Interactions between selected energy use and production characteristics of German manufacturing plants

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Abstract: This paper analyzes the interactions between a number of key energy characteristics of German industrial plants in 2006, using an exceptionally rich dataset comprising more than 44 000 plants. Already by using basic descriptive statistical techniques we find that larger energy users tend to use energy less efficiently. This correlation is particularly prevalent in sectors with high energy intensity. We identify an energy mix effect as the main driver of this interrelation, since larger energy consumers tend to use less electricity in relation to other fuels, and electricity can be deployed more efficiently. The energy mix effect is also one of the reasons behind a negative correlation between energy intensity and the emission factor. From the correlation between plant-level energy intensity and gross output, we infer on the existence of increasing and decreasing returns to energy. We identify increasing returns to energy in most sectors, but decreasing returns to energy in some of the particularly energy intensive sectors.

Keywords: *Energy intensity, Emission factor, Manufacturing, Microdata*

1. Introduction

The industry sector[1] is a major energy consumer and it is receiving growing attention from researchers and politicians, who see it as a prominent battle ground in the fight against climate change, resource scarcity and energy insecurity. According to IEA data for 2006 [1][2], the German industrial sector Germany is responsible for 22 % of total final energy use and 15 % of CO_2 emissions. As the industry sector is fundamental for economic growth and employment in most countries, politicians are reluctant to cut industrial energy use by limiting the overall size of the industry sector. Consequently, policy initiatives mostly aim at boosting industrial energy efficiency and reducing the average carbon factor of energy inputs. Recent examples of policies in Germany include, amongst others, the "Heat-Power Cogeneration Act", the Ecological Tax Reform and the "Large Combustion Plant Directive". The effectiveness of such measures, however, is limited by economic and technological restrictions inherent to the industry sector, and a thorough understanding of these restrictions is vital for policy design. In particular, energy intensity[2] and total energy use are not independent of each other. Several effects link a plant's level of energy use and energy intensity.[3] Conceptually, these effects can result in either a positive or a negative correlation between the two measures.

For example, if the amount of energy needed to produce the last unit of output decreases with rising energy use, larger energy users would on average use energy more efficiently. Such *increasing returns to energy* would imply a negative correlation between energy intensity and energy use. Conversely, in the case of *decreasing returns to energy*, the amount of energy

[1] We define the industry sector as the mining, quarrying and manufacturing sectors with ISIC codes C and D.
[2] We use energy intensity as an inverse measure of energy efficiency and calculate it as the ratio between total energy use (in kWh) of a plant and gross output (in 1000 EUR) of a plant. The use of gross output instead of value added which accounts for inputs is dictated by data availability. See Petrick et al. [3] for further discussion of this issue.
[3] The existing literature on the interaction between energy use and energy intensity as well as their determinants is widely ramified. Since a comprehensive review of the existing literature is beyond the scope of this paper, the reader is referred to the excellent review by Gillingham et al. [4] and the references given therein.

needed for the last unit of output increases with rising output, and energy intensity and total energy use would be positively correlated. Note that in both cases a correlation between energy intensity and output is also implied. In the first case, a (ceteris paribus) concave demand function for energy implies a negative correlation between energy intensity and output, while in the second case the demand function is convex and energy intensity and output are positively correlated.[4] In either case the effect of returns to energy can be distorted by an *energy mix effect*. We hypothesize that with rising overall energy use, the composition of plants' energy mixes changes and, in particular, the share of primary fuels, such as natural gas or coal, rises at the cost of the share of electricity and other processed fuels. Since electricity can be used more efficiently than primary fuels (with regards to output per used kilowatt hour), overall energy intensity is (ceteris paribus) expected to decrease with a rising electricity share and thus to increase with a rising fuel use due to the energy mix effect.

