Decomposition analysis of energy-related carbon emissions from UK manufacturing

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Abstract

Energy-related carbon emissions from UK manufacturing have fallen, between 1990 and 2007, by approximately 2% per annum. This reduction could be caused by a number of effects that can act to increase or decrease the level of emissions. Decomposition analysis has been used to separate the contributions of changes in output, industrial structure, energy intensity, fuel mix and electricity emission factor to the reduction in carbon emissions. The primary reason for the fall in emissions was found to be a reduction in energy intensity. The manufacturing sector was also split into two subsectors: the energy-intensive (EI) subsector, and the non-energy-intensive (NEI) subsector. The NEI subsector, somewhat surprisingly, was found to have made greater relative reductions in its energy-related carbon emissions over the study period. This was principally due to much greater relative improvements in energy intensity. There is evidence that the EI subsector had made greater relative improvements in energy intensity in the period preceding 1990, and so this may have limited improvements post 1990.

Keywords: Decomposition; Efficiency; Carbon Emissions; Energy; Industry; Manufacturing.

1. Introduction

The UK manufacturing sector is responsible for approximately 20% of the UK's final user energy demand [1], the vast majority of this energy is supplied through fossil fuels, either directly, or indirectly through electricity use. Emissions of greenhouse gases (GHGs), primarily carbon dioxide, are associated with the use of this fossil fuel. Emission reduction is important in order to help meet government targets that are designed to limit climate change. Emissions can be reduced by either decreasing the energy demand or supplying the demand in a less carbon intensive way. Decreasing energy demand, through management and efficiency measures, is often seen as the most technologically simple and economic option available. This approach should take precedence, before meeting the reduced demand by the lowest carbon method possible [2-4].

The manufacturing sector is difficult to analyse due to the large variability in the ways energy is used within the sector. Past trends in energy use and the resulting carbon emissions can help us better understand the current situation and influence future decisions aimed at reducing energy-related carbon emissions. However, simply examining the changes in carbon emissions or energy use over time does not offer any insight into the reasons for these changes. Decomposition analysis [5] can split the changes in energy-related carbon emissions over time into a number of different factors. This gives a better understanding of the reasons for the changes observed. The contributing effects to a change in energy-related carbon emissions from the manufacturing sector are:

1. A change in **production**: if the sector output alters, manufacturing more or less product, this will almost always affect energy use.
2. A change in **structure**: over time the composition of the manufacturing sector may vary, and this can affect the energy use. For example, if the relative size of energy-intensive industries declines, the manufacturing sector may appear to be improving its efficiency, when in fact only a structural change has occurred.
3. A change in **energy intensity**: less energy is used to produce the same output.
4. A change in **fuel mix**: different fuels having differing emission factors (the carbon emitted for a given amount of delivered energy).
5. A change in **emission factors**: over time the emission factors of fuels and (especially) electricity can vary.

Previous studies have carried out decomposition analyses of UK manufacturing over the time period from the late 1960s to the mid 1990s [6-15], a review of worldwide Index Decomposition Analysis (IDA) studies up to the year 2000 is provided by Ang and Zhang [5]. Some of these studies cover energy demand rather than carbon emissions, and so only investigate the first three effects outlined above. The current work aimed to undertake a decomposition of the energy-related carbon emissions from UK manufacturing sector over the period 1990-2007, therefore updating these previous studies. The current work focuses on the UK it therefore allows a higher level of sector disaggregation than many studies (although not being as broad as some of these previous studies in comparing the results of different countries). In addition, this work has decomposed the carbon emissions of the energy-intensive (EI) and non-energy-intensive (NEI) subsectors of manufacturing separately. It was anticipated that the EI subsector would exhibit stronger drivers for emissions reduction and improving energy intensity, its performance will be compared to that of the NEI subsector. A study of the Netherlands [16], which decomposed changes in the energy demand of the non-energy-intensive subsector over the years 1988-1999, found no improvement in decomposed energy intensity over the period investigated. Evidence for the effects of production growth, energy prices, fuel mix and previous intensity improvements in determining changes in energy-related carbon emissions have been examined in the current study.

Section 2 discusses methodology, including the split into an EI and NEI subsector, the decomposition technique used, and the sources of data for the study. Section 3 presents the findings of the work. Section 4 discusses the interpretation of these results. Section 5 comprises some brief concluding remarks.

2. Methodology

2.1 Defining energy intensive industry

The manufacturing sector was split into an EI and NEI subsector. This division was intended to be on the basis of the potential strength of drivers to energy intensity improvement. To perform this division the manufacturing sector is split into subsectors, as defined by Standard Industrial Classification (SIC) [17] codes, the criteria used to assess the strength of potential drivers in each subsector were:

1. The aggregate energy intensity[1] (energy use per unit of output), of a subsector.

2. The proportion of total financial costs represented by energy and water for a subsector.

3. The mean energy use per enterprise in a subsector.

The first criterion is a representation of the direct and indirect financial incentives to reducing energy intensity. Legislation (such as the Climate Change Agreements in the UK) also tends to target subsectors with high aggregate energy intensity. The second criterion is obviously heavily related to the potential for financial cost reductions through energy saving measures. Ideally water costs would not be included here, but have been due to limitations of the data source [18]. The third criterion is related to financial savings and legislation. Although the proportion of costs represented by energy may be low at a site, if the firm is a large enough site in terms of its total energy use, it may still make financial sense to employ an energy manager and actively look for saving options. Legislation is also often based on a site's

[1] The term aggregate energy intensity is used to differentiate it from the decomposed energy intensity, found after removing the effects of structural change.

energy use [as in the case of the European Union Emissions Trading System (EU ETS) and Carbon Reduction Commitment (CRC) in the UK]. Ramirez et al. [16] adopted a similar approach in defining subsectors as EI or NEI, using only the first two criteria above, in their study of the Netherlands.

