Kiel
Working Papers

Kiel Institute
for the World Economy

Carbon Efficiency, Technology, and the Role of Innovation Patterns: Evidence from German Plant-Level Microdata

by Sebastian Petrick

No. 1833 | February 2013

Web: www.ifw-kiel.de

Kiel Institute for the World Economy, Hindenburgufer 66, 24105 Kiel, Germany

Kiel Working Paper No. 1833 | February 2013

Carbon Efficiency, Technology, and the Role of Innovation Patterns: Evidence from German Plant-Level Microdata

Sebastian Petrick

Abstract:
We describe the determinants of energy intensity, carbon intensity, and CO2 emissions in the German manufacturing sector between 1995 and 2007, applying the LMDI index decomposition technique not to aggregate but to micro data. We trace back changes in total CO2 emissions from manufacturing to changes in activity level, structural change between sectors, structural change within sectors, energy intensity at the firm level, fuel mix, and emission factors. We use a firm data set on energy use from the AFiD-Panel on German manufacturing plants that allows us to analyze energy use at the firm level with unprecedented accuracy. Our results show that heterogeneity among firms within one sector is a driver of energy intensity, carbon intensity, and CO2 emissions. By stressing the importance of competition between firms for energy efficiency improvements, we highlight a factor that has so far been widely ignored. Firm heterogeneity has so far rarely included in index decomposition analyses. Contrary to wide-spread beliefs, energy intensity improvements at the firm level do not play a significant role in reducing emissions. Based on findings from the decomposition analysis, we use sector-level results on the relative importance of improvements in firm-level energy intensity and intra-sectoral structural change to distinguish two different innovation channels: innovation by technology and by entrants. We show that incumbent firms in a number of sectors, including some of the most energy intensive ones, do not significantly improve their energy efficiency. Innovation takes place via new entrants instead, rendering standard policies targeted at firm-level energy efficiency ineffective.

Keywords: Index decomposition, industrial energy, energy intensity, carbon intensity, structural change

JEL classification: Q40, Q41

Sebastian Petrick
Kiel Institute for the World Economy
24100 Kiel, Germany
E-mail: sebastian.petrick.@ifw-kiel.de

Coverphoto: uni_com on photocase.com

1 Introduction

Manufacturing companies in highly developed economies face a limited set of options for coping with increasing energy prices and complying with regulation aimed at reducing industrial emissions of greenhouse gases. The severity of this problem varies across sectors and industries, but it is especially serious in energy intensive industries such as metal manufacturers or the pulp and paper industry. Once fuel-switching opportunities are exhausted, the only option left is the substitution of capital for energy, through the adoption of energy-efficient technology embodied in new capital goods. Promoting energy efficiency is also popular among policy makers, since efficiency measures are supposed to be sustainable and foster energy security while not corrupting economic efficiency.

At the macro- or mesoeconomic (i.e. sectoral) level, the ratio between energy consumption and gross domestic product or gross value added is often used as an energy intensity measure. However, this ratio lumps together the pure technological component of energy intensity and structural differences. If the output share of an energy intensive sector decreases while a less energy intensive sector's share increases, the aggregate energy intensity of the whole industrial sector drops even though not a single production process has been technologically improved. The same argument holds within one sector for more and less efficient firms, as we will explain below. It is one of this paper's aims to disentangle the structural and technological components of energy intensity as well as, at a later stage, carbon intensity and CO_2 emissions. We want to highlight the importance of intra-sectoral structural change for the development of industrial energy intensity and its implications for the interpretation of improvements in sector-level energy efficiency. As will become clear, intra-sectoral structural cange is a major driver of industrial energy efficiency that has so far been widely ignored. In many previous decomposition exercises, and dictated by the nature of aggregate data, efficiency gains from competition within sectors have been interpreted as technological improvements.

Based on our findings on the role of technological progress at the firm level, we will distinguish different energy efficiency innovation patterns of different sectors: While firm-level energy efficiency innovations play a role in some sectors, other sectors innovate mostly via new entrants. Our conclusion is that policies targeted at firm-level efficiency improvements, such as innovation subsidies, may be ineffective in the sectors innovating via entrants.

In the course of the paper we will first give an overview of the development and the driving forces of energy and carbon efficiency in the German industry sector (section 2). In section 3, we shortly explain index decomposition methods, including an overview of the relevant literature. We present our micro-dataset in section 4. Our results are presented in sections 5 and 6. In the last section we conclude.

2 Energy and Carbon Efficiency in the German Industry Sector

Over the last couple of years, energy intensity in Germany has decreased considerably, as it has in most industrialized countries (EIA 2010). This observation holds for both the economy as a whole, and the industrial sector (cf. Figure 1).

FIGURE 1 ABOUT HERE

However, disparities in energy intensity between the sectors within manufacturing are high: The average energy intensity of four especially energy intensive sectors – metal manufacturing, paper and pulp, chemicals as well as glass, cement and mineral products – is more than three times the average energy intensity of all other sectors in manufacturing (13 464 TJ/bn. EUR compared to 4 264 TJ/bn. EUR, 2007 numbers, own calculations based on Statistisches Bundesamt 2012).

At the same time, there has been significant structural change within manufacturing: While some sectors, like the especially energy intensive sectors mining or glass, cement and mineral products, have decreased in importance, other sectors, like car manufacturers, have gained. Some sectors, like the paper and pulp sector, show a more volatile development, including periods of increasing and decreasing shares (Statistisches Bundesamt 2012).

Structural change between sectors with different sectoral energy intensities leads to changes in overall energy intensity that are not due to technological or behavioural change, but rather to changes in the sectoral composition of manufacturing. To decompose changes in overall intensity into structural changes and “real” energy intensity changes index decomposition techniques are used. This “real” intensity effect reflects changes in individual sectors’ energy intensity. It is often perceived as an indicator for technological progress or stagnation driving overall energy intensity, implicitly assuming a homogeneous structure within the sector. Nevertheless, this assumption ignores – and has to ignore because of data restrictions – a natural second thought about the structural change argument. If there is structural change between sectors, there might of course also be structural change between firms in a sector, which influences the energy intensity of a sector. The structural change effect within a sector could be identified as a change in the companies’ share in the sector’s total output. The sectors' aggregate energy intensities would decrease if relatively energy efficient companies gain market share, while relatively less energy efficient companies lose market share. One can identify the "true" intensity effect – i.e. changes in the firms' energy intensities – by controlling for structural change within sectors.[1]

Especially for the debate on climate change, the relevant indicator is not necessarily energy intensity, but rather carbon intensity, i.e. the ratio between a sector's or firm's CO_2 emissions and the corresponding output. While energy intensity is of course a decisive determinant of carbon intensity, both variables do usually not evolve in a parallel way (for Germany, cf. Figure 2).

Figure 2 *ABOUT HERE*

The difference between the two curves results from changes in the fuel mix and the emission coefficients of the fuels, i.e. the amount of CO_2 that is emitted by using one unit of the respective fuel. Although the emission coefficients are constant for most fuels, they may change over time for some fuels because of changes in the conversion from primary to final energy. This is especially important in the case of electricity, where we observe a shift in the composition of the power plant fleet, but also for hard coal, where the import shares of different countries of origin vary.