Apart from the interaction between total energy use and energy intensity, we analyze the link between energy use, energy intensity and the plant-specific emission factor, i.e. the ratio between CO_2 emissions (in t) and energy used (in kWh). At first glance it appears that exceptionally efficient energy users also try to minimize their carbon footprint (in part in response to policy) since plants with advanced technology are more likely to be both efficient and clean. At second glance, however, the energy mix effect might distort this picture; because the carbon factor of electricity is high due to conversion losses. The energy mix effect could thus lower the emission factor with increasing energy use and increasing energy intensity. To combine the interactions between efficiency of energy use and the carbon factor, we complement this part of the analysis with findings about a plant's carbon intensity, defined as the ratio of CO_2 emissions per gross output (in g/1000 EUR).[5]

In this paper we analyze the impact of returns to energy and energy mix effects on the link between energy use and energy intensity by measuring the net correlation between energy use and energy intensity. We also analyze the link between energy and carbon intensities as well as the plant specific emission factor in order to answer the question whether more efficient

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[4] To understand why increasing returns to energy imply a negative interrelation between output and energy, consider a production function that abstracts from all other production factors. Such a production function *y=f(e)*, where *y* is the output und and *e* is the production factor energy, exhibits increasing returns to energy if it is convex. The implied factor demand function *e=g(y)* is the inverse of the production function and concave, i.e. the second derivative is negative. From the factor demand function, energy intensity (denoted *eint*) can be derived as a function of output:

$$\text{eint} = \frac{g(y)}{y} \tag{1}$$

The sign of the derivative of *eint* with respect to *y* depends on the sign of the difference between marginal productivity and average productivity:

$$\frac{d\,\text{eint}}{dy} > 0 \quad \Leftrightarrow \quad g'(y) - \frac{g(y)}{y} > 0 \tag{2}$$

Since the second derivative of the factor demand function is negative, average factor demand will always be larger than marginal factor demand – which is exactly the intuition of increasing returns to energy (we assume that the Inada conditions hold). Thus, in the case of increasing returns to energy, the interrelation between energy intensity and output should be negative. In the case of decreasing returns to energy, the implied factor demand function would be convex, and the same argument (with exchanged sign) would hold – in the case of decreasing returns to energy, the interrelation between energy intensity and output should be positive.

[5] The same caveat as in the case of energy intensity applies, cf. footnote 2.

plants are also cleaner. To get a better picture of the differences between sectors, we present results not only at the aggregate level, but also for selected sectors of particular interest.

2. Data and Methodology

This paper is part of a research project that uses an exceptionally rich dataset, parts of which have only recently been made available by a research data centre of the German Official Statistics. The "AFiD panels"[6] are a collection of microdatasets comprising observations at the plant and enterprise level for various sectors, including industry. For this paper we use the panel "Industrial Plants" [5] in combination with an energy use module [6]. The combined dataset contains annual observations for up to 68 000 industrial plants per year from 1995 to 2006. In this paper we concentrate on the most recent cross section and use 2006 data, comprising 44 080 plants. An important feature of the data at hand is that it is based on a mandatory survey that each plant with more than 20 employees is required to answer. Thus, the degree of representativeness of our dataset is exceptionally high.[7] A more detailed description including a list of all variables included in the datasets as well as information on the underlying statistics can be found in Petrick et al. [3].[8]

To analyze the interrelation between the energy and production characteristics, we use basic correlation analysis. We calculate Spearman's rank correlation coefficients for all plants in the dataset as well as for selected sectors that are particularly interesting with regards to their energy use patterns. We use Spearman's correlation coefficient instead of Pearson's in order to minimize sensitivity to outliers. However, results based on Pearson's correlation coefficient can be obtained from the authors on request.

3. Results

To study the link between total energy use and energy intensity as well as the underlying mechanisms, we begin with the aggregate effect. For the German industry as a whole we find a strong and significant positive correlation between energy use and energy intensity (Table 1). This implies a negative correlation between energy use and energy efficiency which could be explained either by decreasing returns to energy for energy or by a fuel mix effect.

At the aggregate level, it is not clear whether this correlation is driven mainly by differences between plants or between sectors. Since energy intensive sectors like the cement, glass and ceramics, paper or metal manufacturing industries are responsible for the lion's share of overall energy consumption, plants in these sectors are also large energy users. This is confirmed by Petrick et al. [3], who isolated the heterogeneity between different sectors by calculating the correlation between the sector medians of total energy use and energy intensity.[9] To control for cross-sectoral heterogeneity in this paper, we compute correlation measures within sectors (see Figure 1). We find that energy intensity and total energy use of plants are positively correlated also within sectors. The correlation is particularly strong in sectors that are highly energy intensive, like the paper and pulp, glass and ceramics, mineral

[6] AFiD: "Amtliche Firmendaten für Deutschland", English: Official Firm Data for Germany.

[7] In the process of data cleansing we drop plants with an annual turnover below 10 000 EUR and those that reported an electricity consumption of zero. In 2006, 3 586 out of 47 666 plants were dropped.