To be classified as EI a subsector needs to meet any of the above criteria over a certain threshold. Values chosen for the split should therefore represent a strong incentive to explore and implement energy saving options in comparison to the remainder of the manufacturing sector. The values were set as one and a half times the figure for the manufacturing sector, when analysed as a whole, for criteria 1 and 2. For criteria 3, due to a greater variation in values, and as it is seen as a weaker driver a limit of 100TJ/enterprise was adopted. The values used to define subsectors as EI or NEI are the mean over the years 2002-2006, after removing the highest and lowest values. This was because of incomplete data for some years [18]. These criteria were found to give realistic results.

2.2 Decomposition analysis

There are a number of methodological choices to be made when undertaking a decomposition analysis. They can potentially influence the results from the analysis, and so need to be made carefully, bearing in mind the aim of the study. When comparing various studies it is important to be aware of the limitations in comparing the results arising from methodological differences. The broad technique of decomposition analysis undertaken here is often known as Index Decomposition Analysis (IDA), and is based on statistical data. It was preferred to Structural Decomposition Analysis (SDA), which employs input-output tables. Although SDA analysis can give more refined decomposition of economic and technological effects [19], IDA was used here because of its simplicity, the availability of data, and as previous decomposition studies of the UK [6-15] tend to use IDA. Its use thereby facilitates historical comparison. There are a number of different variant techniques available within IDA. A useful guide to the various options is given by Ang [20]. The log mean Divisia index method I (LMDI I) is used here, it was first introduced by Ang et al. [21]. The method is perfect in decomposition, having no residual term[2]. It is recommended for general use based on theoretical foundation, adaptability, ease of use, and ease of result interpretation [20]. Additive decomposition is used here, where the difference in the factor investigated over a time period is decomposed into the contributing factors. The alternative method is known as multiplicative decomposition, where the ratio, rather than the difference is decomposed. This choice only affects the way results are presented, and the additive approach was favoured here for ease of interpretation.

The methodology employed was adapted from the work of Ang [22]. The total change in carbon emissions (ΔC_{tot}), over a time period (*0* to *T*), is a sum of the changes due to changes

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[2] Meaning all change is fully accounted for by the factors investigated; there is no unexplained residual.

in production volume (ΔC_{pdn}), changes in inter-sector structure (ΔC_{str}), changes in energy intensity (ΔC_{int}), changes in fuel mix (ΔC_{mix}), and changes in emission factor (ΔC_{emf}).

$$\Delta C_{tot} = C^T - C^0 = \Delta C_{pdn} + \Delta C_{str} + \Delta C_{int} + \Delta C_{mix} + \Delta C_{emf}\ , \tag{1}$$

For *i* subsectors of industry, using *j* fuels the total carbon emissions can be given by:

$$C = \sum_{ij} C_{ij} = \sum_{ij} Q \frac{Q_i}{Q} \frac{E_i}{Q_i} \frac{E_{ij}}{E_i} \frac{C_{ij}}{E_{ij}} = \sum_i Q S_i I_i M_{ij} U_{ij}\ , \tag{2}$$

where Q is the output of manufacturing; $S_i(=Q_i/Q)$ and $I_i(=E_i/Q_i)$ are, respectively, the activity share and aggregate energy intensity of subsector *i*; $M_{ij}(=E_{ij}/E_i)$ is the proportion of energy in subsector *i* supplied by fuel *j*, and $U_{ij}(=C_{ij}/E_{ij})$ is the carbon emission factor of fuel *j* in subsector *i*. The components of change in equation (1) are given by:

$$\Delta C_{pdn} = \sum_{ij} L\left(C_{ij}^T, C_{ij}^0\right) \ln \frac{Q^T}{Q^0}\ , \tag{3}$$

$$\Delta C_{str} = \sum_{ij} L\left(C_{ij}^T, C_{ij}^0\right) \ln \frac{S_i^T}{S_i^0}\ , \tag{4}$$

$$\Delta C_{int} = \sum_{ij} L\left(C_{ij}^T, C_{ij}^0\right) \ln \frac{I_i^T}{I_i^0}\ , \tag{5}$$

$$\Delta C_{mix} = \sum_{ij} L\left(C_{ij}^T, C_{ij}^0\right) \ln \frac{M_{ij}^T}{M_{ij}^0}\ , \tag{6}$$

$$\Delta C_{emf} = \sum_{ij} L\left(C_{ij}^T, C_{ij}^0\right) \ln \frac{U_{ij}^T}{U_{ij}^0}\ , \tag{7}$$

where,

$$L\left(C_{ij}^T, C_{ij}^0\right) = \frac{C_{ij}^T - C_{ij}^0}{\ln C_{ij}^T - \ln C_{ij}^0}\ . \tag{8}$$

