Effects of economies of scale and experience on the costs of energy-efficient technologies – case study of electric motors

Daniela Jardot
Fraunhofer Institute for Systems and Innovation Research (ISI)
Germany
daniela.jardot@isi.fraunhofer.de

Wolfgang Eichhammer
Fraunhofer Institute for Systems and Innovation Research (ISI)
Germany
wolfgang.eichhammer@isi.fraunhofer.de

Tobias Fleiter
Fraunhofer Institute for Systems and Innovation Research (ISI)
Germany
tobias.fleiter@isi.fraunhofer.de

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Abstract

Increasing energy efficiency is often discussed as an effective way to protect the climate, even though this is frequently associated with additional (investment) costs when compared to standard technologies. However, the investment costs of emerging energy-efficient technologies can be reduced by economies of scale and experience curve effects. This also brings about higher market penetration by lowering market barriers. Declining cost curves have already been analyzed in detail for renewable energy technologies, but are not as well documented for energy-efficient technologies despite their significance for energy and climate policy decisions. The wider use of energy-efficient electric motors, which are responsible for a large share of industrial electricity consumption, can help to further reduce greenhouse gases. The analysis is based on three methodologies: (1) The classification of energy efficient electric motors within a market analysis, (2) an expert survey with results on opportunities for cost reductions while penetrating the market and (3) the calculation of composite price indices for the years 1995 until 2006 which show the historical cost development for electric motors in a period when so-called "eff2" motors substituted less efficient "eff3" motors on the European market. The results are then compared with the cost reductions observed for other energy-efficient technologies in a literature review.

Introduction

Within the current debate on climate change, improving energy efficiency is discussed as one main option for greenhouse gas abatement. However, improving efficiency is often linked to higher investment costs when comparing standard technologies with new energy-efficient ones. When evaluating the costs of policies to support energy-efficient technologies, e.g. market transformation programs that aim at increasing their market share, the differential costs between the standard and the energy-efficient technology are taken into account. For energy-efficient technologies, which are still regarded as new and have relatively low market shares, the cost difference to the standard technology might be considerable. However, the costs would be overestimated in such a case if this cost difference were assumed to be constant over the whole lifetime of the market transformation program. Indeed, in many cases it has been observed that the costs of the "new" energy-efficient technology converged towards the costs of the mature standard technology with an increasing market share. This is especially true if the cost difference is mainly based on a lower production quantity, or a lower degree of automation. In these cases, the cost difference could be reduced by realizing economies of scale (EOS) or economies of experience (EOE) for energy-efficient technologies.

Up to now, the analysis of cost reduction effects in relation to new technologies and energy policy has concentrated on the energy supply side. Experience and learning curve effects have been widely studied for renewable energies (see Uyterlinde et al., 2007; Vattenfall, 2007; IEA, 2007; Swanson, 2006; Junginger, 2005; Schaeffer, 2004; Neij et al., 2003, Junginger et al., 2003), but only a few studies have been made of the cost declining effects for demand side efficiency technologies (see Weiss et

Table 1. Energy efficiency classes according to IEC-60034-30

Efficiency class	*Denotation*	*Related motors*	*Efficiency interval (4 poles, 60 Hz)*	*Approximate motor prices in € (0.75 kW - 375 kW)*
IE3	Premium Efficiency	NEMA Premium	86.0% – 96.1%	40 – 60% higher than IE1 motors
IE2	High Efficiency	EPAct, MEPS, eff1	82.8% – 95.3%	20 – 30% higher than IE1 motors
IE1	Standard Efficiency	eff2	74.1% – 94.5%	160 – 15,000
Source: own table based on Almeida et al. (2008), IEC (2008)				

al., 2007; Jakob, Madlener, 2004; IEA, 2003; McDonald, Schrattenholzer, 2000).

By improving the empirical base for cost reductions in energy-efficient demand side technologies, this paper aims to contribute to a more reliable estimation of costs in policy analysis. The availability of reliable cost data is an important factor for the enforceability of market transformation programs. This will also help when prioritizing the different options for climate change mitigation. We estimate the past cost development and its determinants for electric motors with a special focus on EOS and EOE. Due to data restrictions, it is not possible to compare the cost development of standard motors with energy-efficient motors. Still we consider differences in the energy efficiency of the motor and the market shares of those motors because electric motors are a highly relevant demand-side technology especially in the industrial sector, where they account for about two thirds of total electricity consumption (see Almeida, 2008; IEC, 2008).

Analysis of energy-efficient electric motors

MARKET ANALYSIS – CLASSIFICATION OF ENERGY-EFFICIENT ELECTRIC MOTORS

A market analysis with regard to motor labeling shows that, until now, the European motor market has been governed by a voluntary agreement (VA) on efficiency classification – the European sector committee of Manufacturers of Electrical Machines (CEMEP) VA with three efficiency classes: “eff1”, “eff2” and “eff3”. Energy could be saved by reducing the share of less efficient “eff3” motors and pushing the market expansion of more efficient “eff2” motors.

In 2009 a new classification is being introduced by the International Electrotechnical Commission (IEC), establishing worldwide harmonized efficiency classes for single-speed, three-phase, 50 Hz and 60 Hz, cage-induction motors that have a rated voltage U_N up to 1,000 V, a rated output P_N between 0.75 kW and 375 kW and which have either 2, 4 or 6 poles[1] (see Table 1). According to the IEC 60034-30 standard, “IE3” motors currently represent the best available technology (BAT). The IEC-scale will be used as a reference for further regulation within the scope of the EUP-Directive (Eco-design Requirements for Energy-Using Products) (see Knoll, 2008).