So far, we explained five drivers of carbon intensity in the manufacturing sector: Firstly, composition of manufacturing as a whole, made up by sectors of different energy intensity, secondly, division of the sectors into firms of different energy intensity, thirdly firm-level energy intensity, fourthly firm-level fuel mix and fifthly fuel-specific emission coefficients. In addition, we will add the level of activity, i.e. the overall output level, in order to move from carbon intensity to CO_2 emissions, as one of the most important indicators for the sustainability of manufacturing. In total, we identify 6 drivers, or effects, on changes of total CO_2 emissions: the effects of changes in economic activity, structural change between sectors, structural change

---

[1] Although we make the bold claim to identify the "true" intensity effect, the above argument can obviously be extended to finer and finer aggregation levels, from the firm level to the plant level, and further on to the product or process level, finally even to the level of the individual machine. In that sense, we see a firm as the homogeneous entity which it of course in practice is not. Still, a firm is naturally much more homogeneous than a sector. For our question of interest there is a downside to disaggregation: To compare energy intensities at a fine aggregation level with aggregate intensities, which are necessarily measured in energy per monetary unit (e.g. kwh/EUR), also the disaggregated intensities will have to be per monetary unit and not per physical unit (which may be the preferred measure for other applications). We argue that below the firm level, prices paid between the different plants of a firm (or processes etc.) do not necessarily reflect realistic values of the physical flows due to the very flexible internal accounting procedures within firms. We therefore use the firm as our smallest unit, even though our data would permit to identify plant specific energy intensities.

between firms within economic sectors, firm-specific energy intensity, firm-specific fuel mix and the effect of a changing emission factor of the individual fuels.

3 Index Decomposition Methodology

To identify the described effects and lay the foundations for a better understanding of what is driving the observed trends in energy and carbon intensity, we apply an index decomposition technique. Index decomposition techniques have been widely used to disentangle structural and technological components of trends in energy intensity, carbon intensity, and emissions at the sector level. They make use of the fact that the industry-wide CO_2 emissions can be regarded as a weighted average of the described 6 effects at the sector level, where the emission shares of the sectors are the weights. Since the methodology is based on the decomposition of changes between two points in time, the researcher has to decide whether to use the weights of one of the two points in time or to compute an (not necessarily arithmetic) average of the two. The different decomposition procedures in the literature differ widely in how they address this weighting decision. Three popular types of indices are Laspeyres Indices, which use weights from the first of the two periods, Paasche Indices, which use weights from the second period, and Tornqvist Indices, which use an arithmetic average of the two periods. All three indices are discrete approximations to a continuous Divisia Index.

The first applications of index decomposition techniques in the field of energy economics date back to the late seventies: Among the first publications are contributions from Hankinson and Rhys (1983) on the decomposition of energy use in the UK, or from Jenne and Cattel (1983) on the decomposition of energy intensity. While early research relied mainly on the Laspeyres index, other, more complicated approximations to the more general Divisia Index, in particular the Tornqvist index, became widely accepted following up on the work of Boyd et al. (1988). An early and still useful systematisation can be found in Liu et al. (1992). Liu et al. (1992) also introduced the Adaptive-Weighting-Divisia Method, which intends to overcome the arbitrariness in weighting. The Adaptive-Weighting-Divisia did, however, not gain much popularity. All methods mentioned have the disadvantage that, after re-aggregating the different components – in our case activity effect, two structural effects, intensity effect, fuel mix effect, and emission coefficient effect – an unexplained residuum remains in comparison with the initial total effect. This problem was addressed by Sun (1998), who simply distributed the remaining residuum equally among the components. Similar concepts to Sun’s index have been developed by Diezenbacher and Los (1998) and Albrecht et al. (2002).

A different approach has been taken by Ang et al. (1998) on the basis of a logarithmic mean of the weights of the two periods. Ang and Liu (2001) refined and simplified this method, calling the revised index the *Logarithmic Mean Divisia Index* (LMDI). In the analysis below we use their LMDI (for details see Ang/Liu 2001 or the practical guide by Ang 2005). The first articles using index decomposition methods usually focussed on energy intensity or energy use and distinguished between a structural and an intensity effect. Today a growing number of studies also include fuel mix and emission factors and decompose emission intensity or emissions as opposed to energy intensity or energy use – like we do (cf. for example Schipper et al. 2001, Diakoulaki/Mandaraka 2007 or Hatzigeorgiou et al. 2009). Liu and Ang (2007) provide a fairly comprehensive review of studies using index decomposition techniques up until 2007.[2]

From a methodological viewpoint, the recent discussions about “zero values” and about correct deflators are of interest. Although LMDI has a number of desirable properties, it cannot handle zero values in its most basic form. The creators of LMDI originally recommend substituting zeros by very small values and calculating LMDI according to the original formula (Ang et al. 1998, Ang 2005). Wood and Lenzen (2006) criticize this approach and show that significant errors can occur even with small values of the recommended size (around 10^{-10} to 10^{-20}), especially if the original data set contains a large number of zeros. They show that a large occurrence of changes in the disaggregated effects (i.e. the explanatory factors) from a positive number to zero or vice versa leads to especially high errors. As a solution, they suggest to replace the LMDI-weights by their limits if the weight is undefined, as is the case for any zero-value change. Since we do not decompose meso- or macroeconomic aggregates, but firm-level data, zero values occur frequently in our dataset, because firms enter or leave the market, or start or terminate consumption of a specific fuel. We therefore follow Wood and Lenzen (2006) in replacing undefined LMDI-weights by their limits.

In a decomposition study about Chinese energy consumption, Ma (2010) points out that the choice of the deflator may be crucial for the result of a decomposition study which may be biased if differences in price changes between sectors are not properly accounted for. As a reaction to Ma’s critique, we use sector-level price indices instead of one industry-wide price index.

As mentioned before, this study takes the decomposition method to the firm level. This has the principal benefit that we can account for changes in the output shares

---

[2] Liu and Ang(2007) concentrate exclusively on studies that focus both on the manufacturing sector and energy use as a whole and in a disaggregated way. They count a little less than 70 contributions since 1978.

between firms within a sector that would otherwise be attributed to the sectoral technology effect. In doing so, we provide a more differentiated assessment of technology-driven changes in energy and carbon intensity which explicitly accounts for heterogeneity across firms within a sector. In contrast, the finest level of aggregation in decomposition analyses so far has usually been the sector level.[3]

The following identity summarizes how the 6 components described above add up to the aggregate CO_2 emissions in industry:

$$CO_2 = \sum_s \sum_{i \in s} \sum_f \underbrace{Y}_{\text{activity component}} \cdot \underbrace{\frac{Y_s}{Y}}_{\text{structural change between sectors component}} \cdot \underbrace{\frac{Y_i}{Y_s}}_{\text{structural change within sectors component}} \cdot \underbrace{\frac{kWh_i}{Y_i}}_{\text{intensity component}} \cdot \underbrace{\frac{kWh_{if}}{kWh_i}}_{\text{fuel mix component}} \cdot \underbrace{\frac{CO_{2if}}{kWh_{if}}}_{\text{emission factor component}} \tag{1}$$

where s indexes sectors within manufacturing, i indexes individual companies and f different fuels. CO_2 denotes CO_2 emissions, Y denotes output, and kWh denotes final energy use. Depending on subscript, the variables are either defined for fuel-firm combinations, the firm level, aggregated to the sector level, or aggregated to the whole industry level. The industry-level variables are not subscripted. Using formula (1), changes in CO_2 can be traced back to changes in each of the 6 components described above, which correspond to the 6 factors of the product after the summation signs. These ceteris paribus effects then deliver the hypothetical change in total CO_2 emissions given only one of the components had changed and the others not. They are calculated by aggregating the change in that respective component from the fuel per plant level to the total level, calculating the weighted average change over all fuels, companies and sectors. The respective weights for the fuel-firm combinations are delivered by the LMDI-procedure and are determined by the share of the fuel-firm combinations in total CO_2 emissions in all manufacturing sectors. Details on that procedure can be found in Ang and Liu (2001) or Ang (2005).

---

[3] One exception is Martin (2012) that takes the same direction. She, however, uses a different methodology in an another context.