The outputs of equations (3)-(7) are referred to as the production effect, structural effect, intensity effect, fuel mix effect, and emissions factor effect respectively. The intensity effect can provide an indication of changes in energy efficiency, whereby a falling intensity effect can indicate an improving efficiency. The decomposed intensity is only an approximate measure of efficiency however. The intensity effect will also include the effects of structural change that occur at a more disaggregate level than that used when splitting manufacturing into subsectors for the decomposition analysis (intra-sector structural change). Additionally as energy use at a manufacturing site is not directly proportional to output, there will usually be a fixed energy overhead [6]. So if output increases, intensity will tend to decrease, with more output produced for every unit of energy demand. This decreasing intensity can occur with no efficiency improvement at the process level.

2.3 Data and measures used

The manufacturing sector examined here is defined by SIC codes 15-37, excluding the subsector defined by SIC 23 (Manufacture of coke, refined petroleum products and nuclear fuel), and SICs 16 and 37, for reasons discussed below. Details of these subsectors are given in Table 1. Energy demand is measured in terms of Gross Calorific Value (GCV) [Higher Heating Value (HHV) in US usage], and final energy demand, obtained from the 'Digest of United Kingdom Energy Statistics' (DUKES) [1] and 'Energy Consumption in the UK' (ECUK) [24]. Energy use was split between eight different fuels, as detailed in Table 4. Measuring energy in terms of final demand means that improvements in electricity generation, both in terms of generation efficiency and carbon emissions factor of the fuels utilised are encapsulated in the emission factor effect (ΔC_{emf}). Due to limitations of the data used, this method does not account for the use of combined heat and power (CHP) by some subsectors and the reduced primary energy use and emissions this entails. This would lead to a reduced emissions factor for electricity for those subsectors that do use CHP. Only the emission factor of electricity is varied in this study, with other fuels' emissions factors held constant, this is approximately true. Emission factors are taken from the '2009 Guidelines to Defra / DECC's GHG Conversion Factors for Company Reporting' [25]. The emissions factor in terms of carbon equivalents on a grid rolling average basis is used for electricity, this includes the emissions of all major GHGs and smoothes out large year-on-year fluctuations that may occur due to the variation of fossil fuel prices [25].

Table 1. Subsector split of the manufacturing sector used in this work.

SIC code	Description
15	Manufacture of food products and beverages
16	Manufacture of tobacco products
17	Manufacture of textiles
18	Manufacture of wearing apparel; dressing and dying of fur.
19	Manufacture of leather and leather products
20	Manufacture of wood and wood products
21	Manufacture of pulp, paper and paper products
22	Publishing, printing, and reproduction of recorded media
24	Manufacture of chemicals, chemical products and man-made fibres
25	Manufacture of rubber and plastic products
26	Manufacture of other non-metallic mineral products
27	Manufacture of basic metals
28	Manufacture of fabricated metal products, except mach and equipment.
29	Manufacture of machinery and equipment NEC
30	Manufacture of office machinery and computers
31	Manufacture of electrical machinery and apparatus NEC
32	Manufacture of radio, television and communication equip and apparatus
33	Manufacture of medical, precision and optical instr, watches and clocks
34	Manufacture of motor vehicles, trailers and semi-trailers
35	Manufacture of other transport equipment
36	Manufacture of furniture; manufacturing NEC
37	Recycling

Measuring the useful output of a manufacturing subsector when constructing an efficiency indicator is a topic that has received considerable attention [23, 26-31]. Physical output is generally accepted as the best measure of useful output from a site or subsector of manufacturing [16, 27-29, 31-37] being objective [23] and not subject to the price fluctuations of economic measures of output. This makes physical output measures more suitable for comparison over long time periods [23, 32] and between nations [31, 32]. However using physical output measures can be difficult in practice due to the problem of aggregating different outputs in a meaningful way [23, 28, 34]. Techniques have been developed to allow physical output measures to be used at a more aggregate level [27, 32, 34, 37]. However, these can be both time consuming and require large amounts of data [27, 34], the quality of data limiting the results more than the choice of methodology [34]. For the current study, sufficient data for all subsectors was not available to enable the use of a physical output measure.

Measuring output in economic terms overcomes the problem of aggregating outputs as a common unit is adopted. Nevertheless, due to variability in the price of a product, economic measures may include not only the change in output, but also a change in price. Economic measures can, under certain situations and datasets, track efficiency with greater accuracy than physical output [26], although this is not a common finding. The aim of an economic output measure when used in an efficiency indicator is to track the change in physical output. Value added, value of production, and value of shipments are three possible measures of output. Given a perfect price index, (that is an index to adjust for the change in price of a product over time, due to inflation, demand and other factors) the percentage change in value of production should be equal to the percentage change in physical output [28]. However, in reality, price indices are not perfect [28], and considerable variability has been observed in the way value-based measures track physical output [27, 28, 30, 31]. There is no measure that is universally recognised as being superior in this regard. The economic measure that best tracks physical output can vary by nation [31] and dataset [34]. Worrell et al. [31] noted that, for the iron and steel sector of developed countries, value added generally best tracked physical production. However, other studies have found value added more likely than value of production to exaggerate changes in the efficiency indicator [16, 28, 30]. Value added tends to be the most widely used of the economic output measures (for example in previous decomposition studies [7, 8, 10-15]). This may be because it is also the most widely reported. As value of production does not subtract the cost of inputs from gross output as value added does, there are concerns about the double counting this may induce [8, 16, 34], although this double counting is thought, by some studies, to be minimal [30]. Value of production was used in the current study due to it best tracking physical output in theory; on the balance of evidence it appears less likely to exaggerate changes in intensity than value added; and due to data availability. It is recognised that the choice of output measure may affect results and so the results presented here are only applicable to this methodology. The Index of Production (IoP) [38] is used with economic output data in current terms for 2005, taken from the 'Annual Business Inquiry' (ABI) [18] to calculate the value of production at constant 2005 prices. Data on costs and number of enterprises in each subsector are taken from the ABI [18], whilst energy price data are extracted from the 'Quarterly Energy Prices' publication [39].