To accelerate the market penetration of efficient motors, the implementation of minimum efficiency standards are being discussed by the European Commission (EC). It is recommended that specific size groups have to fit different eco-design requirements. According to IEC 60034-30, “IE1” motors above 375 kW must have a minimum efficiency of 94%. Furthermore there are three possible scenarios being proposed for the introduction of minimum efficiency performance standards for electric motors in Europe based on the classification scheme defined by the IEC (see Almeida et al., 2008; EC, 2008):

1. Motors in the power range of 0.75 kW - 375 kW manufactured in or imported into the EU after January 1, 2011 must meet or exceed the “IE2” efficiency level.
2. Motors in the power range of 0.75 kW - 375 kW manufactured in or imported into the EU after January 1, 2011 must meet or exceed the “IE2” efficiency level. High-powered motors in the power range 7.5 kW - 375 kW manufactured in or imported into the EU after January 1, 2015 must meet or exceed the “IE3” efficiency level.
3. Motors in the power range of 0.75 kW - 375 kW manufactured in or imported into the EU after January 1, 2011 must meet or exceed the “IE2” efficiency level. Moreover, lower-powered motors from 0.75 kW as well are included in the minimum efficiency scheme so that motors in the power range of 0.75 kW - 375 kW manufactured in or imported into the EU after January 1, 2015 must meet or exceed the “IE3” efficiency level.

The decisive implementing measures are currently being discussed by the EC and will soon be voted on. Implementing minimum efficiency standards would help to put the European market on a comparable efficiency level with other large economies. In the USA, “IE2” and “IE3” motors have a market share of 70%, whereas in Europe (EU-27) their market share stands at about 15% at present (see EC, 2008; Brunner, 2007).

EXPERT SURVEY

Approach

We designed an expert survey to back up the decrease in costs of energy efficient electric motors with empirical data. A questionnaire was sent to different domestic and European manufacturers of energy efficient electric motors and experts experienced in this area (e.g. contacts at associations for electric drives, working groups for energy efficient products and appliances or universities and other research institutions specialized on energy efficient electric motors) (see Table 2). The selection represents multinational companies, affiliated groups and medium-sized firms which develop or manufacture energy efficient electric motors or spend time on measures to increase energy efficiency. Thereby the questionnaire was primarily sent to CEOs or the head of the departments for R&D, production or energy efficiency. The aim of the survey was to obtain

1. The efficiency levels defined in IEC 60034-30 (2008) are based on the test methods specified in IEC 60034-2-1 (2007). It defines new efficiency classes but does not include rules on their implementation (see ABB, 2008).

Table 2. Consulted contacts in regard to energy efficient electric motors

Contacts	*Germany*	*other European countries*
Manufacturers	28	8
Associations	2	1
Working groups	1	2
Universities	2	1
Other research institutions	3	5
Total	36	17

qualitative and quantitative results giving indications for cost reductions in the case of electric motors. The results give an overview of the state of technology and the relevance of energy efficiency increase in the prevailing environment. The survey was restricted to the engine-power classes between 5.5 kW and 90 kW regarding "IE1", "IE2" and "IE3" motors in accordance with IEC 60034-30. "IE1" motors serve as a reference because they have been used for a longer time compared to innovative motors which are new on the market and thus have only little experience.

Contents of the questionnaire

The questionnaire combines three essential parts (I-III) about the valuation of future cost trends of efficient electric motors. Part I points out common questions with regard to the manufacturer's market situation including the market share and the production lot of the company in the last year. Part II analyzes the costs of efficient motors. Therefore the particular IEC-classes and the specific cost types (material, energy, labor and miscellaneous) were requested. The classification was made to show how particular cost types (such as material or labor costs) change after an efficiency class or engine-power class increases its market share. In part III, the contact person should give qualitative answers about cost reductions, saving potentials as well as possible future cost reduction effects.

Evaluation and Results

Willingness to cooperate and rate of return

It was difficult to find suitable manufacturers of energy efficient electric motors who agreed to participate in the analysis of cost reductions. Reason for that was the fear that direct competitors could get a too detailed insight in the internal cost structures when the survey results were published. Thus, an important competitive advantage could be lost. Another point was the difficulty to identify a detailed cost breakdown inside of the company. The willingness to cooperate was obtained from three companies (two medium-sized and one large manufacturing company). The rate of return only represents 5.66%, but bearing in mind the market shares of the respondents the results are still representative even with limited input data. Moreover, the survey contents regard internal cost data, so this is an acceptable value. Table 3 shows the most important results.

Possibilities for an increase in energy efficiency regarding electric motors

Many consulted manufactures are already working on innovative methods to increase energy efficiency. Moreover, high efficient electric motors are already built, but price and information deficits particularly are hampering an accelerated market diffusion. Higher prices can mainly be traced back to larger material needs which let the prices of efficient motors increase additionally when commodity prices (foremost iron, steel, copper) are increasing as during the past two years. That is why the cost reduction potentials regarding energy efficient electric motors are estimated to be rather small when using current construction methods. But innovative approaches which increase energy efficiency without using more material can lead to future cost reductions.

Thereby the efficiency increase need not come along with a higher dimensioning of the motor but via some techniques the motor efficiency as well can be increased without the use of more material. Those variants are very important because due to rising commodity prices a lower material input can enhance the manufacturers' margins and due to the cost saving lower list prices can be given to the customers, respectively.

Currently an increase in motor efficiency is mainly obtained with two measures: (1) the reduction of copper losses, e.g. via a motor construction with a higher wire cross section and (2) the reduction of iron losses, e.g. via a material input with better electrical property. The method of copper die-casting is an effective measure to increase the motor efficiency solely through a higher copper input (no further iron or steel requirements; no larger motor construction). For this purpose the rotor is made from copper which leads to a better conductivity up to 50% so that an equal, low-loss motor or a smaller motor with equal kW-performance can be fabricated. Moreover, many electric drives nowadays have a variable engine speed. Additionally, the motor or motor system efficiency can be increased via permanent-driven synchronous motors or variable speed drives (VSD) which are attached on fans and pumps to adjust the speed to the exact demand of the application.

But, the input of more material need not result imperatively in a higher motor dimensioning (measured against the diameter of the stator). Furthermore the total engine efficiency can be increased by using complete system solutions (motor, drive, electronic within one appliance) which determine all cutting sites so that there are lower friction and electricity losses. The motor efficiency of such a system can be clearly higher than the efficiency of "IE3" motors.[2]

2. Due to a non-disclosure agreement of specific business data, a reference cannot be listed. Each of the data indications was collected out of interviews with different contact persons.