[8] Presentation of results is limited by the legal requirement to preserve the confidentiality of data on individual plants. For this reason, all research output has to be approved by staff at the research data centre before publication.

[9] Aiming to get results that are robust towards large differences between different plants of different sectors is one reason why we use Spearman's rank correlation coefficient instead of Pearson's correlation coefficient.

processing (incl. cement) or iron and steel sectors. Since energy use and carbon emissions (and also energy intensity and carbon intensity) are highly correlated, we also find a positive correlation between carbon emissions and energy intensity, as well as between carbon intensity and energy use (Table 1).

Table 1. Spearman's rank correlation coefficients for selected variables at the plant level (2006 data).

	Energy use (kWh)	Energy intensity (kWh/1 000 EUR)	CO_2 emissions (t)	Carbon intensity (g/1 000 EUR)	Emission factor (g CO_2/kWh)	Share of electricity in total energy use (%)
Energy intensity (kWh/1 000 EUR)	0.60					
CO_2 emissions (t)	> 0.9	0.58				
Carbon intensity (g/1 000 EUR)	0.59	> 0.9	0.61			
Emission factor (g CO_2/kWh)	-0.15	-0.20	-0.02	-0.01		
Share of electricity in total energy use (%)	-0.14	-0.21	(-0.01)	-0.03	> 0.9	
Gross Output (1 000 EUR)	0.68	-0.09	0.69	-0.08	(-0.01)	-0.01

Own calculations. In cases of ">0.9" the exact value is not available to ensure confidentiality of the data. Coefficients in brackets are not significant at the 1 % level.

While increasing returns to energy should allow larger plants to use energy more efficiently, this is obviously not the case in the data, either because there are no increasing returns to energy or because increasing returns to energy are outweighed by a counteracting fuel mix effect, as described in section 1. To shed more light on this issue, we study the correlation between energy intensity and gross output. Aggregated across all sectors, we find a statistically significant but very weak positive correlation. This picture becomes more diverse as we look at the correlation in specific sectors (Figure 1). In energy intensive sectors, namely in the paper and pulp, glass and ceramics, mineral processing as well as iron and steel sectors, correlation between energy intensity and gross output is positive, indicating decreasing returns to energy. Notable exceptions among the energy intensive sectors are the mining, quarrying, chemicals as well as the non-ferrous metals and foundries sectors. In most other sectors energy intensity and gross output are negatively correlated, indicating increasing returns to energy. Nevertheless, since the correlation coefficient does not usually exceed 0.25 in absolute value and the correlation between energy intensity and gross output is only a rough indicator, the impact of increasing or decreasing returns to energy seems to be limited.

Apart from increasing and decreasing returns to energy, we earlier identified an energy mix effect as another potential driver linking energy use and energy intensity. As the negative correlation between the share of electricity in the energy mix and total energy use of a plant illustrates, excessive energy users tend to use relatively little electricity but rely more on other fuels (Table 1 and Figure 1). Natural gas is especially important as an alternative; in certain cases also coal (e.g. in the iron and steel sector, the mineral products sectors or the mining and quarrying sectors) or renewables like biomass (the pulp and paper sectors are one example; cf. Petrick et al. [3]). Since electricity is already a highly processed fuel, it can be employed very efficiently – energy intensity and the electricity share in a plant's fuel mix are negatively correlated, both at an aggregated and mostly also at the sectoral level (Figure 1). Note that the correlation coefficients for electricity share and energy intensity as well as for the electricity share and total energy use are much larger than the correlation coefficient for energy intensity and gross output, in most sectors and at the aggregate level. From this we infer that the strong positive correlation between energy use and energy intensity found at the sectoral and aggregate level is mainly driven by the energy mix effect: with rising overall energy use the share of electricity in a plant's fuel mix decreases. Since electricity can be used rather efficiently, overall energy intensity is expected to rise accordingly.