2.4 Timescale and disaggregation level of analysis

Some studies have found the level of disaggregation used in a decomposition analysis can significantly affect results [40]. Structural change, for example, can be underestimated if analysis is not undertaken at a high enough level of disaggregation [9]. As discussed above, in Section 2.2, these extra structural contributions will be included in the intensity effect. This can give a false impression of the change in intensity, and hence the indicator of efficiency.

Analysis was conducted at the highest level of disaggregation possible with the data utilised. This resulted in the manufacturing sector being split to 22 subsectors, based on the SIC system [17]. This subsector split is shown in detail in Table 1. It would be desirable to perform the analysis with a higher level of subsector disaggregation. Suitable data that would allow this were restricted in timescale however, and so not appropriate for this study. This level of disaggregation, detailed in Table 1, was also used for the split into the energy-intensive and non-energy-intensive subsectors.

The decomposition analysis covered the time period 1990-2007. Due to methodological changes in the collection of energy data [1] over the periods 1995-1996, 1998-1999 and 2000-2001, analysis could not span all years. The recycling subsector (SIC 37) could not be included in the decomposition analysis due to a lack of output data. The tobacco sector (SIC 16) was also omitted due to concerns about the accuracy of data; it comprises only a very small proportion of energy use and carbon emissions in manufacturing (this meant there were twenty subsectors included in the full analysis).

3. Results

3.1 Defining energy-intensive industry

There are eight subsectors of manufacturing classified as EI, in this study, these subsectors are labelled in Figure 1. To be defined as EI a subsector requires an aggregate intensity greater than 6.46MJ/£, and/or energy and water costs greater than 3.3% of total costs, and/or energy demand per enterprise greater than 100TJ[3]. The EI subsector is responsible for approximately 65% of energy demand, whereas the NEI subsector contributes approximately 65% of economic output. This leads to an aggregate intensity in the EI subsector of approximately four times that in the NEI subsector.

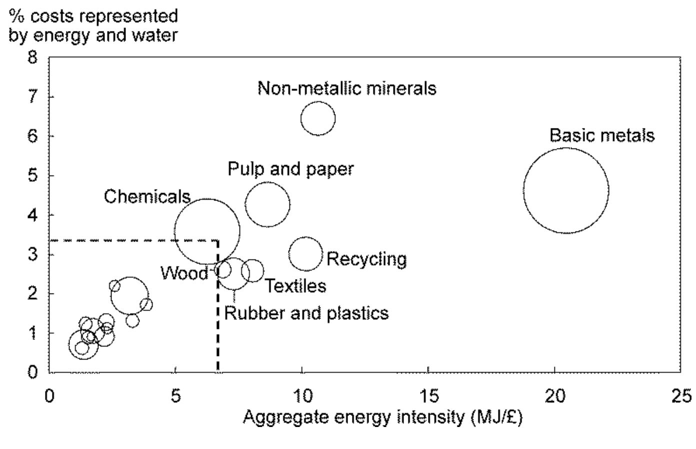

Figure 1. Subsectors of UK manufacturing split into an EI and NEI subsector, 2002-2006. [NB: The energy use per enterprise is represented by the area of data points.]

[3] In this case all subsectors classified as EI met one of the first two criteria and so the energy demand per enterprise was redundant.

3.2 Decomposition analysis

Figures 2, 3 and 4, and Table 2 below show results from the decomposition analysis of energy-related carbon emissions from the UK manufacturing sector at a 2 digit SIC level of disaggregation for 1990-2007. The effect of changes in production (Pdn), structure (Str), energy intensity (Int), fuel mix (Mix), emissions factor (Emf) and the total change in carbon emissions (Total) are shown separately. The dotted lines indicate those periods that cannot be directly compared due to methodological changes in the compilation of data sources. The values shown are the cumulative change since 1990, shown as a percentage relative to the level of carbon emissions in 1990. The mean annual change caused by each of the effects contributing to changes in carbon emissions are shown in Table 2. Total change is given as a percentage of the previous year's emissions (note this annual mean change does not include those years for which methodological change prevents comparison).