Table 3. Survey results with regard to cost reductions of energy efficient electric motors

	Company A	*Company B*	*Company C*
Market share concerning the efficiency class	IE1: medium	IE1: high	IE1: n.a.
	IE2: low	IE2: medium	IE2: n.a.
	IE3: marginal production	IE3: low	IE3: n.a.
Material costs	Increase traced back to iron and steel; with each engine-power class improvement more material is used	Increase (15-20%) per efficiency class switch traced back to increased commodity prices	Increase is traced back to the recent cost increase regarding the purchase of iron, steel, aluminum and copper
Energy costs	Decrease with each efficiency class and each increase in engine-power class	n.a.	n.a.
Labor costs	Decrease with each efficiency class and each increase in engine-power class	n.a.	n.a.
Miscellaneous costs	Decrease with each efficiency class and each increase in engine-power class	n.a.	n.a.
Relevant factors for production expansion	Increase in material costs, decrease in energy, labor and miscellaneous costs		n.a.
Significance of	EoS: low	EoS: high	
	EoE: low	EoE: low	EoE: high
Monitoring of EoS and EoE effects in the past	No monitoring		Special system solutions
Possibilities for future EoS and EoE seen for	Synchronous motors or special motor systems		
Intended expansion of the production spectrum	IE2	IE3	n.a.
n.a.: not applicable; source: own table based on expert interviews			

CALCULATION OF COMPOSITE PRICE INDICES AND ANALYSIS OF COST COMPONENTS

In a next step we used a statistical approach based on composite price indices and an analysis of the cost components of the (gross) value added in order to measure cost reductions for energy-efficient electric motors. After a short introduction to the basic approach of calculating composite price indices including a plausibility check, the detailed analysis is presented which was used to identify possible cost reduction effects for electric motors in the statistical category "Electric motors, generators, transformers and components". In order to derive these possible effects for energy-efficient electric motors, we analyzed the development of material commodity prices and labor costs in detail. Finally, a future scenario is developed to reveal possible future cost reductions.

Methodology and data sources

The basic concept is that the production costs for the year 2006 can be deduced from those for the year 1995 by considering volume and price effects due to changes in material use and labor intensity and that these can then be compared with real cost data from 2006.[3] From this comparison, it is possible to deduce cost reduction effects due to improved labor productivity and more efficient material use. We developed composite price indices that combine the indices for single cost drivers and can be compared with producer price indices. The index generation is based on the Laspeyres[4] formula which recalculates final year prices (or costs or quantities) from base year conditions by keeping all components fixed (see McNabb, 2004). In this analysis, the period 1995 to 2006 was chosen as the time frame because this was when "eff2" motors replaced "eff3" motors. If "eff2" motors had been more expensive than "eff3" motors, or had remained at the same price level, a noticeable cost increase would have been observed without cost reduction effects due to EOS and EOE based on the increase in material commodity prices during the same period.

Calculation basis are different statistical sources[5] which contain producer prices, labor productivity and the development of production as well as cost structures and the Bills of Materials (BoMs) for energy efficient electric motors from the Energy-Using-Products (EUP) Directive (see Almeida et al., 2008; Statistisches Bundesamt, 2008, 2007a, 2007b, 2006b). The indices were built for the statistical category "Electric motors, generators, transformers and components" (NACE 31.10) in the price statistics for production goods established by the Fed-

3. Unlike nominal prices, real prices are already inflation-adjusted.

4. The Laspeyres index is the classical approach to calculate price indices. It has also been commonly used for the factor analysis with energy indicators. An improved method may be based on the Divisia Index which removes the problem of the second order interaction terms between the different factors.

5. Annual price surveys by the German Federal Statistical Office (Statistisches Bundesamt Deutschland) form the basis of the productivity-, producer price- and labor productivity index. Within those surveys the consulted companies state the relative change in prices of a realized product (or service) compared to the previous year. The companies must guarantee comparable quality and quantity. Averaged over a number of years and over all consulted companies, qualities and quantities can change because over the course of time the basket of commodities shifts gradually and is adjusted periodically (see Fraunhofer ISI et al. (2008), p. 156).

eral Statistical Office Germany which is very close to our object of investigation. It further provides the breakdown on different cost components. For comparison purposes we selected further the more aggregate statistical categories "Engineering" (NACE 29) and "Appliances for electricity generation and allocation" (NACE 31).

In the statistical price data, there is no single category for electric motors. The category "Electric motors, generators, transformers and components" is a sub-category of the class "Appliances for electricity generation and allocation". The category "Engineering" was chosen because it also covers many applications for electric motors. A plausibility check was made to see how strongly electric motors are weighted in this category. The production statistics show (exemplarily for the year 2006) the composition of the total production values. 65.52% of the production value are linked to electric motors, 34.47% to transformers and about 0.01% to generators (see Statistisches Bundesamt, 2006a). Electric motors do indeed dominate the production value of the category, but the results could be biased due to a considerable fraction of transformers.[6]

Analysis of the cost development

Cost structures in industry

In order to understand the development of the cost structures in the statistical category "Electric motors, generators, transformers and components", we also analyzed the broader statistical classes "Appliances for electricity generation and allocation" and "Engineering" for comparison purposes. For each of these three categories, we obtained the producer price index[7] from the statistics (see Statistisches Bundesamt). To understand the development of the producer price index, we also collected the share of the following cost components (*CC*) of the inflation-corrected gross production value (*GPV*) from the statistics:

1. material consumption
2. energy consumption
3. labor cost per employee
4. employees per (gross) production value
5. depreciation
6. miscellaneous costs
7. costs for (outsourced) wage labor

In order to compare the seven cost components with the price index, we converted, to make the data homogenous, each of the seven components first to a cost index (c_j) based on 1995, the starting year of our investigation (see formula 1 below), then weighted the change in each of these indices since 1995 with the share of each cost component in the *GPV* in the year 2000, which was in the middle of the period 1995 to 2006 under consideration. Thus, the changes in the indices, developed from the cost components, are a proxy for different components of the change in the producer price index and can be compared with it. The results for the three statistical categories are shown in Fig. 1 to Fig. 3.

