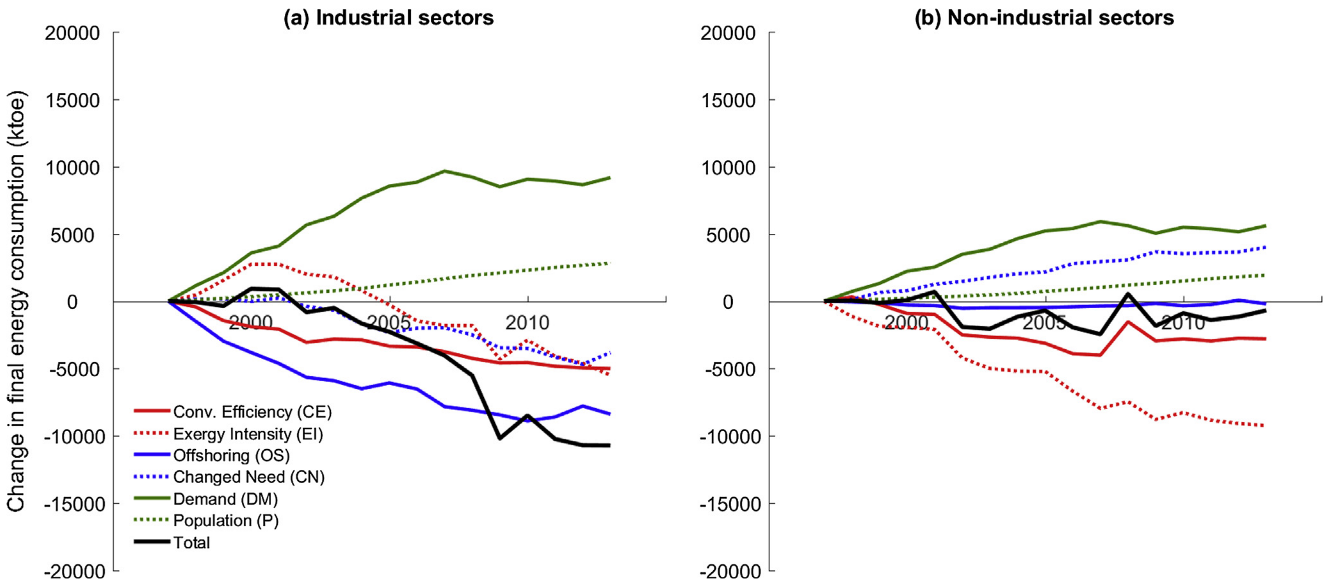

Fig. 4. Results of the extended decomposition analysis showing the allocation of change in final energy consumption to the decomposition factors for (a) the industrial sectors and (b) the non-industrial sectors. For each year the cumulative change since 1997 is shown.

Table 3

Results of the extended decomposition analysis for different time periods and decomposition factors. The results are obtained by first applying Eq. (4) to each effect, sector and year and then summing the results across all sectors and over the relevant time periods.

ktoe	1997–2001	2001–2005	2005–2009	2009–2013	Total
Conversion efficiency	−3046	−3418	−1061	−272	**−7797**
Exergy intensity	653	−6139	−7591	−1660	**−14737**
Offshoring	−4939	−1602	−2066	25	**−8582**
Changed need	1501	−1671	375	−13	**191**
Demand	6630	7130	−220	1233	**14,773**
Population	767	1168	1505	1313	**4754**
Total	**1566**	**−4533**	**−9057**	**626**	**−11398**

In the non-industrial sectors this result is not so surprising because in these sectors monetary output is less related to the production of physical products. However, even in the industrial sectors, the relative proportions of energy savings allocated to the conversion efficiency and exergy intensity effects vary widely between sectors. In the Construction and Textiles, Clothing, Leather & Footwear sectors, the two effects even have opposite signs, with one effect increasing energy use and one effect reducing energy use. The inconsistent contributions of thermodynamic conversion efficiency to energy intensity reductions make it difficult to assess what has been driving the reductions in energy intensity in the UK. The exergy intensity effect captures the components of energy intensity reductions that are not attributed to increasing thermodynamic conversion efficiency. It incorporates many factors that not captured elsewhere. This makes it difficult to determine what has been driving the reductions in exergy intensity.

On the one hand the exergy intensity effect might capture real reductions in the ratio of the useful exergy needed to produce the monetary output of a sector. For example, if higher quality products are produced using the similar conversion processes and similar amounts of useful exergy. Another source of reductions in the ratio could be structural change within sectors. The structural change effect in this study only captures shifts between the 15 sectors analysed. Any energy savings produced by output shifts within the 15 sectors would therefore show up in the exergy intensity effects. Using very detailed data for the US, Weber [40] shows that energy savings can shift significantly from the energy intensity to the structural change effect if a more detailed resolution of sectors is employed. In the UK productive sectors the Chemicals sector provides the largest share of energy savings allocated to the exergy intensity effect in the industrial sectors, accounting for 45%. Some of these reductions in exergy intensity are almost certainly due to structural changes within the sector as the output share of the pharmaceutical sector within chemicals, which has a relatively low energy-intensity, has significantly risen. However, the lack of detailed sectoral energy data for the UK makes it difficult to assess how important this effect could be across all the sectors.