Figure 2 shows the results of the analysis for the whole manufacturing sector. The effect of alteration in the fuel mix has had a net positive effect on the carbon emissions over the period. The bulk of the effect due to fuel mix has been since 2001. This is mainly caused by an increase in the proportion of electricity used [1], which has a higher emission factor than other fuels. This higher emission factor primarily being due to the losses involved when generating and transporting centralised electricity. Production has displayed a net growth over the period 1990-2007, causing an increase in manufacturing energy-related emissions. During the early 1990s there was a recession in the UK, causing the negative contribution to emissions from the production effect. The most recent recession (2008-present) is likely to cause a similar, or more pronounced effect, in years subsequent to this study. Structural effects have had little impact over the time period, causing only a slight reduction in energy demand. The bulk of the decrease in carbon emissions is caused by a decline in intensity and, to a lesser extent, the changes in electricity emissions factor (specifically in the years up to 2000). This decline in electricity emissions factor was primarily caused by an increase in the use of natural gas in electricity generation (and a corresponding decline in coal and oil) during the 1990s [41]: the so called 'dash for gas'. A slight increase in emissions factor after this period was caused by a decrease of nuclear in the generation mix [41]. Prior to 2000 the reduction in the emissions factor of electricity limited the effect seen in shifts of the fuel mix towards electricity, whilst post 2000 the increase in emissions factor has accentuated the fuel mix effect due to an increase in electricity use.

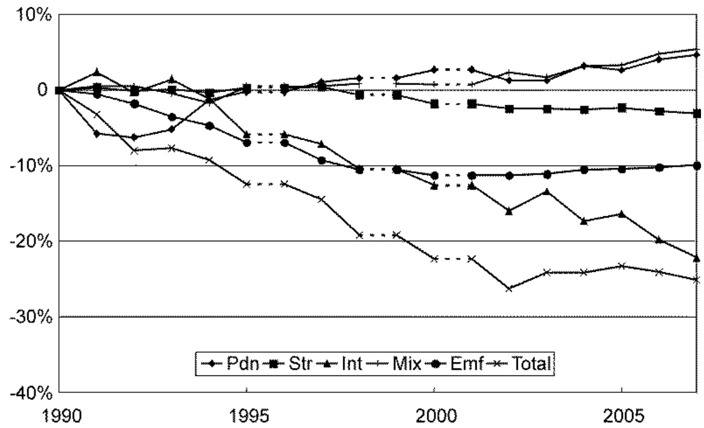

Figure 2. Decomposition of carbon emissions in the UK manufacturing sector, 1990-2007. The cumulative change in carbon emissions (Tot), due to changes in production (Pdn), structure (Str), energy intensity (Int), fuel mix (Mix) and emissions factor (Emf), are shown as a percentage, relative to the level of carbon emissions in 1990.

It is useful to consider the EI and NEI subsectors separately. Figure 3 shows the results for only the EI subsector, and Figure 4 those for just the NEI subsector (with corresponding numerical results in Table 2). Note that the results in Figure 3 and Figure 4 are both shown in relation to the carbon emissions of the corresponding subsector in 1990. Comparing Figure 3 and Figure 4 it can be seen that the NEI subsector has made greater relative reductions in its carbon emissions over the period 1990-2007. This is mainly due to a much greater reduction in the intensity effect over this period. This is surprising as the split into the EI and NEI subsectors was adopted on the basis that the EI subsector is subject to notionally stronger drivers to reducing energy intensity than the NEI subsector.

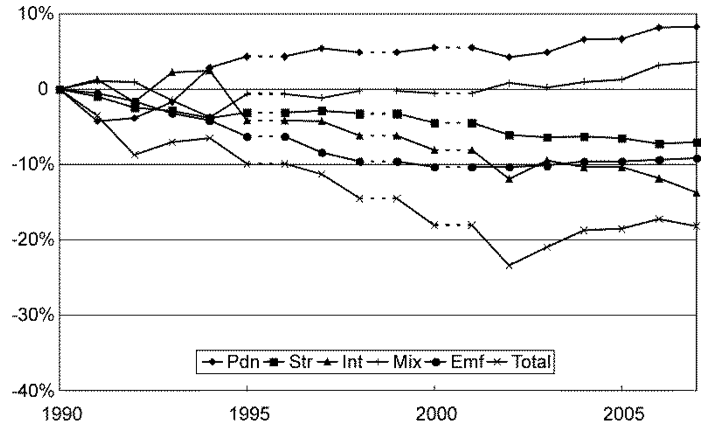

Figure 3. Decomposition of carbon emissions in the EI subsector of UK manufacturing, 1990-2007. The cumulative change in carbon emissions (Tot), due to changes in production (Pdn), structure (Str), energy intensity (Int), fuel mix (Mix) and emissions factor (Emf), are shown as a percentage, relative to the level of carbon emissions in 1990.