$$c_j = \frac{CC_{j,2006}}{CC_{j,1995}} \text{ ; for } j = 1 \text{ to } 7 \qquad (1)$$

(for each above-mentioned cost component)

$$weighted\ cost\ change_j = cost\ change_j * weight_j \text{ ; for } j = 1 \text{ to } 7 \qquad (2)$$

with $cost\ change_j = (c_j\text{-}1) * 100$ and

$$weight_j = \frac{CC_{j,2000}}{GPV_{2000}} \text{ ; for } j = 1 \text{ to } 7$$

Fig. 1 shows the change in the producer price index and in the single cost categories between 1995 and 2006 for the category "Engineering". The observed increase in producer prices (first column) is mainly caused by rising material and labor costs per employee. A similar trend is apparent in Fig. 2 for the category "Appliances for electricity generation and allocation", for which material and labor costs are again the main cost drivers.

The category "Electric motors, generators, transformers and components" shows a different development (see Fig. 3). The producer prices here decreased even though several cost components rose considerably: the costs for material, the labor cost per employee, (outsourced) wage labor and miscellaneous costs. The main compensating factor was the number of employees per *GPV*. This indicates a possible reduction in production costs per unit.

Within the period from 1995 to 2006, material costs grew in each of the three categories. The labor costs per employee decreased in all statistical categories. However, this was not the consequence of lower wages, but of a declining number of employees per *GPV* which compensated partially or fully the labor cost increase per employee and some of the other cost factor increases.

Generation of composite price indices to analyze possible cost reductions

The aim of this section is to recalculate the cost structures of the production in 2006 based on the caused structures in 1995 and to derive possible cost reduction effects caused by a productivity increase (more efficient use of labor and of materials; energy costs were too small during the period considered and did not contribute substantially to a productivity increase) from the comparison with the really observed cost structure in 2006.

The determination of cost reductions takes place in four steps: (A) Starting point is the structure of real cost factors of the year 1995 (see column A of the following diagrams in Fig. 4 to Fig. 6; 1995 = 100%). (B) Volume effects caused by increasing production between 1995 and 2006 are captured by the producer index of the year 2006 (see column B). The volume effect is calculated by multiplication of the distinct cost shares in the year 1995 with the increase of the production index in 2006 compared to 1995. Column B thus demonstrates the increase in the production value without any change in the cost structure.

6. The solely consideration of the year 2006 is adequate because the individual values (in %) of the last years barely have not been modified.

7. The Producer Price Index comprises different indices which measure price changes for goods and services at the wholesale level.

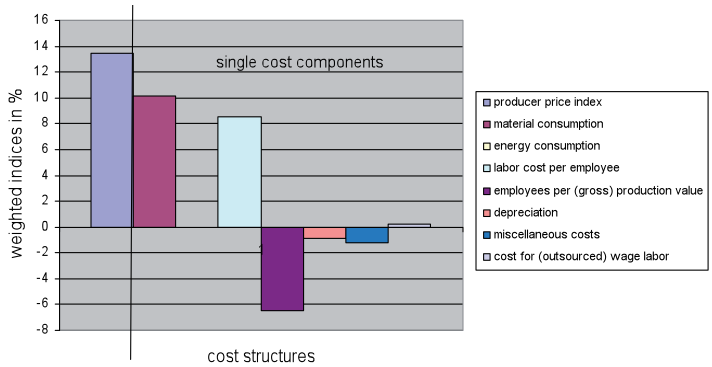


Figure 1. Index development for the category "Engineering"

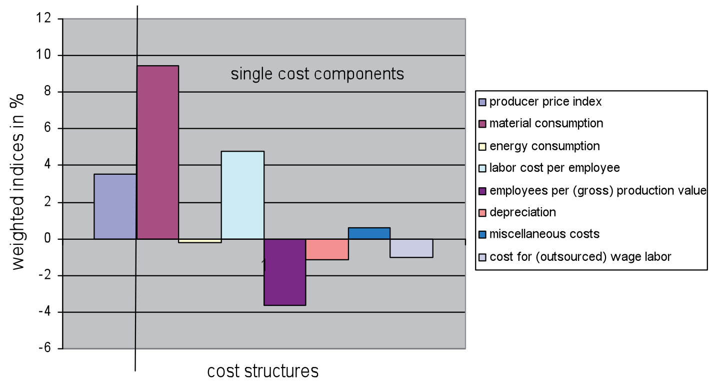


Figure 2. Index development for the category "Appliances for electricity generation and allocation"

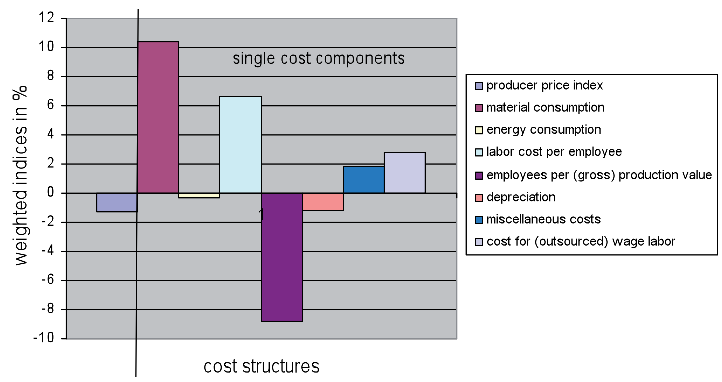


Figure 3. Index development for the category "Electric motors, generators, transformers and components"