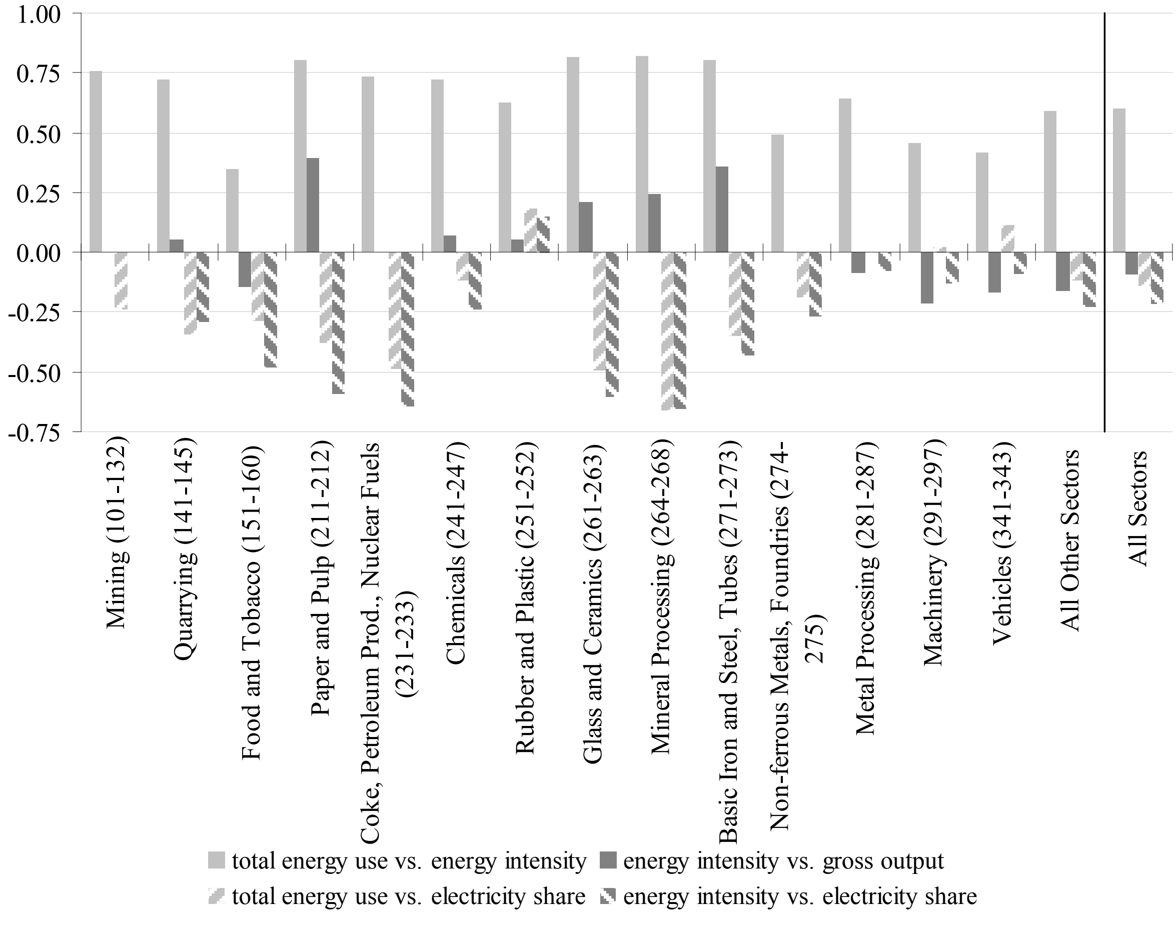

Figure 1. Spearman's rank correlation coefficients between selected variables within sectors (2006). Only coefficients that are significant at the 1 %-level are shown. The three-digit sector identifiers refer to the corresponding ISIC codes.

Apart from the link between total energy use and energy intensity, we also analyze the mechanisms linking energy use – and thus energy intensity – and the emission factor. The emission factor (or carbon factor) is the ratio of emitted CO_2 from fuel combustion per unit of energy (in g CO_2/kWh). We find a statistically significant negative correlation between emission factor and energy use as well as energy intensity (Table 1). The link between energy intensity and emission factor stands out in particular. Contrary to intuition, more energy efficient plants actually use a dirtier fuel mix in the sense of a higher carbon factor. This result not only holds for all sectors in general, but also for most individual sectors, especially for the energy intensive ones, with the exception of the rubber and plastics sector (Figure 2).