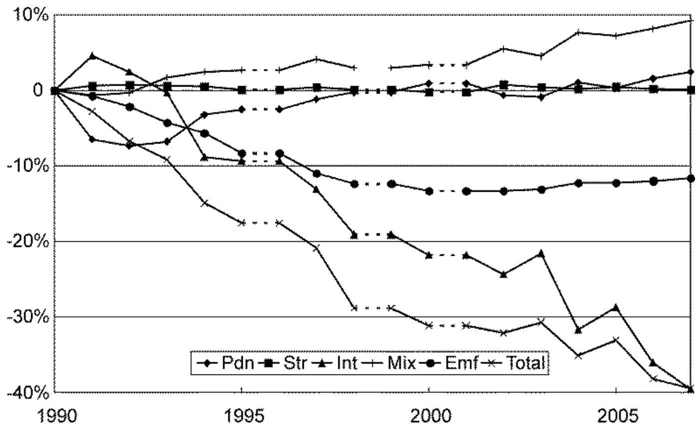

Figure 4. Decomposition of carbon emissions in the NEI subsector of UK manufacturing, 1990-2007. The cumulative change in carbon emissions (Tot), due to changes in production (Pdn), structure (Str), energy intensity (Int), fuel mix (Mix) and emissions factor (Emf), are shown as a percentage, relative to the level of carbon emissions in 1990.

Table 2. Decomposition of carbon emissions in the UK manufacturing sector, 1990-2007. [NB: Total change is the mean annual percentage change in carbon emissions, compared to the previous year's emissions.]

	Manufacturing sector	EI subsector	NEI subsector
Production	0.46%	0.72%	0.31%
Structure	-0.27%	-0.59%	-0.00%
Intensity	-1.92%	-1.14%	-3.52%
Fuel mix	0.49%	0.33%	-0.81%
Emissions factor	-0.77%	-0.69%	-0.95%
Total	-2.01%	-1.37%	-3.35%

4. Discussion

4.1 Historical context

It is useful to place the current results in a historic context. Energy use first became an important issue for many companies following the first, so called, oil crisis in 1973, and the subsequent energy price rise. Although the data used for the main analysis does not cover the period prior to 1990, previous studies and data have covered the period 1973-1990.

Table 3 shows the results from a decomposition analysis, published by the former Department of Trade and Industry (DTI) in Energy Paper 64 (EP64) [6]. These cannot be directly compared to those of the current study, due to differences in methodology and data sources. The EP64 analysis also only covers final energy demand, rather than carbon dioxide emissions. However, general trends can be extracted in order to aid the understanding of the results from the current study. EP64 is not the only study that carried out a decomposition analysis of the UK industrial sector pre-1990 [7-15]. The results from EP64 are presented in a form that could be most easily extracted for comparison purposes and the analysis was also undertaken at the greatest level of disaggregation. Other studies are generally in agreement in the main trends seen here[4].

It can be seen from Table 3 that prior to 1990 there has been an overall reduction in energy demand from the manufacturing sector. As in the post 1990 period the main contributor is a falling energy intensity, with structural change having a relatively small impact in reducing energy demand. In contrast, there were significant falls in pre-1990 production (up until the mid 1980s). The greatest period of energy demand reduction was 1979-1984, where the largest relative annual drops in production, intensity and structural effect combined to give by far the greatest reduction in energy demand seen in the twenty year period from 1973-1993.

Table 3. Decomposition of final energy demand, 1973-1993, adapted from EP64 [6]. [NB: Total change is the mean annual change in the final energy demand, given as a percentage of the mean energy demand over the period.]

	1973-1979	1979-1984	1984-1989	1989-1993
Production	-0.77%	-1.93%	4.30%	-1.14%
Structure	-0.01%	-1.19%	-0.26%	-0.52%
Intensity	-0.75%	-4.37%	-3.00%	0.74%
Total	-1.52%	-7.49%	1.04%	-0.92%

4.2 Production growth

As manufacturing output rises, intensity is often observed to improve. An increase in output is usually coupled with investment in new plant, new equipment is generally more efficient than older equipment, and so intensity improves [9, 15] (assuming no significant change in intra-sector structure). The results shown in Figures 2 to 4 can support this idea. In the early 1990s a recession caused production to decrease, or at least remain constant. The intensity was relatively uniform over this period. As production recovered and grew, intensity decreased. This is not a simple relationship however. Part of this effect may be due to the presence of an energy overhead, as discussed in Section 2.2 above. The so-called ‘rebound effect’ may also provide a link between increases in efficiency and output. This is the mechanism through which improvements in efficiency actually lead to increases in energy demand. The effect can be either direct or indirect, according to Sorrell [42]. An example of a direct rebound effect in the manufacturing sector would be that improved efficiency encourages the substitution of energy for labour, or other inputs, in production [43]. An indirect effect example is that the cost savings from efficiency gains may be reinvested in additional equipment, which itself will have an energy requirement to produce [42]. Indirect effects can also take place outside of the manufacturing sector [42]. It is difficult to quantify the rebound effect in manufacturing [43], partly due to complex inter-sector linkages. In the context of the results presented here some increase in production could be caused by the falling intensity. The link between production growth and energy intensity is not always consistent. Table 3 shows that production

[4] There is some disagreement over the importance of structural changes, see Section 4.3.

decreases were coupled with falling intensity between 1973 and 1984, particularly so in the second half of this period.

4.3 Energy price

Higher energy prices increase the financial benefits of reducing energy use, and so can act as a strong driver for energy saving measures. Figure 5 shows how energy price in the industrial sector has varied between 1970 and 2009, for a number of fuels and for the annually weighted total fuel price. Over the majority of the period studied here (1990-2007) energy prices have been lower, in real terms, than for the previous two decades. Prices tend to have fallen during the 1990s, although in the late 2000s have risen to levels comparable to the peaks of the early 1980s.