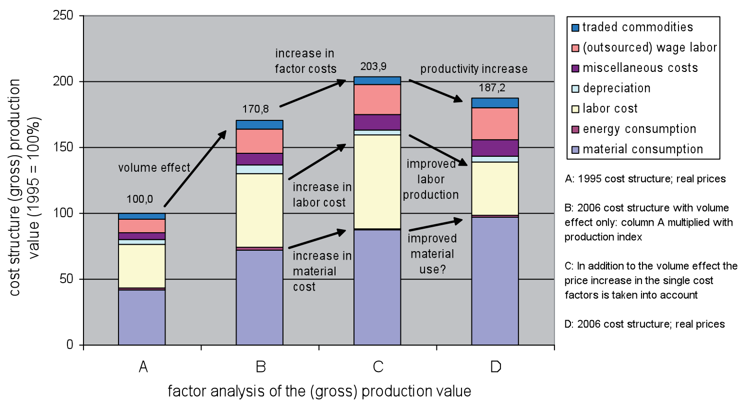
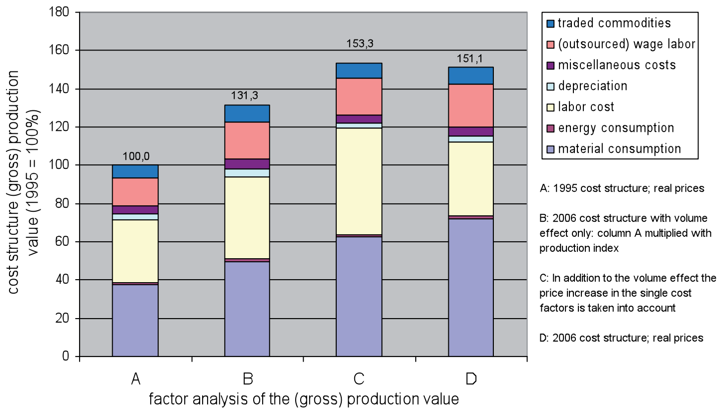
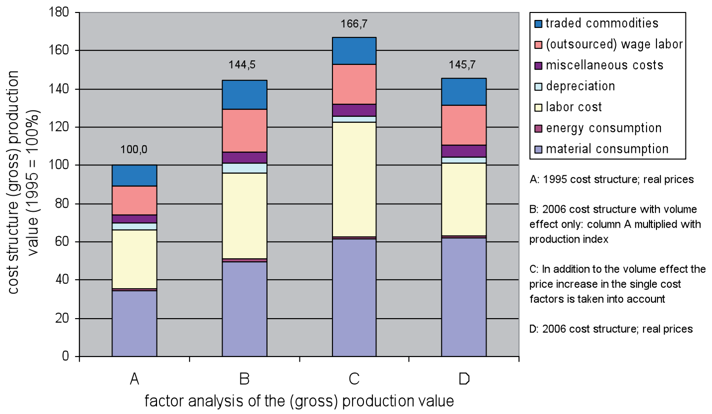


Figure 4. Cost structure of the (gross) production value between 1995 and 2006 for the statistical category "Electric motors, Generators, Transformers and Components"



Data source: Statistisches Bundesamt (2008, 2007b, 2006b)

Figure 5. Cost structure of the (gross) production value between 1995 and 2006 for the statistical category "Engineering"



Data source: Statistisches Bundesamt (2008, 2007b, 2006b)

Figure 6. Cost structure of the (gross) production value between 1995 and 2006 for the statistical category "Appliances for electricity generation and allocation"

(C) In the next step the impact of price changes for the different cost components is illustrated additionally (see column C). We calculated the rates of change of the cost factors since 1995 and multiplied with this factor the different components obtained in column B. For labor costs we used the increase derived from the increase in cost per employee. Column C thus shows the increase and change in the (gross) production value, if volume and price effects would have occurred but no productivity increase would have taken place. (D) Column D shows the real increase and the cost structures of the (gross) production value in 2006 including productivity increase. A comparison of both, volume and price effects with the real costs of 2006 reveals the impact of cost reductions due to EOS and EOE and answers the question as to which cost factor was responsible for the decrease in costs.

Composite price indices for the category "Electric motors, generators, transformers and components"

This section analyzes the cost reduction in the category "Electric motors, generators, transformers and components". Column B in Fig. 4 shows that the volume effect contributes to increasing the *GPV* by almost 71% between 1995 and 2006. Consequently, if there were no increase in productivity, the demand for material, energy and labor would increase proportionally.

After allowing for the volume effect, we added the increase in prices due to material cost increase, the increase in labor cost per employee as well the increase in outsourced labor cost in column C. Because of their smaller relevance, the other cost factors can be excluded from the analysis. When comparing column C with column D in Fig. 4, it becomes apparent that the real material costs (+10% in D) increased more than the volume and price effects included in column C would imply. This is a consequence of the fact that column C includes the net effect on materials of increasing prices for commodities and productivity gains or speaking in other words, this part of column C would be considerably higher if only volume effects and the price increase in material prices would be considered (see the discussion on commodity prices in the next section). The comparison between column C and D is much clearer with regard to labor costs, i.e. labor costs per employee: The real data of 2006 in column D show a decrease in labor costs of more than 30%; productivity gains have compensated for the increase in labor costs.

For the categories "Engineering" (see Fig. 5) and "Appliances for electricity generation and allocation" (see Fig. 6) the cost structure development is more or less the same; there were cost reduction effects in the reference time period, but the decrease in costs is not linked to decreased material consumption. If