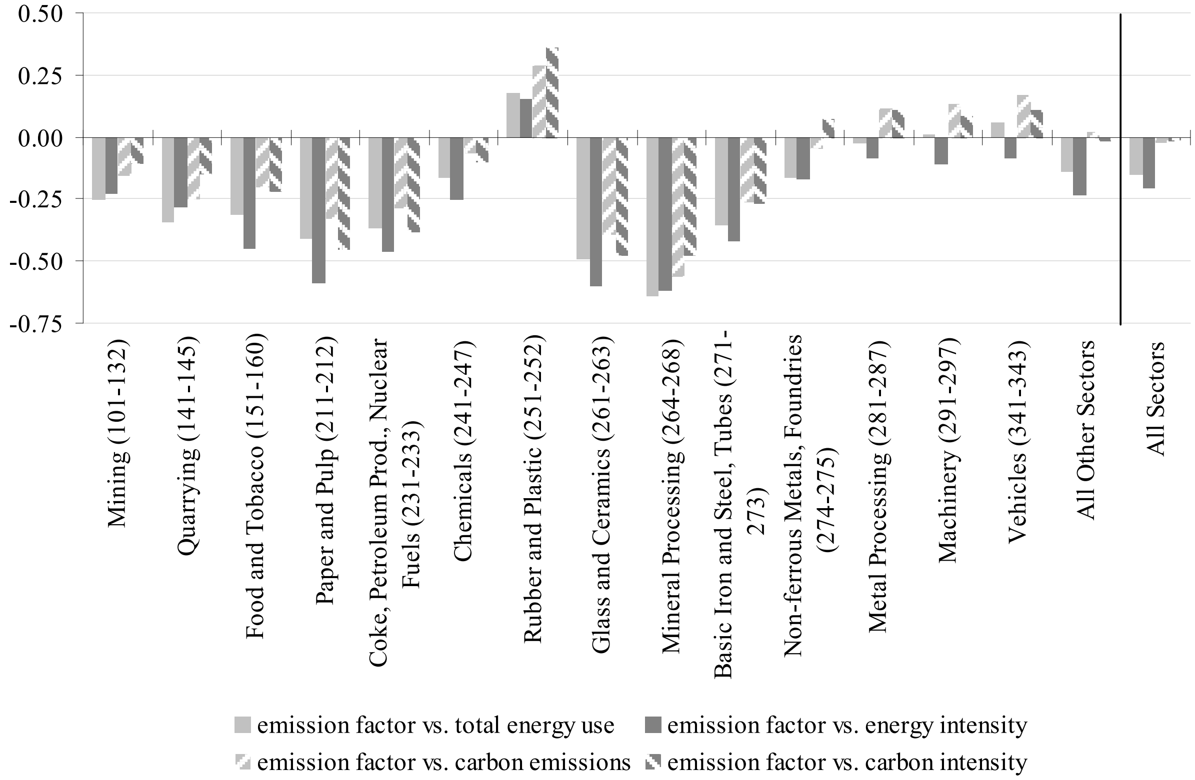

Figure 2: Spearman's rank correlation coefficients between emission factor and selected variables within sectors (2006). Only coefficients that are significant at the 1 %-level are shown. The three-digit sector identifiers refer to the corresponding ISIC codes.

To understand this paradox, it is vital to understand the role of electricity. As mentioned before, electricity can be used very efficiently, but at the same time its emission factor is high due to conversion losses in the energy conversion sector. In fact, the 2006 carbon factor for electricity was 2.9 times the carbon factor of natural gas and still 1.7 times the carbon factor of hard coal.[10] Consequently, a production technology that uses a lot of electricity may be very energy efficient, but since the carbon factor of electricity is very high, the carbon efficiency advantage of that technology may be smaller than the energy efficiency advantage relative to a technology less intensive in electricity. These two opposing effects also account for a low correlation between the emission factor and carbon intensity for some sectors and for the aggregate of all sectors (Figure 2). Some particularly energy intensive sectors, like the glass and ceramics sector, the mineral processing sector or the paper and pulp sector, are exceptional here. In these cases energy intensity and emission factor are especially highly correlated, implying that the energy efficiency advantage of using electricity is particularly large (cf. also the correlation between energy intensity and electricity share for these sectors from Figure 1). In fact, it is large enough to outweigh the carbon factor disadvantage, leading to the paradoxical situation of a high emission factor together with low carbon intensity.

[10] The carbon factor of electricity in 2006 was 585 g per kWh. It is calculated for the average German electricity mix as the ratio of all direct CO_2 emissions from fossil fuel combustion divided by the available electricity supply. Thus, different emission factors for the primary fuels used by the power plants are accounted for, but indirect emissions through production and transport of the primary fuels are not accounted for (own calculations on the basis of AGEB [7] and Umweltbundesamt [8]).