On the other hand the exergy intensity effect might also be influenced by inaccuracies in the data. For example increases in sector output might not be related to increased physical production if the monetary production data is not appropriately corrected for inflation. Similarly uncertainties in the energy data would influence the energy intensity effect. For example a key uncertainty in this analysis is the treatment of the industrial energy consumption that is "unclassified" and hence not allocated to a specific industrial sector. This category of energy use was added to the energy consumed by the Other Industries sector because there was some evidence that the changes of the two were inversely related. However, this presents a very crude assumption. Despite accounting for 20% of all industrial energy consumption in 1997, the Other Industries sector only contributes 2% of the reductions in industrial energy use between 1997 and 2013. This disproportionally small contribution might indicate that some of the energy intensity reductions in the other sectors has been exaggerated by the reallocation of energy consumption from specific sectors to the "unclassified" category. However, such a reallocation would not affect the energy intensity values for the industrial sectors as a whole.

4.2. The role of offshoring in structural change

The MRIO model results used in this study have allowed a more detailed investigation of the drivers of structural change, which are generally not considered in other decomposition analyses. Three key results stand out from the analysis.

Firstly, the energy savings attributed to the offshoring effect are a lot larger than the energy savings attributed to the changed need effect, even within the industrial sectors. Interestingly, this result is not caused by a general divergence between the shares of industrial output in the UK and in the output embodied in UK final demand. In fact, the relative decline of industrial output in the UK has been mirrored by a similar decline in the industrial output embodied in UK final demand. This decline in the industrial output embodied in UK demand produces the energy savings associated with the changed need effect in the industrial sectors (Fig. 4a). However, the energy savings assigned to the offshoring effect are significantly bigger than the savings assigned to the changed need effect, because of different structural changes within the industrial sectors. While industrial sector output in the UK has, in relative terms, moved away from high-energy sectors such as Iron & Steel, Chemicals or Textiles, Leather & Clothing, this trend has been less strong or even reversed for the industrial output embodied in UK final demand.

The second key result is the fact that the energy savings from the changed need effect in the industrial sectors are completely offset by increased energy use associated with the changed need effect in the non-industrial sectors. Given that the non-industrial sectors have a lower energy intensity this result is somewhat counterintuitive. This result can be explained by the fact that the sectors analysed in this study do not constitute the total economy. Specifically the transport and fuel-producing sectors are excluded. Both of the excluded sectors show declining shares in total UK output, with the changes being especially pronounced in the fuel producing sector which declines from 10% to 5% in total output over the period of the study. The overall neutral contribution of the changed need effect in this analysis is therefore the result of two different structural changes in the UK economy. Firstly, there is a shift from industrial to non-industrial sectors, which should yield a net reduction in final energy consumption as non-industrial sectors are less energy intensive. Secondly, however, the overall output of the productive sectors analysed in this study is increasing its share in total UK output, as the shares of the transport and fuel producing sectors are declining. This reduces the observed impact of the structural change effect on final energy consumption. Both of these changes happen similarly in the UK economy as well as in the output embodied in UK consumption so that they only show up in the changed need effect but not in the offshoring effect.

The third key result is the strong decline in the rate of energy savings attributed to the offshoring effect. This temporal pattern of the offshoring effect essentially reflects the change in the gap between industrial output in the UK and the industrial output embodied in UK demand. Up to 2009 UK industrial output generally grew more slowly (or declined more strongly) than the industrial output embodied in UK demand leading to energy savings from the offshoring effect. However, this trend was reversed between 2009 and 2013 as industry output in the UK grew slightly more than the industrial output embodied in UK final demand. However, while the level of offshoring is no longer increasing the production of the goods and services embodied in UK demand is still highly dependent on industrial production in other countries. For all industrial sectors, except construction, the ratio of output in the UK to global output embodied in UK demand is below 1 in 2013. For four sectors it is even below 0.5, namely in the Iron & Steel, Non-ferrous metals, Electrical & Instrument Engineering sectors as well as the Textiles, Clothing, Leather & Footwear sector.

The observed results are supported by the results of other studies investigating the UK energy, carbon and material footprints, which generally show a widening gap between consumption and production-based accounts up to the financial crisis and a change in trend thereafter [26,27,41–43]. However most of these studies do not extend far beyond the financial crises. It is interesting to see that there has been no return to an regular energy savings from the offshoring effect up to 2013.