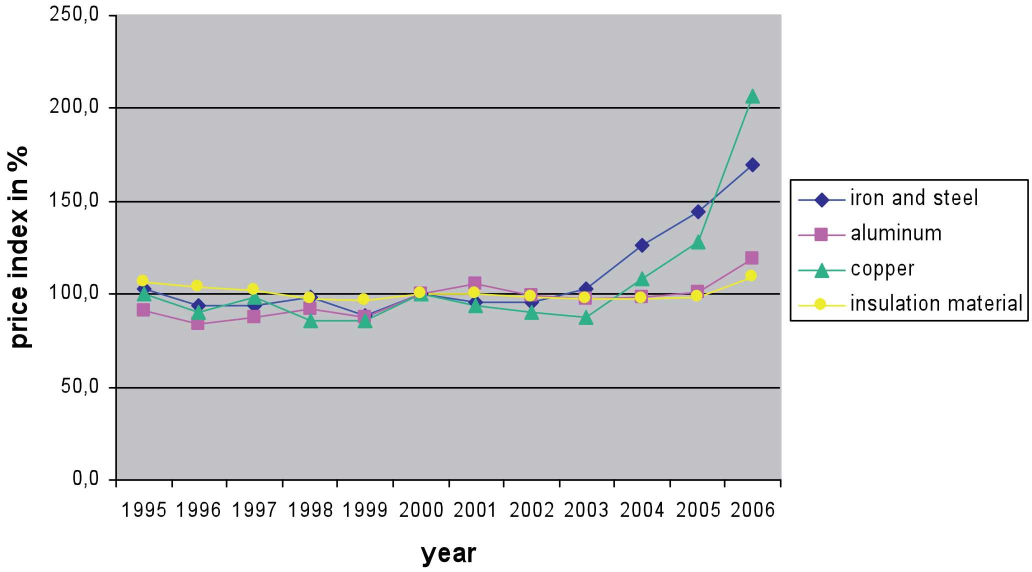


Figure 7. Historical development of selected commodity prices between 1995 and 2006 (2000 = 100%)

Table 4. Bill of materials for "IE1" motors

Material	*Motor power and material fraction*					
	1.1 kW	*%*	*11 kW*	*%*	*110 kW*	*%*
1: Iron and steel (kg/kW)	9.40	75.87	5.85	78.95	6.77	90.27
2: Aluminum (kg/kW)	1.70	13.72	0.90	12.15	0.18	2.40
3: Copper (kg/kW)	1.24	10.00	0.64	8.64	0.54	7.20
4: Insulation material (kg/kW)	0.05	0.41	0.02	0.26	0.01	0.13
Source: Almeida et al. (2008)						

Table 5. Bill of materials for "IE2" motors

Material	*Motor power and material fraction*					
	1.1 kW	*%*	*11 kW*	*%*	*110 kW*	*%*
1: Iron and steel (kg/kW)	12.1	73.11	6.80	77.98	7.30	90.01
2: Aluminum (kg/kW)	2.50	15.11	1.00	11.47	0.20	2.47
3: Copper (kg/kW)	1.90	11.48	0.90	10.32	0.60	7.40
4: Insulation material (kg/kW)	0.05	0.30	0.02	0.23	0.01	0.12
Source: Almeida et al. (2008)						

such large savings with regard to labor costs had not taken place, no overall cost reduction might have occurred.

Commodity price development

In order to understand the development of material costs between 1995 and 2006, we analyzed the commodity price development during this period to generate a base for further calculations. The analyzed materials are:

1. Iron and steel
2. Aluminum
3. Copper
4. Insulation material

Fig. 7 shows the historical development of commodity prices since 1995. For all commodities a price increase can be observed; mainly in the years from 2003 to 2006 (insulation material: 2.2%, aluminum: 31%, iron and steel: 64%). For copper the price increased by 107% which is more than a doubling.

Bills of Materials and weighting of commodity prices

In the next step, we took into account that, during the period 1995 to 2006, the more efficient "IE1" (eff2) motors penetrated the market at the expense of "eff3" motors. In a future scenario later on we also simulate the penetration of "IE2" motors (which now have a small market share compared to "IE1" motors). For each purpose we calculated a composite material price index which is based on the composition of "IE1" and "IE2" motors. The Bills of Materials (BoMs)[8] for "IE1" and "IE2" motors are taken from Almeida et al. (2008) who distinguish the power classes 1.1 kW, 11 kW and 110 kW for each efficiency class (see Table 4 and 5). In this way the material cost development per efficiency class increase becomes evident. The percentage of iron and steel is the most significant by far and accounts for most of the increase in material costs followed by similar shares of aluminum and copper. The absolute values in kg per kW for all materials decrease with each increase in motor power class.

8. A Bill of Materials (BoMs) represents structured compositions of materials or components which are essential to produce specific products.

However, the relative material fraction does not decrease for all materials. This is due to the high share of iron and steel so that even a decrease in materials is reflected in a relative increase in material prices.

To calculate the motors' weighted commodity prices (wcp_i) for each of the above mentioned power classes and efficiency levels, the following formula is applied based on the commodity price development normalized to the year 2000[9] (cp_i) and the specific material fractions for energy-efficient "IE1" or "IE2" motors (mf_i). The calculated values form the basis for the recalculated material price index considered later on.

$$wcp_i = \sum (cp_i - 1) * mf_i \text{; for } i = 1 \text{ to } 4 \quad (3)$$

(see above-mentioned commodities)

Analysis of cost reduction effects for "IE1" motors

This section analyzes the material cost development in more detail. We took the real material cost data for "IE1" motors, taking into account the weighting of energy-efficient motors in the BoMs in Table 4. We then replaced the material price increase from column C in Fig. 4 with the recalculated material price index according to Almeida et al. (2008) based on a typical 11 kW "IE1" motor consisting of 79% iron and steel, 11% aluminum, 8% copper and 2% insulation material.[10] This results in a weighted material price index (see formula 3) of approximately 1.63. Consequently, between 1995 and 2006 the weighted material prices for this type of motor have risen by about 63%. In Fig. 8 we have introduced the so modified material price index (which now does not contain any productivity gains on the materials) in the new column C. Compared to column D the material block is higher. The other cost components remain unchanged when compared to the analysis illustrated in Fig. 4.

Comparing column C and D shows both the impact of cost reductions caused by improved labor productivity and the impacts due to more efficient material input. It is also interesting to compare column B and D as well. The real cost data of 2006 (column D) are about 10% higher than the volume effect generated in B. This means that the prices of electric motors should have risen by about this amount in the period 1995 to 2006, but, as seen in one of the previous sections, the producer prices actually remained more or less constant in the category "Electric motors, Generators, Transformers and Components". This could be caused by methodological differences in the way the production index used to calculate column B is set up as compared to the definition of the price index, but this would actually enhance the calculated cost reduction effects. If column B was slightly higher due to methodological differences, column C and hence the difference between D and C due to productivity improvements would also be even larger, giving more credit to our arguments.