The same argument explains why larger energy consumers have lower emission factors, both across and within sectors. Since plants that use more energy tend to rely less on electricity, they do not have to shoulder the burden of conversion losses in their specific emission factor. At the same time, their energy intensity tends to be higher. The two effects partly offset each other and the effect of the emissions factor on total CO_2 emissions is small, although still negative, with the same aforementioned exceptions (Figure 2).

4. Discussion and Conclusions

In this paper we use new microdata on 44 000 industrial plants to analyze the use of energy in industrial production in Germany. Our dataset allows for the analysis of plant-level energy use and emission patterns with extraordinary detail, accuracy and representativeness. Since the dataset also includes information on the plants' monetary gross output, we are able to draw conclusions not only about the level, but also about the productivity of industrial energy use in Europe's largest economy.

We find that energy use and energy intensity are positively correlated, both at the aggregate level and within specific sectors, i.e. larger energy users tend to use energy less efficiently. This correlation is especially high for sectors with high energy intensity. We identify an energy mix effect as the main driver of this interrelation, since larger energy consumers tend to use less electricity in relation to other fuels, and electricity can be deployed more efficiently. Increasing and decreasing returns to energy are of less importance and not uniform across sectors. By means of the correlation between energy intensity and gross output, we identify increasing returns to energy in most sectors, but decreasing returns to energy in some of the particularly energy intensive sectors. The energy mix effect is also one reason for a negative correlation between energy intensity and the emission factor, since energy efficient plants tend to use more electricity, which has a comparably high emission factor. The efficiency advantage of electricity is outweighed by a carbon factor disadvantage, at least for industry as a whole.[11]

Our paper sheds light on the crucial role of electricity. Despite the fact that electricity is often seen as a climate friendly alternative in industrial production in the public discussion, we find that the carbon burden from conversion inefficiency in the power producing sector usually leads to higher emissions in end use. Nonetheless, it would be hasty to discard the emission saving potential of electricity in industrial final energy use in future policies because the emission factor of electricity is decreasing over time (Figure 3). In 1995, the emission factor of electricity was 694 g CO_2/kWh, i.e. 110 g more than in 2006. Once the share of low-carbon fuels and renewables in electricity generation is sufficiently high, their emission-reducing effect might outweigh the detrimental effect of conversion losses. Technological progress is also working in favor of electricity, enhancing not only end use efficiency but also conversion efficiency in the power sector. This adds to the many other arguments for using electricity in the industrial sector, such as the high flexibility of use, resilience towards supply insecurities because of substitutability of primary fuels and ease of handling.

On balance, this paper has shown that the plant-level energy mix, energy intensity and level of energy use are not independent of each other. Hence, it is important to take into account the energy mix when designing policy measures targeted at reducing energy intensity.

[11] A note of caution is advised with regard to the methodology. We focus on absolute correlations that should not be interpreted as causal relationships. Analysis of partial correlations, e.g. via regression analysis, is left as a task for future research.

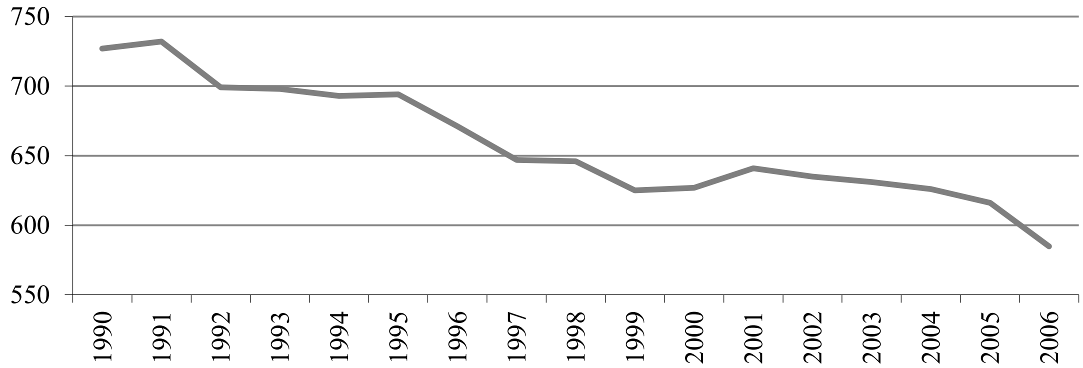

Figure 3: Development of average emission factor of electricity in the German public grid (in g CO_2/ kWh). Source: 1995-2005:Umweltbundesamt [9], 2006: own calculations based on the same source.

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