4.3. Implications for the future of final energy consumption in the UK

Overall the reduction in final energy consumption in the UK productive sectors has been driven by some trends that can be considered desirable from the perspective of climate change mitigation. There have been significant reductions in energy intensity across sectors and there have also been energy savings from a reduced dependence on industrial production, both in the UK and in the output embodied in UK final demand.

However, in spite of these encouraging trends, this analysis has highlighted several features that question whether there will be an imminent return to the rates of reduction in energy consumption that were observed between 2001 and 2009:

1. Rates of increase in thermodynamic conversion efficiency and of reduction in exergy intensity of production have been slowing down and are very small between 2009 and 2013. In addition energy savings from the two effects before 2009 were very concentrated in the Iron & Steel and Chemicals sectors. Although there remains some potential for further savings it is unlikely that these two sectors can contribute further energy savings at the same magnitude as observed before 2009 [44,45].

2. Energy savings from structural change have been very important and absolute reductions in final energy consumption in the productive sectors would have been much smaller without these contributions. However, it is questionable whether further energy savings from structural change are forthcoming and whether these are desirable from the perspective of climate change mitigation, as outlined in points 3 and 4.
3. The UK government is currently pursuing an active industrial strategy with the aim of increasing labour productivity and competitiveness of the economy and ending the period of low growth after the crisis [46]. While the strategy explicitly refers to the whole economy and not only the sectors conventionally considered to be ‘industrial’, it is difficult to imagine that it can achieve its aims while continuing the trend of deindustrialisation that the UK has seen over the past decades. This likely to reduce further energy savings from structural change in the UK.
4. To contribute to global efforts of climate change mitigation any energy savings from structural change in the UK would have to be matched by similar structural changes in the economic output embodied in UK final demand. The magnitude of the offshoring effect in this article as well as other evidence suggests that such an alignment has been very limited in the past [26,41]. Hence a return to higher growth rates of GDP and final demand is likely to lead to renewed growth in the energy use associated with UK final demand.

These findings point to three key of implications for energy and economic policy in the UK.

Firstly, efforts to further reduce energy consumption in the UK will need to target a wide range of sectors. One interesting option would be to explore how the materials produced by energy-intensive sectors could be more efficiently used in later stages of the industrial supply chain [47]. In addition there also needs to be a strong focus on non-industrial sectors of the economy. After years of reduction in energy consumption in the industrial sectors, the non-industrial sectors now account for almost half the total energy consumption in the UK productive sectors. The Public Administration sector in the UK presents an encouraging example, as energy consumption was reduced by 25% between 1997 and 2010 even though sector output grew by 79%. The UK government has had carbon reduction targets for the Public Administration sector in place for several years [48]. The results of this study that these targets have been effective, but further research would be useful to determine how the Public Administration sector in the UK has achieved its reductions in energy consumption.

Secondly, it should be a priority for policy makers to ensure that the industrial strategy will shape the UK economy towards a low-energy structure. If past trends continue, increasing efficiency on its own is unlikely to lead to substantive reductions in final energy consumption in the productive sectors, especially in combination with economic growth.

Thirdly, in order to effectively contribute to global climate change mitigation efforts, energy and economic policy in the UK needs to consider the energy consumption in other countries that is associated with UK final demand. This is not an easy task, as the interconnected and globalised nature of the economy means that there are very different forces shaping the structure of the UK economy and the structure of output embodied in UK final demand.

Overall, the future development of final energy consumption in the UK productive sectors is very uncertain. Between 2009 and 2013 energy consumption in the productive sectors was characterised by a peculiar phase of stagnation with very little change in the decomposition factors investigated in this study (Table 3). This is a reflection of the wider economic stagnation. More recent data on final energy consumption suggest that there also have only been very small further reductions in final energy consumption in 2014 and 2015 and that final energy consumption in the productive sectors (as well as in the transport and domestic sectors) has actually slightly increased in 2016 [49]. Whether and how this period of stagnation ends, and the nature of economic development that will follow, will be crucial in determining of whether the UK can continue to reduce final energy consumption and achieve its climate change targets.

This article has focused its attention on energy consumption in the productive sectors. These sectors are only responsible for a part of final energy consumption in the UK with large amounts of energy used in the transport and domestic sectors. While the latter two sectors are often treated separately, energy use in the transport and domestic sectors is related to wider economic developments, such as growth and structural change. These links are complex and work through a variety of mechanisms. For example energy use for personal transport and domestic purposes is linked to growth in income and associated changes in lifestyle. Similarly, all the technological devices that consume energy for transport or in homes are ultimately produced in the productive sectors (e.g. cars, houses, TVs). The widespread adoption of new technologies and shifts in behaviour intended to reduce energy consumption will therefore have significant impacts on the productive sectors. Such interlinkages between the sectors would provide a fruitful avenue for further research.