4 Data

Our analysis uses of a number of official German statistics, namely the “AFiD-Betriebspanel”, augmented with an energy data module that has recently been made available to approved researchers at the Research Data Centres of the German Federal Statistical Office and the statistical offices of the German Länder. The AFiD-panel currently comprises annual data from 1995 until 2007 on the universe of German manufacturing plants with more than 20 employees (about 50,000 plants per year).[4] Originally designed as a data set for plant-level productivity analysis, the data also comprise detailed data on energy consumption by fuel type. During the first half of the panel (1995-2002) only the main, traditional fuel types are covered in detail (e.g. different types of coal, gas, electricity and oil). From the year 2003 onwards, questions on energy use have been asked in a separate survey on energy consumption which now covers usage and stocks of more than 30 different fuel types. This survey has been matched to the AFiD panel by the Research Data Centres. We exploit this information to conduct precise calculations of the energy and carbon intensities of production at the plant level. We are not aware of any other dataset on plant-level energy and carbon intensities which would be comparable to the German data in terms of scale and scope. The data thus provide us with a unique opportunity to study the determinants of energy intensity, carbon intensity, and CO_2 emissions at the micro level. To avoid bias in the valuation of plant-specific output due to arbitrary firm specific accounting rules, we aggregate our plant-specific data to the firm level.

Unfortunately, the only output variable available for all firms in our panel is gross output. For firms below 500 employees, value added is only available for some firms. A new sample is drawn from all firms every four years. Since one focus of our analysis is structural change within sectors, it is vital that we have a complete set of firms over time, since otherwise we would misinterpret firms merely leaving the sample as closing down completely. At the same time, energy or carbon intensities based on gross output instead of value added do not account for the inputs used. In principle, the gross output-based intensities are still meaningful, but count all intermediate goods repeatedly: In the producing plant and in all plants downstream the product chain. For this reason, we run an auxiliary analysis using value added, additional to using gross output as the output variable. While the sample using gross output utilizes all German manufacturing firms,[5] we run the decomposition analysis

---

[4] For some sectors, mainly among the food producing sectors, the cut-off threshold is 10 employees.

[5] By “all” we mean all firms in our sample, i.e. with less than 20 employees are not included, see above (the cutoff is indeed based on plants, not firms). We also discard firms reporting implausible data, e.g. firms with a yearly turnover of less than 10 000 EUR, a value added of less than 5 000 EUR or zero electricity use.

based on value added for the subset of firms with more than 500 employees.[6] Note that the subset of these large firms is much smaller (929 firms, 6 020 observations) than the whole sample (50 963 firms, 350 636 observations). We report the results only for the structural change and intensity effects, since the different output variable has no effect on the fuel mix effect and the emission factor effect. Differences in the activity level are negligible for our purpose.

To account for price changes as well as possible and as a response to Ma's (2010) critique (cf. Section 3), we construct sector-specific deflators from product-level producer price indices. We form sectoral averages from product-level producer price indices and match them to our data at the sector level. The original price data and the weighting scheme were provided by the German Federal Statistical Office (Statistisches Bundesamt 2009). Our attempt to construct firm-specific price indices based on information about production in physical units and turnover did not yield plausible results.

We go down to the three-digit sector level, this means we distinguish 110 different manufacturing sectors (cf. Statistisches Bundesamt 2006). This includes all manufacturing sectors, apart from energy production sectors (coal mining, oil and gas production etc.).

5 Results of the Decomposition Analysis

Total CO_2 emissions for the whole manufacturing sector did not change much between 1995 and 2007. Considerable reductions in some years, such as 1996 and 2005, were offset by increases in total emissions in other years, such as 2000, 2004 and 2006 (cf. Figure 3).[7]

We begin the discussion of the individual components with the effect of activity on CO_2 emissions, i.e. how CO_2 emissions would have changed from year to year if structure, energy intensity and fuel mix remained unchanged. Figure 3 shows that, over the whole period, an almost monotonic increase in economic activity had a strongly expansive[8] impact on CO_2 emissions. Annual activity effects of course resemble the German business cycle, with recessions around 1996 and 2001/2002 as well as boom periods between 1996 and 2000 and between 2005 and 2007.

---

[6] Firms are disregarded for the subsample if their employee count drops below 500 at least once.

[7] Any changes based on energy use information between 2002 and 2003 should be interpreted with caution, due to a break in the energy statistics (see above). It seems that the broader variety of fuels covered after 2002 led to a more comprehensive picture, especially for energy from renewable sources.

[8] With expansive (contractive) we mean that the emission level of a component is higher (lower) in a period compared to the previous period. In other words, the rate of change of the component is positive (negative).

Ceteris paribus, annual increases of up to 8 % add up to a hypothetical increase in CO_2 emissions of about 40 % from 1995 to 2007 due to economic activity (cf. Figure 3). This massive expansion highlights the dire need for the decupling of production and emissions. To some extent, this has already taken place: The considerable gap between the hypothetical and the actual emissions path points to a significant impact of the other five effects.

Figure 3 *ABOUT HERE*

One important driver of this difference is the effect of structural change between sectors, i.e. a shift from energy intensive sectors to less energy intensive sectors. With the exception of 1997, we observe only contractive (or negligibly expansive) structural effects between sectors for all manufacturing sectors (cf. Figure 4). We can confirm this result for structural change measured in terms of value added instead of gross output structural for large firms: structural changes between sectors are almost continuously contractive after 1998 (cf. Figure 5). For both output measures, but especially when observed for all firms, it is mainly the structural change between sectors which compensates the expansive effect of the increase in activity.

Figure 4 *AND* Figure 5 *ABOUT HERE*

With regard to the intensity effect, i.e. the change in the companies' energy use per output ratio, we can utilize the finer aggregation level of our micro-perspective compared to previous studies with the usual meso-perspective. Our firm-level data allows us to differentiate between firm-level energy improvements (the intensity effect) and intra-sectoral structural change, as opposed to sector-level studies that by construction have to merge the effect of intra-sectoral structural change into the intensity effect. Consequently, while decomposition studies at the sectoral level usually find contractive intensity effects,[9] we cannot confirm this finding on the micro-level. We find that changes in energy intensity are more volatile and often have an expansive effect on CO_2 emissions. The latter is especially true for value added and for the firms with more than 500 employees. As Figure 5 shows, the effect of changes in energy use per value added increased emissions both before 1998 and after 2003. Over the whole observation period, energy use per value added increased by almost 30 %. Also if we calculate energy intensity relative to gross

---

[9] In their review of 20 decomposition studies that include results for Germany, Liu/Ang (2007) list only one case, where the authors found an expansive intensity effect. Since the reported results are always multi-year decompositions covering between five and 15 years, so that expansive intensity effects of one year may be compensated by other years with contractive effects, this result does not mean that the other 19 studies would not have found a single year with an expansive intensity effect. Nevertheless, we believe it is a hint that expansive intensity effects are a rare exception from the rule of

output and for all firms in the panel, we cannot confirm the clear-cut emission saving influence of changes in energy intensity that some previous studies have postulated (cf. footnote 9). Even though the overall intensity effect is slightly negative (-2.6 % in 2007 compared to 1995), its impact is negligible, compared to the other effects. In some periods the intensity effect is even expansive.

The intensity effect is often regarded as a measure of technological progress. A contractive (expansive) intensity effect, in other words a smaller (higher) energy intensity, means that a firm is able to produce the same amount of output with less (more) energy. Comparing Figure 4 and Figure 3, it is striking that the intensity effects are especially low at the end of boom periods, such as until 2000 or after 2004, and especially high at the end of recession periods, such as from 2001 to 2003. We see this as an indication that the intensity effect is not exclusively driven by technological changes, but also to a significant extent by rigidities in the adaptation of energy use to changes in production. In other words, some fixed amount of energy that is used independent of the level of production. We admit, however, that these indications can only be generalized to a limited extent, since our sample covers only a small number of complete business cycles.