The previous analysis highlighted a cost reduction for "IE1" motors of approximately 20% in the period 1995 to 2006 which compensated the increases in material prices and wages (see Fig. 8). Hence, the cost reduction is comparable to the empirical evidence found for efficiency technologies or renewable energies in the literature review which will be presented at the end of this paper (see Table 6). The reduction is caused by EOS in material costs amounting to 15% and a 43% productivity improvement in labor. The results represent an important empirical validation of previous model assumptions for energy efficient technologies where it was assumed that cost reduction effects may also be valid for efficient electric motors (see Fraunhofer ISI et al. 2008).

For the categories "Engineering" and "Appliances for electricity generation and allocation" it was not possible to generate a specific material price index in the same way. This is because there were no empirical data available on the detailed material composition of the multitude of products in these larger categories so that an extensive analysis was not able to be carried out at this point.

Analysis of possible future cost reductions for a transition from "IE1" to "IE2" motors

Based on the previous results, in a next step, a future scenario was developed up to the year 2013 which could be relevant for the activation of further cost reductions regarding highly efficient motors, in particular "IE2" motors.

Fig. 9 shows the possible decline in costs due to EOS and EOE for energy-efficient motors in a future scenario up to the year 2013. The following assumptions were made when calculating the scenario: 3% production growth per year, higher material prices, increasing material efficiency, higher automation leading to higher labor productivity, higher labor costs per employee and rising energy costs. To simplify the calculation, all other values remain constant. Assuming that "IE2" motors will dominate the market in the period until 2013, the material price index must be calculated in accordance with the BoMs for these motors. We based our calculations on an 11 kW "IE2" motor with 78% iron and steel, 11% aluminum, 10% copper and 1% insulation material (see Table 5). Under the assumption of an increasing commodity price development, the weighted material price index is approximately 1.77 (column C in Fig. 9). Regarding EOS and EOE, a possible future decrease of about 6% for material costs and 45% (calculation see formula 3) for labor costs could be achieved. If commodity prices rose only moderately in the future, the overall cost reductions would be much higher than calculated in this scenario with approximately 7%. If energy efficiency improvements were possible without increased material demand, the scope for future cost reductions would also be much larger.

Limits and uncertainties of the methodology

The index generated to weight the material components for energy-efficient electric motors was chosen as a methodology to obtain evidence for previous cost reductions in the reference category for electric motors. Using only empirical data, the analysis does deliver results which are statistically covered. However, the main drawbacks of such an approach should be mentioned and possible limiting factors of the analysis are presented below.

One criticism is the lack of transparency regarding the composition of the production index. This could lead to falsified results if, for example, more products of a certain category were

9. We normalized the data values with the year 2000 because that year is in the middle of the considered time period.

10. The BoMs for "IE1" motors had been taken as a basis because those motors dominate the market between 1995 and 2006.

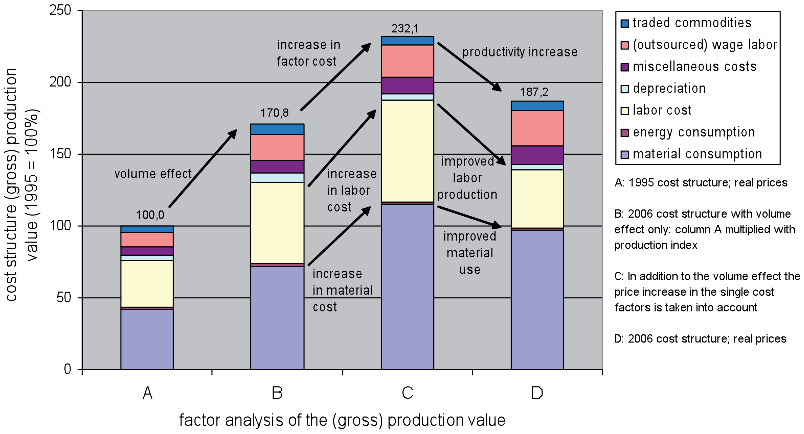


Figure 8. Cost structure of the (gross) production value between 1995 and 2006 for the statistical category "Electric motors, Generators, Transformers and Components" taking into account cost reduction effects for materials (based on the material bill of "IE1" motors")

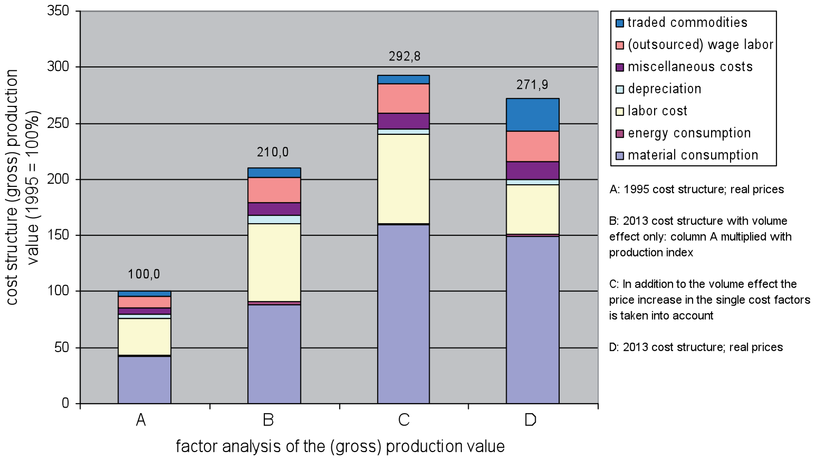


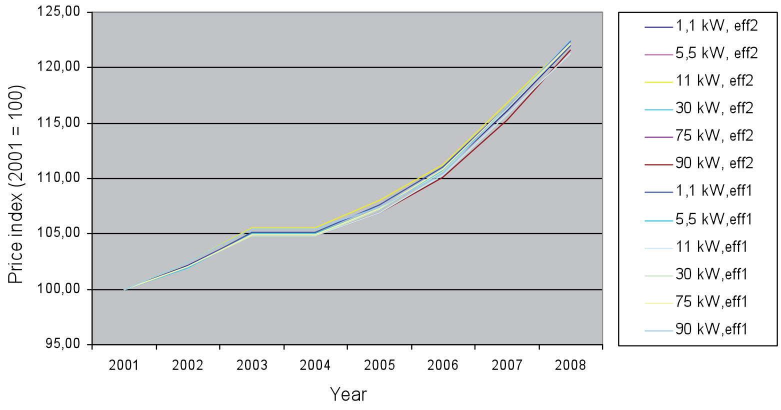
Figure 9. Future cost structure of the (gross) production value until 2013 for the statistical category "Electric motors, Generators, Transformers and Components" taking into account cost reduction effects for materials (based on the BoMs of "IE2" motors between 2006 and 2013)