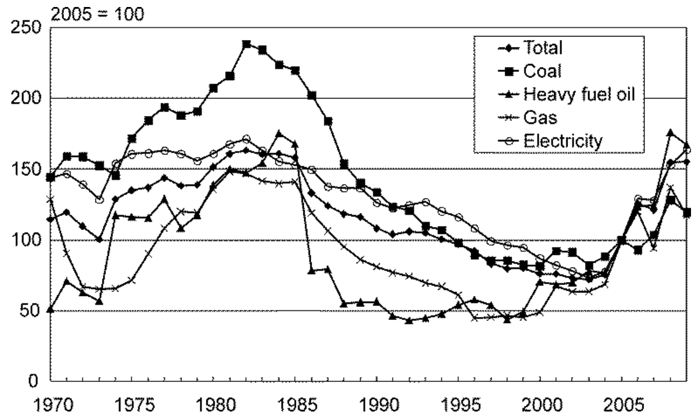

Figure 5. Fuel price index for the industrial sector, relative to GDP deflator, 1970-2009. Indexed to 2005. Adapted from QEP [30]. [NB: This includes the Climate Change Levy (CCL) from April 2001.]

It appears that in the current study energy prices have had little impact, Figures 2 to 4 show fairly constant reductions in the intensity effect (ignoring small annual fluctuations), outside the period of recession. Decreases in energy price during the 1990s were coupled with a continuing decrease in energy intensity. The effect of recent price rises may be yet to be seen, due to a delay, or lag, between price rises and companies taking action to improve their efficiency. This seems to be reasonable conjecture. It may take a sustained period of high prices to cause a reaction from the manufacturing sector, and the projects that result from this may take some time to be implemented [15]. The results shown in Table 3 can be used to examine the effects of energy prices pre-1990. The greatest intensity improvements were seen in the period 1979-1984, and 1984-1989. Figure 5 shows that energy prices started to increase sharply in 1973, peaking in 1984, and then falling thereafter until the most recent rise. This supports the idea that there may be a delay between an increase in prices and the reaction (characterised by lowered intensity) of industry.

Conflicting reports regarding the influence of energy prices on intensity can be found. Howarth et al. [8] examined the link between price and energy intensity improvements in eight OECD countries. They found that intensity did not increase more rapidly when energy prices were high. In fact the greatest improvements were often seen when energy prices were low and growth was stimulated. This led, as discussed above in section 4.2, to lowered intensity. Conversely, Greening et al. [15] found a link between large falls in energy intensity and increasing prices. Energy prices can also influence the structure of industry as rising prices encourage a move towards less energy-intensive manufacturing [9]. It is difficult to draw any conclusions on the effect of energy price on production and structural changes over the period 1990-2007 as prices have been relatively low. Prior to 1990 periods of high energy prices corresponded with falls in production, with the only period of output growth, 1984-1989, coupled with a drop in energy prices (see Table 3 and Figure 5). There is some disagreement in the literature over the influence structural changes had on industrial energy demand following the first oil crisis (compare for example [9] to [6, 8]).

Increasing energy prices through policy, either directly or through options that penalise emissions, is a common method used by governments to encourage more efficient use of energy in manufacturing. However, this is a difficult balancing act as high prices can also limit growth (which can harm improvements in intensity) and have the potential to stimulate energy-intensive manufacturing within 'emerging' nations (such as those in South East Asia) with lower energy prices, and associated 'carbon leakage' [44]. The UK already relies on imported products to meet its needs. It was estimated that the UK imported over 30% of its carbon emissions in 2004 [45], based on where products and services were consumed, rather than produced. An increase in the level of imports may help the UK manufacturing sector reduce its emissions, but this would be a somewhat misleading reduction. Climate change due to emissions is a global problem and moving activities to other areas of the world can have a negative effect, due to increased transportation requirements and possibly less stringent local environmental legislation.

4.4 Fuel switching

Falls in energy intensity can be due to fuel switching. For example natural gas can usually be used more efficiently than coal due to the greater control afforded. Adams and Miovic [46] noted this effect as being partly responsible for a falling energy intensity, despite falling energy prices. Table 4 shows the change in fuel mix over the period 1990-2007. Increases in the proportions of natural gas and electricity are thought to be responsible for some of the intensity improvement observed. In the case of electricity this intensity improvement is offset by having a greater emissions factor than other fuels (see section 3.2). Future decarbonisation of electricity generation may also make electricity attractive from a carbon emissions perspective. The shifts in fuel mix can be influenced by the fluctuations in price of individual fuels. During the 1990s all the major fuels except oil showed significant price falls (see Figure 5). This can partly explain the move away from oil as a fuel in the manufacturing sector. Coal although also falling in price has other disadvantages, requiring additional transport and storage [15].

Table 4. The fuel mix of manufacturing, the EI and NEI subsectors. 1990 and 2007. Adapted from DUKES [1] and ECUK [23].