The difference between our findings for the intensity effect at the plant level and other studies' findings at the sector level is explained by the third effect in Figure 4 and Figure 5, the structural effect within sectors. Irrespective of the subsample, it is almost exclusively contractive. Throughout the observed period, changes in the structure of the different sectors usually led to relatively energy efficient companies taking market share from inefficient companies in the same sector. Over the whole observation period, structural change within sectors the most important contractive effect. It played a pivotal role in counteracting the large expansion of emissions due to increasing production: if it had not been for structural change within sectors, CO_2 emissions would have increased by 7.5 % between 1995 and 2007 instead of decreasing by 2.2 %. When structural change is measured in terms of value added instead of gross output, emissions of all firms with more than 500 employees would even have increased by 55.4 % instead of 27.9 % between 1995 and 2007. This is caused mainly by large shifts in market shares in 2006 and 2007.

We mentioned earlier the difference between our micro-level analysis and standard decomposition analyses at the meso-economic level. The aggregation level of our data allows us to introduce and analyse a new factor: the intra-sectoral structural change effect. To illustrate the difference and to highlight our results' interpretation for the interpretation of the intensity effect in meso-level analyses, we show how our

---

contractive intensity effects. For all studies covered by Liu/Ang (2007), the ratio of expansive vs.

results would have differed, if we had conducted our analysis with the aggregated (i.e. sector-level) data instead. In this case, structural change within sectors would have been included in the intensity effect. The intensity effect would have looked pronouncedly different, as can be seen in Figure 6 and Figure 7. The intensity effect at the sector level ("intensity and structure within sectors" in the figure), is downward biased compared to the intensity effect at the firm level. Expansive intensity effects are less frequent and less pronounced. In some years, the intensity effect at the sector level even has a different sign than the intensity effect without the intra-sectoral structural change. A considerable share of energy efficiency improvements, which appear on the sector level, is not caused by technological or managerial improvements within a firm, but by the "dirty" firms losing market shares or even closing down entirely, while "clean" firms gain market shares.

Figure 6 *AND* Figure 7 *ABOUT HERE*

The two remaining effects are the impact of a change of the fuel mix and changing emission factors (cf. Figure 8). Quite surprisingly, the composition of the fuel mix had virtually no effect on total CO_2 emissions of the whole sample between 1995 and 2002. This changes a bit after 2002, probably also because the newly established energy statistic covers of renewable energies like biomass better. Changes in the emission factors were usually contractive, which led to a steady ceteris paribus decrease of CO_2 emissions, caused mainly by changes in the power plant fleet.

Figure 8 *ABOUT HERE*

6 Sector-specific energy innovation patterns

In the previous section, we presented the aggregated results of our decomposition analysis and refrained from making detailed statements about specific sectors. Nevertheless, we gain insights on the nature of the innovation process towards more efficient energy use in different sectors from the sector-level contributions to the various effects. The sector-level contributions are the summands of equation (1) before summing up across all sectors, but after summing up fuels across each firm and firms across each sector. As before, a positive contribution of a sector to one of the effects increases emissions, while a negative contribution decreases emissions. In this section, we contrast the energy saving effect of intra-sectoral structural change with the contribution of firm-level energy efficiency improvements at the sector level.[10]

---

contractive intensity effects is 48 over 274 studies.

We distinguish four types of sectors: (1) Sectors with energy innovation through entrants are sectors whose firms mostly increase their energy intensity and which at the same time show energy-saving intra-sectoral structural change. (2) Sectors with innovation through technological progress are sectors whose firms by the majority decrease their energy intensity (i.e. improve in energy efficiency), while intra-sectoral structural change is not energy-saving. (3) A minority of sectors saves energy both through entrants and technology improvements, this means the median contribution over all firms is energy-saving, both for the intra-sectoral structural change effect and for the intensity effect. (4) The remaining sectors increase their energy use via both effects. We do not analyse them in detail.

From this classification of sectors we draw conclusions about the potential for firm-level improvements in energy intensity in the future. While analysts and policy makers pin their hopes on energy efficiency improvements in industrial firms,[11] we have shown in the previous section that firm-level energy efficiency improvements have not contributed a lot to curbing CO_2 emissions during our sample period. One reason for that are the considerable number of firms in sectors that innovate via entrants only. Contrary to new entrants, incumbents in these sectors are relatively unlikely to innovate themselves. We can only speculate about the potential reasons: Technological lock-in because of prohibitive switching costs could be one, especially since less energy intensive production is generally possible in these sectors, as shown by the efficiency level of new entrants. In any case, political measures targeted at firm-level energy efficiency improvements will usually be ineffective for this type of sector.

If, however, a sector innovates via technological progress, firms are able to adjust their energy productivity. In these sectors we can assume untapped potential through innovation on the firm level. This potential might be activated by future energy price shocks – or future political interventions for that matter. In this case, the high hopes placed on energy efficiency improvements might still be fulfilled.

As Figure 9 shows, the sectors' classification into the different groups varies over the years due to year-specific effects. To identify the long-term affiliation of a sector, we assign a sector to a group, if the sector is in this group for more than half of the years (see last column of Figure 9), similarly to a smoothing effort. Accordingly, the overall number of sectors that fall into the first three classes in the long run is lower than for the annual classification. The number of undetermined sectors increases, mostly because both their median effects turn zero.

---

[10] For the sake of representativeness and brevity, we concentrate on energy intensity with respect to gross output only and disregard our auxiliary analysis based on value added in this section.

[11] Cf. e.g. the McKinsey marginal abatement cost curve, as e.g. in Enkvist et al. (2010).

Figure 9 *ABOUT HERE*

We presume that firms in especially energy intensive sectors, where low energy costs are a decisive competitive advantage, are more likely to reap the benefits from energy efficiency improvements than their counterparts in less energy intensive sectors. We argue that firms in these especially energy intensive sectors will be especially active in enhancing their energy productivity, resulting in larger energy intensity changes. We therefore pay special attention to our findings for the 10 % of most energy intensive sectors, which are twelve in total (see solid bars in Figure 9).[12]

Among the most energy intensive dozen sectors, we can identify some that follow relatively pronounced patterns in their attempt to cut down on energy use: A number of sectors, such as Pulp and Paper (211), Basic Iron and Steel (271) or Casting of Metals (275), belong to group 2 and innovate via technology. We can identify a consistent pattern of negative median growth rates of energy intensity at the firm level, while structural change within a sector does not play a significant role. The same is true for one of Germany's most prominent (but not exceptionally energy intensive) sector, the car manufacturers (Motor Vehicles, 341). In these industries, the median growth rate of energy intensity was negative almost throughout the whole observation period. Firms in these sectors seem to be able to innovate and compete within their sectors by investing in less energy intensive technologies. We take this as an indication for successful tapping of energy efficiency potentials.

In other especially energy intensive sectors, such as Tiles and Flags (263) or Baked Clay (265), consistent progress towards more efficient production has been made, but not in the form of firm-level improvements in energy intensity, but in the form of competition within the sector instead (group 1). In these sectors, more efficient firms gained market shares on the cost of their less efficient counterparts in a lot of the years, while energy intensities at the firm level did not change a lot. We argue that firm-level innovations in energy efficiency are less probable and the effectiveness of policy measures targeted at firm-level energy intensity is questionable.

---

[12] Defined by median energy intensity of the firms in the respective sector over the whole period of observation. This includes (thee-digit sector codes in parenthesis) Mining of Hard Coal (101), Other Mining (145), Finishing of Textiles (173), Pulp and Paper (211), Man-made Fibres (247), Ceramics (262), Tiles and Flags (263), Baked Clay (264), Cement (265), Basic Iron and Steel (271) and Casting of Metals (275). We have to exclude Salt Extraction (144) because of data confidentiality requirements due to the small size of the sector.

7 Summary and Conclusions

Based on a detailed firm data set on the German manufacturing sector, we perform a decomposition analysis of industrial CO_2 emissions. Thanks to our micro dataset, we can identify the effects of intra-sectoral competition and energy efficiency improvements on the firm level, additional to the effects of changes in economic activity, sectoral structure, fuel mix, and emission factors.