5. Conclusion

This study has introduced two novel features into a decomposition analysis of the final energy consumption in the UK productive sectors. These features have provided new insights into the drivers of energy savings. Estimates of the conversion efficiency from final energy to useful exergy have been included to further break down the measure of energy intensity and multi-regional input-output analysis has been employed to assess the contribution of offshoring to structural change in the UK. The analysis has revealed some trends between 1997 and 2013 that are encouraging with regard to climate change mitigation. Energy intensity reductions have been the biggest contributor to the reductions in energy consumption and are driven by both increasing conversion efficiency from final energy to useful exergy as well as from reductions in the ratio of useful exergy used per unit of produced output. In addition there are some indications of desirable structural change with a slight de-industrialisation of the economic output embodied in the goods and services produced for final demand in the UK. However, the analysis also highlights several issues suggesting that further reductions in energy consumption at the rate seen between 2001 and 2009 cannot be taken for granted. Firstly, rates of increase in thermodynamic efficiency as well as rates of reductions in exergy intensity have been slowing down. Secondly, savings from energy intensity reductions have only slightly exceeded increases in energy use from increased output. Hence, energy savings from structural change have played a key role in delivering absolute reductions in energy consumption. However, this analysis suggest that almost all these savings from structural change are a result of offshoring as they have not been matched by a similar change in the structure of economic output embodied in UK final demand.

The trends in energy consumption strongly reflect the economic stagnation between 2009 and 2013, with a significant slow-down in the growth rates of output and final demand, as well as in the rates of energy savings from structural change, thermodynamic conversion efficiencies and exergy intensity. How the ongoing economic stagnation is resolved will have significant impacts on the energy consumption in the UK. Therefore the industrial strategy currently developed by the UK government presents a unique opportunity to shape the economic development in the UK for a low-energy future. However, to take up this opportunity, policy aimed at reducing energy consumption has to be rethought in a more holistic way. It needs to go way beyond the energy-intensive industrial sectors and pay equal attention to the less energy-intensive industries as well as the non-industrial sectors, such as public administration and commercial services. In addition energy policy needs to go beyond the UK borders and consider how energy consumption in the UK and abroad is driven by the growth and changing nature of UK final demand.

More research is needed to support the development of effective policy interventions for reducing energy consumption. This article has studied the effect of offshoring on energy consumption in the UK but it has not investigated the change in the energy footprint of UK final demand. Gaining a better understanding of what is driving changes in the energy footprint of UK final demand would be a fruitful area for further research. Another interesting avenue would be the relationship between changes in energy intensity and economic structure on the one hand and prices and costs in the economy on the other. Research on this topic would be useful to assess the potential economic impacts of policies intended to significantly reduce energy consumption. This topic is also related to the question of how energy consumption in the transport and domestic sector might be linked to energy consumption in the productive sectors studied here.

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Appendix A

See Table A.1.

Table A.1

Change in final energy consumption between 1997 and 2013 attributed to the different decomposition factors for each sector. The results are obtained by first applying Eq. (4) to each effect, sector and year and then summing the results for each sector across the whole time period.

ktoe	Conversion efficiency	Exergy intensity	Out-sourcing	Changed need	Demand	Popu-lation	Total
Industrial Sectors							
Iron & Steel	−163	−1767	−1727	−64	702	175	−2844
Non-ferrous Metals	−329	−13	−671	55	309	88	−561
Mineral Products	−163	−25	−554	−201	760	285	102
Chemicals	−1935	−2494	−1816	239	1843	491	−3673
Mechanical Engineering and Metal Products	−166	−342	−377	−432	476	138	−704
Electrical and Instrument Engineering	−95	−26	−428	78	258	86	−127
Vehicles	−270	−542	24	−243	440	122	−469
Food, Beverages & Tobacco	−554	−254	−306	−1354	1028	316	−1125
Textiles, Clothing, Leather & Footwear	−83	532	−836	−279	301	92	−273
Paper, Printing and Publishing	−501	−20	−555	−485	677	212	−674
Other Industries	−761	−152	−1159	−1039	2168	753	−189
Construction	13	−397	20	−90	209	65	−181
Total industrial	**−5007**	**−5501**	**−8385**	**−3817**	**9172**	**2821**	**−10717**
Non-industrial sectors							
Agriculture	−475	404	−286	−384	315	95	−332
Commercial Services	−1404	−4130	11	2896	3245	1190	1808
Public Administration	−911	−5509	78	1496	2042	647	−2156
Total non-industrial	**−2790**	**−14737**	**−197**	**4008**	**5602**	**1932**	**−681**
Overall total	**−7797**	**−14737**	**−8582**	**191**	**14,773**	**4754**	**−11398**

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