Fuel	EI		NEI		Total	
	1990	2007	1990	2007	1990	2007
Coal	14%	11%	5%	1%	11%	8%
Natural gas	32%	35%	39%	50%	34%	40%
Manuf. fuel	20%	14%	0%	0%	13%	10%
LPG	2%	0%	2%	0%	2%	0%
Fuel oil	9%	4%	13%	2%	10%	4%
Gas oil	3%	6%	13%	7%	6%	7%
Electricity	21%	29%	27%	40%	23%	33%

4.5 The energy-intensive and non-energy-intensive subsector

A greater level of fuel switching in the NEI subsector (see Table 4) can partly explain the greater comparative improvements in intensity, compared to the EI subsector. The NEI subsector has shown less production growth however, which is often linked to intensity reductions, see section 4.2. Additional reasons for the intensity improvement in the NEI subsector are sought, and the period prior to 1990 is examined to provide some insight.

It was possible to undertake some additional analysis using the same measure of output as for the core study and energy demand data from EP64 [47]. This analysis consisted of decomposing final energy demand into the effects of changes in production, structure, and intensity. The analysis was limited to two discrete five year periods, 1979-1984 and 1984-1989, with this data. Results are not directly comparable with the post 1990 period as energy data is drawn from a different source. However results from this analysis should be sufficient to examine any large differences between the EI and NEI subsectors pre-1990. The associated results from this analysis are shown in Table 5.

Table 5. Decomposition of final energy demand, in the EI and NEI subsector, 1979-1989. [NB: Total change is the mean annual change in the final energy demand, given as a percentage of the mean energy demand over the period.]

	1979-1984		1984-1989	
	EI subsector	NEI subsector	EI subsector	NEI subsector
Production	-2.02%	-2.21%	4.35%	3.62%
Structure	-0.07%	0.49%	-0.21%	-0.41%
Intensity	-7.22%	-2.91%	-3.41%	-1.43%
Total	-9.33%	-4.63%	0.73%	1.78%

The structural and output effects are similar between the two subsectors, but the intensity effect indicates that the EI subsector made much larger improvements between 1979 and 1989 in comparison with the NEI subsector. For any company, or subsector of industry, there tends to be a number of opportunities for saving energy that are relatively easy to implement and have attractive economics. These are sometimes referred to as ‘low hanging fruit’. One possibility for the better energy intensity performance seen in the NEI subsector, is that due to the notionally stronger drivers to reducing energy intensity in the EI subsector, it made greater intensity improvements pre-1990, in comparison to the NEI subsector. Consequently within the NEI subsector there may have been relatively easier options to improve energy intensity over the period 1990-2007, in comparison to the EI subsector. Examining the whole manufacturing sector there is evidence from previous studies for energy intensity improvements slowing since the late-1980s, both within the UK and more widely in other developed nations [11, 12]. Part of this trend may result from the fact that opportunities for improving intensity are becoming more difficult to realise [48]. This does not mean energy intensity improvement has 'run its course'. Further potential improvements in energy efficiency within manufacturing have been identified [49, 50]. Significant future improvements may require substantial process redesign and material substitution [50], rather than relying on, relatively small, continual improvements in efficiency [51] however.

5. Concluding remarks

Energy-related carbon emissions from UK manufacturing have fallen by approximately 2% per annum over the period 1990 to 2007. The principal reason for this drop was the improving energy intensity, with a fall in the emission factor of electricity also having a significant effect. The EI subsector of manufacturing, with notionally greater drivers to reducing energy-related carbon emissions and reducing intensity, has actually shown significantly less relative progress than the NEI subsector in terms of reducing intensity.

Energy prices have generally been falling over the period of the study, being low in relation to previous decades. Prices seem to have had little influence on changes in intensity. Some of the improvement in intensity may have been stimulated by growth and the new facilities and equipment this entails. It is also thought that some of the intensity improvement is due to fuel switching towards electricity and natural gas, which can generally be used more efficiently than alternatives. Improvements in energy intensity can also be due to more efficient technology being employed, better control and housekeeping or due to a change in the feedstock (utilising a higher proportion of recycled materials). Additionally intra-sector structural change may also cause changes in energy intensity. The better performance of the NEI subsector may be partly due to the EI subsector showing greater improvements in energy intensity in the pre-1990 period. As energy intensity reductions are made the easier options (the 'low hanging fruit') are taken first, and so making further intensity improvements can be more challenging.

The analysis conducted here is from a broad, top-down perspective. It therefore covers the manufacturing sector as a whole and can indicate general trends, but cannot determine the real efficiency (rather than intensity) gains made at a subsector level. A limitation on any decomposition, or top down study is the level of disaggregation, methodology and data used. The split into EI and NEI subsectors could also benefit from greater disaggregation as, especially in subsectors that are heterogeneous in their energy use (specifically food and drink and chemicals), there may be subsectors that would fall under different classifications.

Acknowledgments

The funded research of the first author (GPH) on industrial energy demand and carbon emissions reduction currently forms part of the research programme of the UK Energy Research Centre (UKERC); Phase II renewed in 2009. This national centre is funded by three of the UK Research Councils—the Economic and Social Research Council (ESRC), the EPSRC, and the Natural Environment Research Council (NERC). The second author (JBN) is supported by a research studentship co-funded by the Great Western Research (GWR) Alliance, EDF Energy and EDF R&D (Ecleer) (jointly supervised by Professor Hammond and Professor Catherine Mitchell of the University of Exeter's Cornwall Campus). Both the authors are grateful to the support given by Pascal Terrien and his team at Ecleer (EDF R&D, Moret-Sur-Loing, France) to the project.

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