We show that, despite a large increase in economic activity, CO_2 emissions in the German manufacturing sector did not change much between 1995 and 2007. Structural change between and within economic sectors as well as a cleaner electricity generation mix prevented an upsurge of CO_2 emissions. We see the large contractive effect of structural change between sectors as evidence supporting the pollution haven hypothesis: Production of especially carbon intensive goods has moved away from Germany, where regulation is comparably strict.

Changes in energy intensity at the plant level played only a negligible role in reducing overall emissions and actually increased emissions for the subset of large firms. In any case, we cannot confirm that energy intensity improvements in the manufacturing sector led to any significant improvement in CO_2 emissions when measured at the micro level. Adding structural change within sectors to the analysis reveals that a contractive energy intensity effect at the sector level, as often found in comparable studies, is at least in our case mainly due to structural change within the sectors rather than to progress in efficiency at the plant level. We find that over time comparably inefficient firms in a sector lose market shares in favour of energy efficient firms.

From the prevalence of firm-level energy efficiency improvements and intra-sectoral competition, we identify different innovation patterns on the sector level. In some cases, technological or behavioural innovations which improve CO_2 or energy intensity penetrate the market through new entrants instead of by being adopted by the incumbents. We can only speculate about the reasons for the incumbents' lack of enthusiasm to improve energy efficiency, even though technological lock-in may be one of them. We diagnose that in this case policy measures targeted at improving firm-specific energy intensity, such as innovation subsidies, do not bear much potential for future improvements of overall energy efficiency. Hopes on these measures are more justified in sectors that innovate mostly via technology instead of competition through entrants. Among the most energy intensive sectors, we find examples for both innovation patterns.

References

AGEB (ed.) (2002): *Preface to the energy balances for the Federal Republic of Germany*. Download from http://www.ag-energiebilanzen.de/componenten/download.php?filedata=1224339899.pdf&filename=vorengl.pdf&mimetype=application/pdf (May 23, 2010).

Albrecht, J., D. Francois and K. Schoors (2002): *A Shapley decomposition of carbon emissions without residuals*. Energy Policy 30, pp. 727-736.

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

Ang, B. W. and F. L. Liu (2001): *A new energy decomposition method: perfect in decomposition and consistent in aggregation*. Energy 26, pp. 537-548.

Ang B. W., F. Q. Zhang and K-H. Choi (1998): *Factorizing changes in energy and environmental indicators through decomposition*. Energy 23, pp. 489-495.

Boyd, G. A., D. A. Hanson and T. Sterner (1988): *Decomposition of changes in energy intensity*. Energy Economics 10(4), pp. 309-312.

Diakouli, D. and M. Mandaraka (2007): *Decomposition analysis for assessing the progress in decoupling industrial growth from* CO_2 *emissions in the EU manufacturing sector*. Energy Economics 29(4), pp. 636-664.

Diezenbacher, E. and B. Los (1998): *Structural Decomposition Techniques: Sense and Sensitivity*. Economic Systems Research 10(4), pp. 307-323.

EIA (2010): *International Energy Statistics – Energy Intensity Table.* Download from http://www.eia.gov/cfapps/ipdbproject/IEDIndex3.cfm?tid=44&pid=44&aid=2 (May 22, 2010).

Enkvist , P.-A., J. Dinkel and C. Lin (2010): *Impact of the financial crisis on carbon economics: Version 2.1 of the global greenhouse gas abatement cost curve.* Download from http://solutions.mckinsey.com/climatedesk/default/en-us/Files/wp211154643/ImpactOfTheFinancialCrisisOnCarbonEconomics_GHGcostcurveV2.1.pdf (November 23, 2012).

Hankinson, G. A. and J. M. W. Rhys (1983): *Electricity consumption, electricity intensity and industrial structure*; in: Energy Economics 5(3), pp. 146-152.

Hatzigeorgiou, E., H. Polatidis and D. Haralambopoulos (2009): CO_2 emissions in Greece for 1990-2002: *A decomposition analysis and comparison of results using the Arithmetic Mean Divisia Index and Logarithmic Mean Divisia Index techniques*. Energy 33, pp. 492-499.

Jenne, C. A. and R. K. Cattel (1983): *Structural change and energy efficiency in industry*. Energy Economics 5(2), pp. 114-123.

Liu, N. and B. W. Ang (2007): *Factors shaping aggregate energy intensity trend for industry: Energy intensity versus product mix*. Energy Economics 29(4), pp. 609-635.

Liu, X. Q., B. W. Ang and H. L. Ong (1992): *The Application of the Divisia Index to the Decomposition of Changes in Industrial Energy Consumption*. The Energy Journal 13(4), pp. 161-177.

Ma, C. (2010): *Account for sector heterogeneity in China’s energy consumption: Sector price indices s. GDP deflator*. Energy Economics 32, pp. 24-29.

Martin, L. A. (2012): *Energy efficiency gains from trade: greenhouse gas emissions and India's manufacturing firms*. Draft: February 2, 2012, download from http://www.leslieamartin.org/LeslieMartin_JMP_Nov20updated.pdf?attredirects=0 (May 31, 2012).

Schipper, L., S. Murtishaw and F. Unander (2001): *International Comparisons of Sectoral Carbon Dioxide Emissions Using a Cross-Country Decomposition Technique*. The Energy Journal 22(2), pp. 35-75.

Statistisches Bundesamt (2006): *Übersicht über die Gliederung der Klassifikation der Wirtschaftszweige, Ausgabe 2003*. Wiesbaden. An English translation is provided by Statistisches Bundesamt (2003): *German Classification of Economic Activities, Edition 2003 (WZ 2003)*. Download from https://www.destatis.de/DE/Methoden/Klassifikationen/GueterWirtschaftklassifikationen/klassifikationwz2003englisch.pdf?__blob=publicationFile (June 21, 2012)

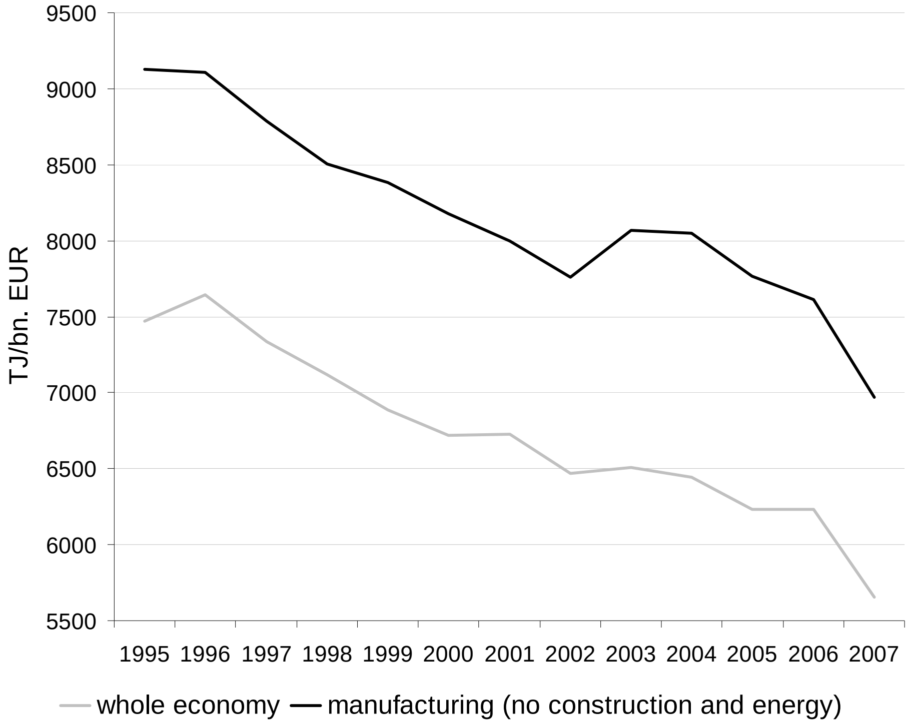
Statistisches Bundesamt (2009): *Index der Erzeugerpreise gewerblicher Produkte (Inlandsabsatz) nach dem Güterverzeichnis für Produktionsstatistiken, Ausgabe 2002 (GP 2002). Lange Reihen von Januar 1995 bis Dezember 2008*. Fachserie 17, Reihe 2.

Statistisches Bundesamt (2012): *Volkswirtschaftliche Gesamtrechnungen des Bundes* and *Umweltökonomische Gesamtrechnungen*. Downloaded from GENESIS database, https://www-genesis.destatis.de/ (December 12, 2012).

Sun, J. W. (1998): *Changes in energy consumption and energy intensity: A complete decomposition model*. Energy Economics 20(1), pp. 85-100.

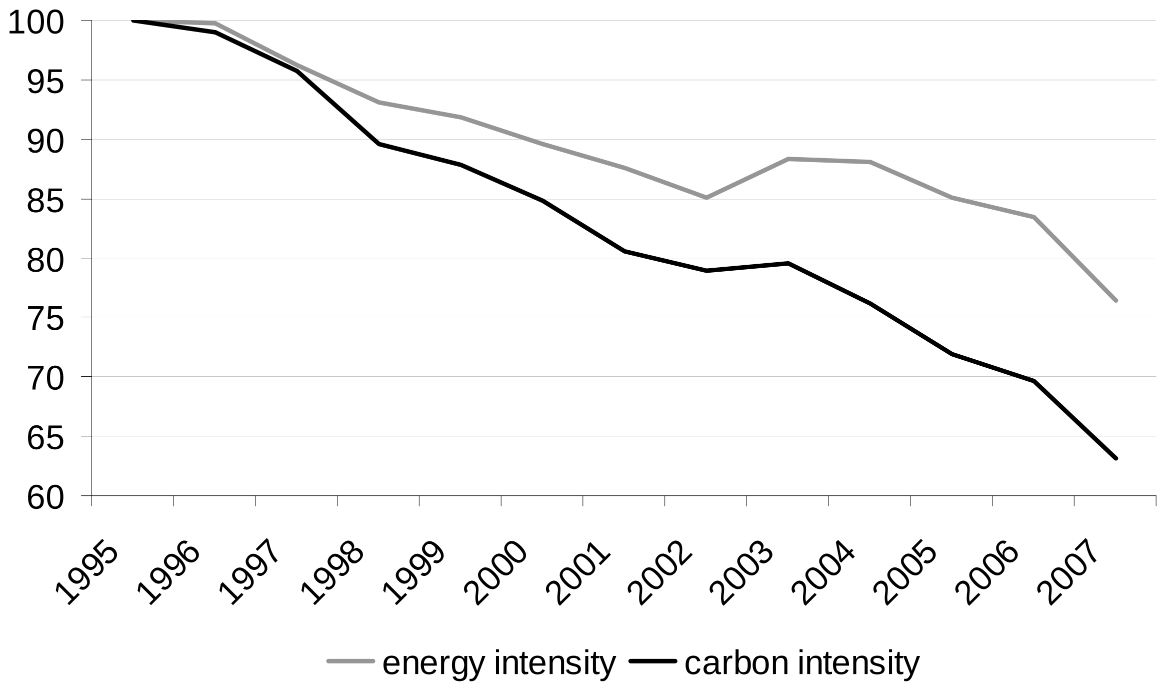
Figures

Figure 1: Final Energy Use per Nominal GVA, whole economy and manufacturing



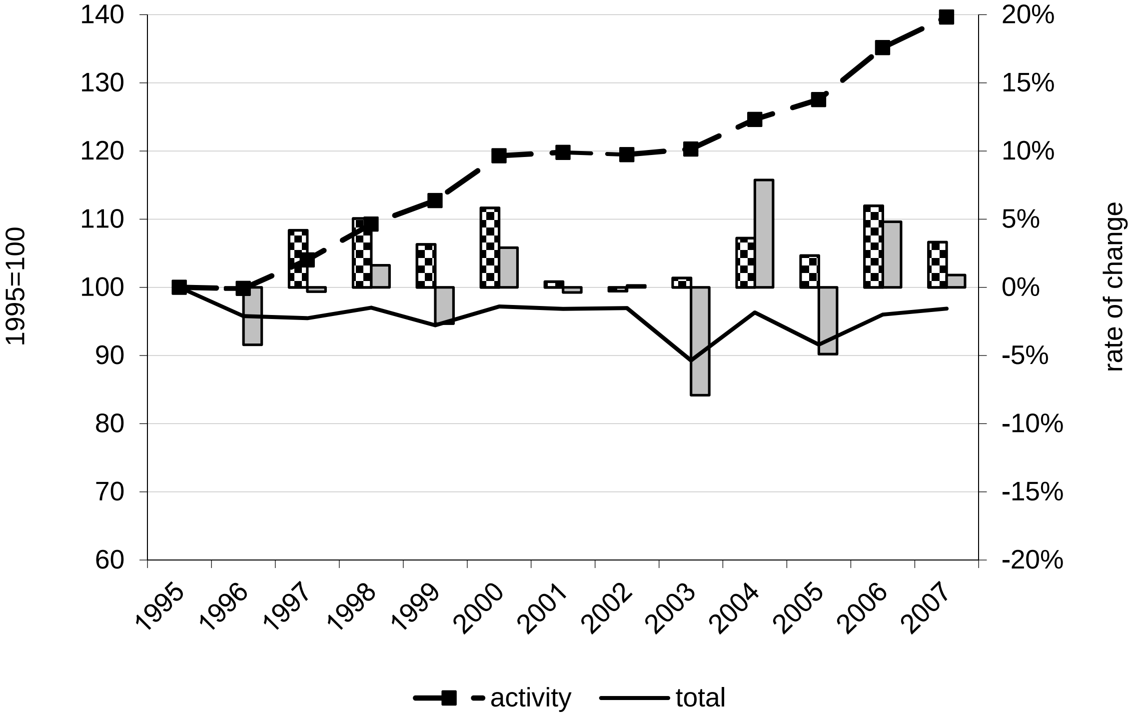
Source: Statistisches Bundesamt.

Figure 2: Intensities in Manufacturing (1995=100)



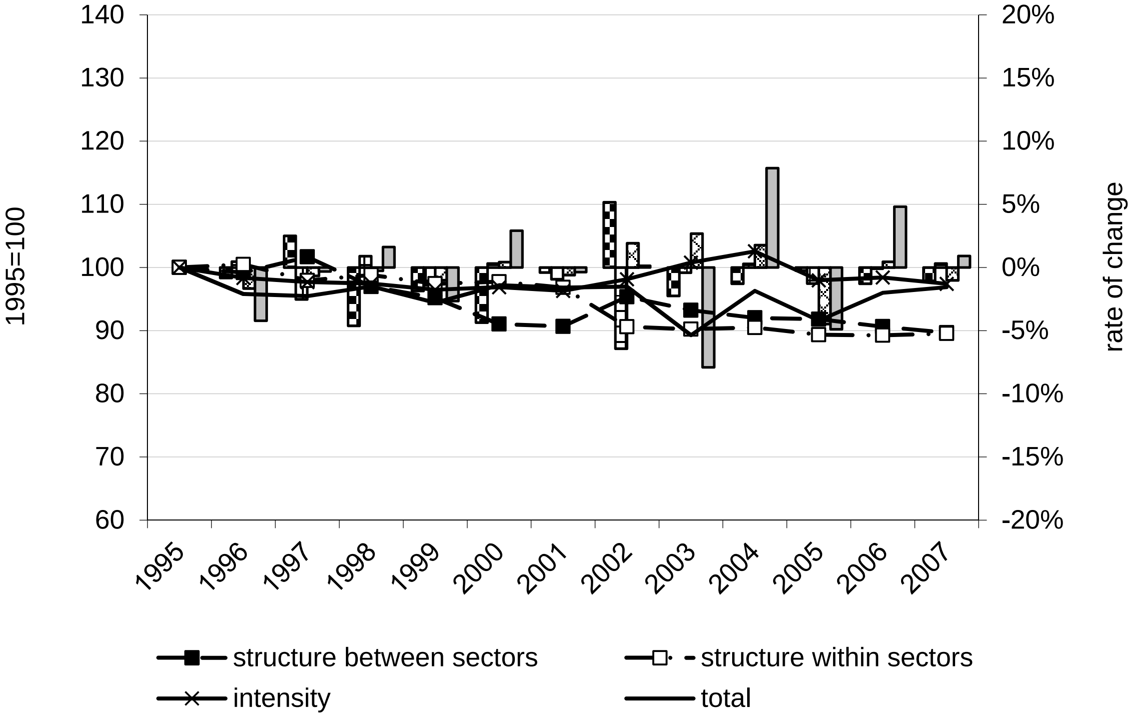
Source: Statistisches Bundesamt.

Figure 3: Total CO_2 Emissions and Emissions Due to the Activity Effect (Based on Gross Output)



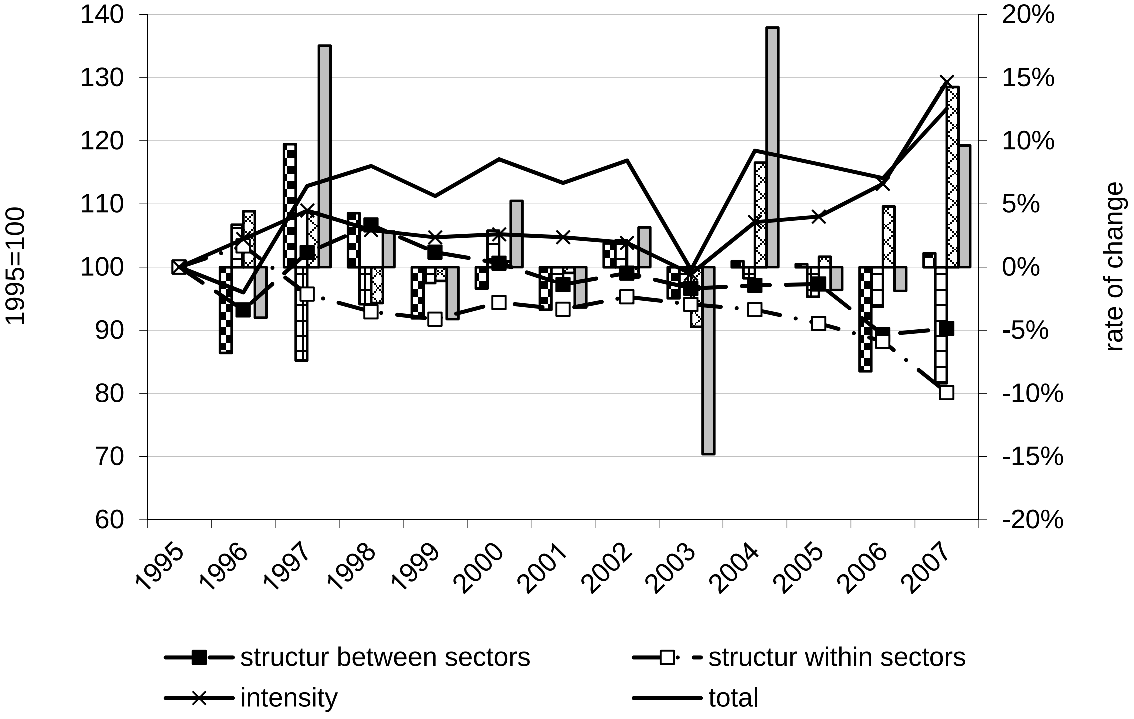
Own calculations.

Figure 4: Structural Change and Energy Intensity Effects (Based on Gross Output)



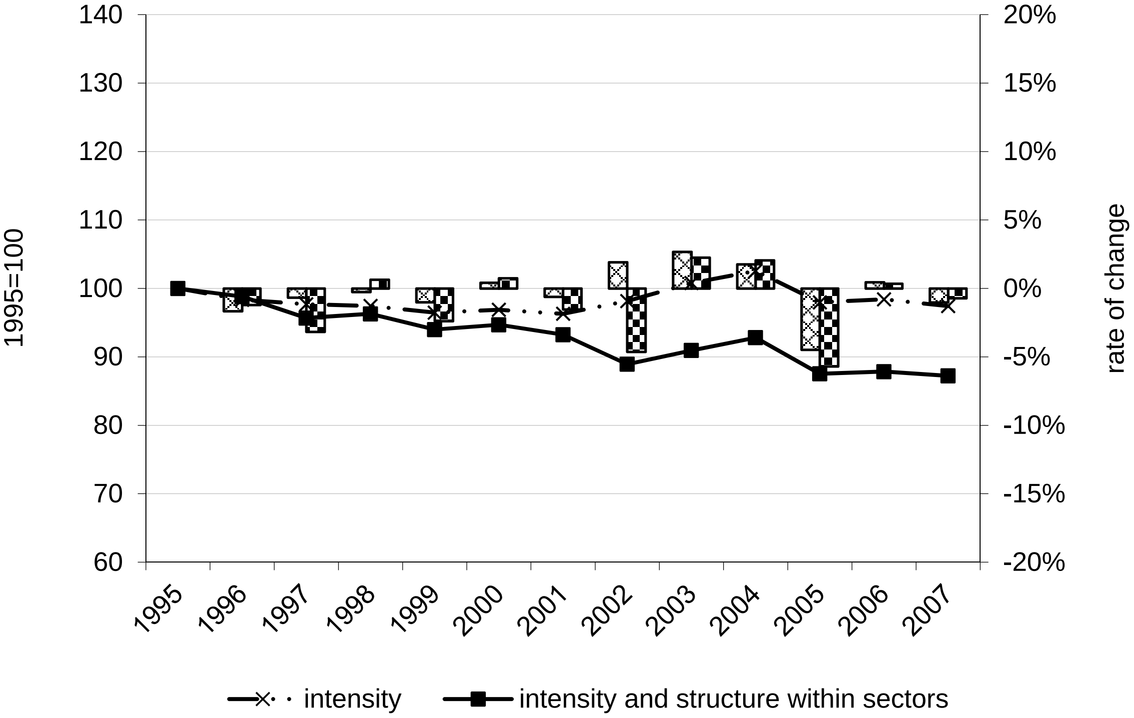
Own calculations.

Figure 5: Structural Change and Energy Intensity Effects (Based on Value Added)



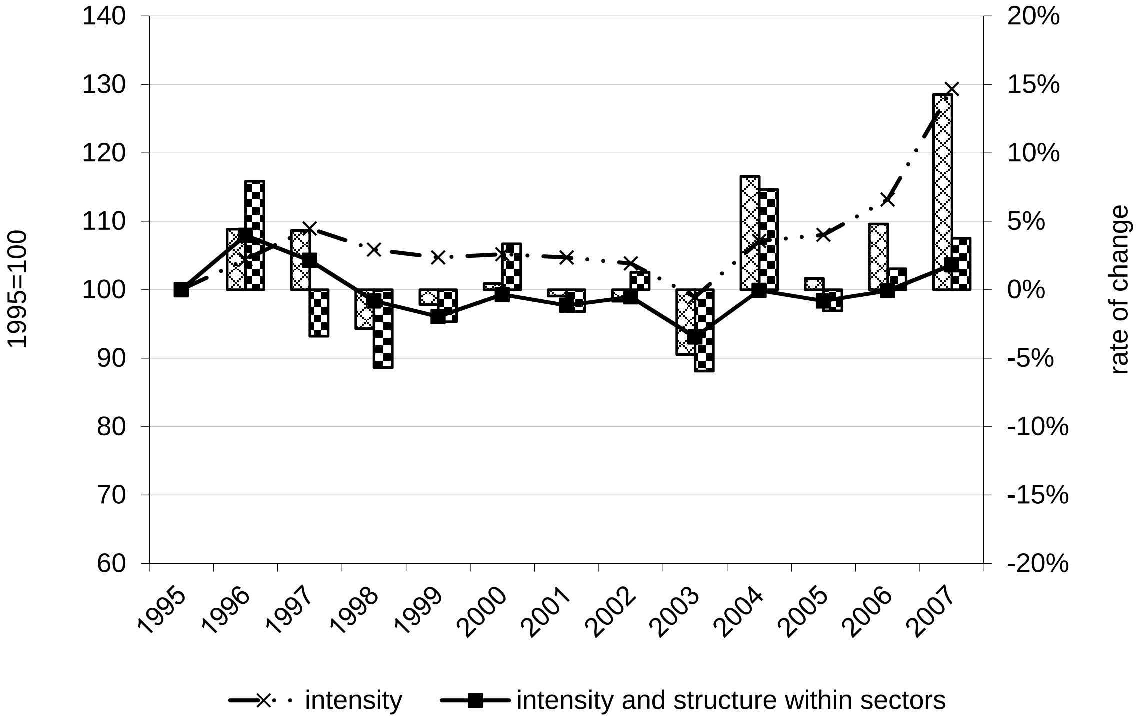
Own calculations.

Figure 6: Intensity Effects at Plant (“intensity”) and Sector (“intensity and structure within sectors”) Level (Based on Gross Output)



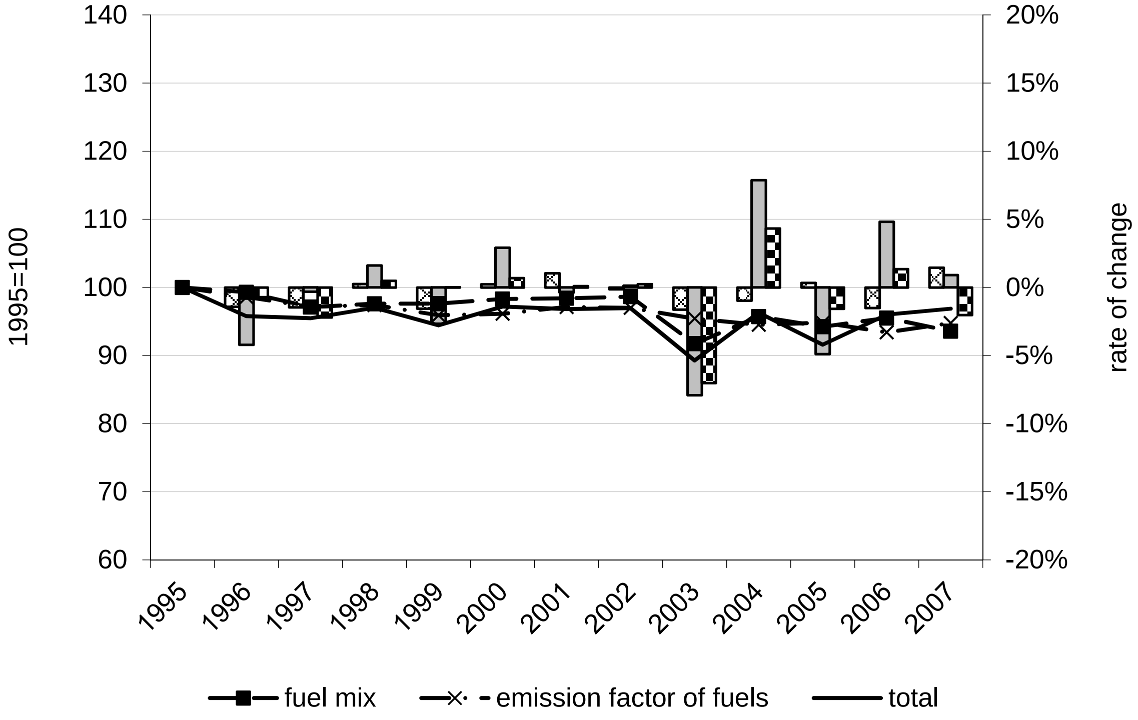
Own calculations.

Figure 7: Intensity Effects at Plant ("intensity") and Sector ("intensity and structure within sectors") Level (Based on Value Added)



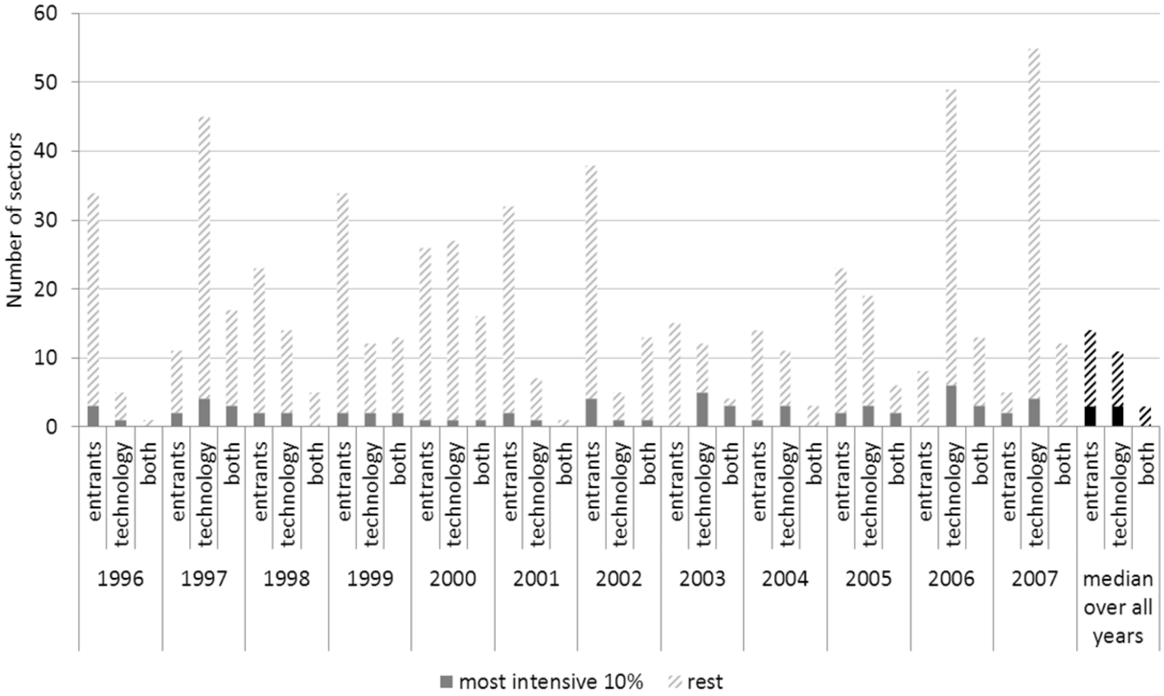
Own calculations.

Figure 8: Fuel Mix and Emission Factor Effects (Based on Gross Output)



Own calculations.

Figure 9: Sectors' energy innovation patterns of sectors



Innovation through entrants (lock-in): median intensity effect over all firms of a sector is non-negative, median effect of structural change within the sector is negative. Innovation through technology (no lock-in): median intensity effect over all firms of a sector is negative, median effect of structural change within the sector is not negative. Innovation through both (no lock-in): median intensity effect and median effect of structural change are negative. Own calculations.