sold. If promotion or incentives to purchase a particular good were introduced, the sales volume would increase accordingly and other products would lose weight. Adopting the calculation to such a situation only delivers inaccurate results. Further, it was not possible to generate historical data for efficient electric motors alone. Electric motors only represent 65% of the reference category; the other large product group was transformers. Considering these separately could avoid possible sources of error. In addition, the separation into single categories (e.g. electric motors versus transformers) would allow a better comparison of the cost reductions obtained with other values in the literature.

The above investigation is limited in the sense that it shows that energy efficient motors have experienced a cost reduction but it does not prove that the gap between efficient technologies and standard motors is closing. The shift from "eff3" to more efficient "eff2" (IE1) motors took place during the studied period 1995 to 2006. One argument could be that the analyzed cost reductions could have turned out to be even more important if there had not been a market penetration of the more expensive "eff2" at the expense of "eff3" motors. According to one manufacturer (a multinational company with a respectable market share), the cost development for "eff2" runs parallel to "eff1" and is more or less identical, i.e. despite market penetration there has not been a stronger cost reduction for "eff2" motors (see Fig. 10). This runs counter to the expectation that, once efficient technologies have penetrated the market, the cost differential to the previous standard technology will be reduced or vanishes. Fig. 11 shows such an expected development of price alignments. It would, however, be unlikely that "eff2" motors would have penetrated the market so largely as observed if the motors would have been substantially more expensive.

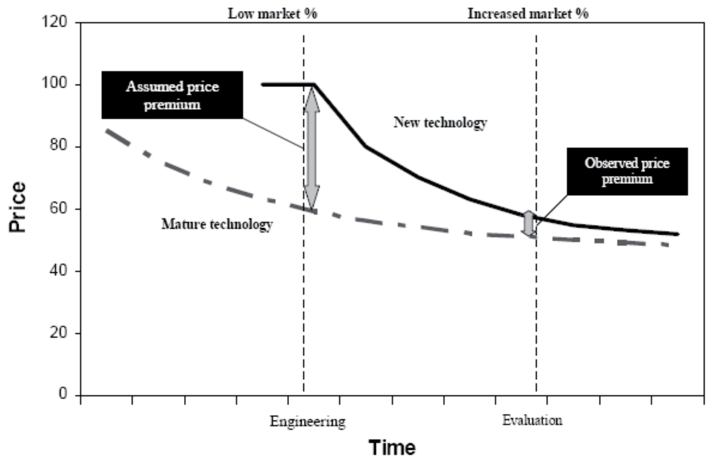
Mathematical description of the experience curve and learning rates for different efficiency technologies

The literature analysis provides information about already analyzed cost reductions based on the concept of learning and experience curves which states that the production costs decrease by a constant factor with each doubling of the cumulated quantity (see Hieber, 1991). The decrease in cost at a constant



Data source: Own illustration based on manufacturer information

Figure 10. Price data for energy efficient "eff1" and "eff2" motors (nominal prices)



Data source: Ellis (2007)

Figure 11. Price impact of market growth for energy efficient technologies as compared to standard technologies

percentage is known as the "learning rate". Up to now there have been learning rates of up to 30% depending on the product or technology (see Table 6)[11]. In mathematical terms, the experience curve is described as:

$$c_{sp} = c_0 \cdot X^{\log 2(1-LR)} \qquad (4)$$

with c_{sp} for the specific costs, c_0 for the costs of the first produced quantity, X for the cumulative production and LR for the learning rate.

Since 1978, the analyzed technologies in Table 6 show learning rates of up to 26% for renewable energies (energy supply from photovoltaic systems had the highest LR, followed by wind energy and biomass). Similar rates were recorded for windows and facades in energy-efficient buildings between 1975 and 2001 and for household appliances, in particular, for washing machines: the costs here have fallen substantially since 1988 due to a LR of approximately 30%.

The results for electric motors cannot be directly compared with learning rates since we do not know how much the production of "IE1" motors increased in the period 1995 to 2006. However, we can derive a rough estimate from the CEMEP agreements (www.cemep.org). They show that the market share of "IE1" motors increased from 30% in 1995 to 85% in 2006[12]. At the same time, our previous analysis indicates that the volume of the total motor market increased by 71% between 1995 and 2006. From these figures one can estimate an increase in the "IE1" market by a factor of five between 1995 and 2006. A LR of around 9% can be calculated from these figures with the help of formula (4). Thus, the calculated cost reductions for energy-efficient electric motors of about 9% are shown together with the learning rates for other energy efficient and renewable technologies in Table 6. These results should be an incentive for a closer look at the cost development of energy-efficient electric motors which may also help to promote the market penetration of efficient electric motors more strongly and benefiting from EOS and EOE.

11. Mostly new technologies show higher learning rates than standard technologies. This means that innovative technologies learn faster from the realization of market experience than established ones.

12. These figures are for the European Union, but they should be also representative for Germany as the largest motor market in the EU.

Table 6. Cost reductions of analyzed efficiency technologies

Technology		*Time period*	*Country/Region*	*Cost indicator*	*Experience indicator*	*LR [number of production doubling]*	*reference*
Renewable Energies	Wind energy	1990 – 2001	EU	sp. prod. costs [€/kW]	cum. installed cap. [MV]	15% – 19% [9.5]	Junginger et al. (2003), p. 146
		1981 – 2000	Denmark	sp. price [€/kW]	sp. price [€/kW]	9% [8.6]	Neij et al. (2003), p. 28 f.
		1984 – 2000	Spain	sp. inv. price [€/kW]	cum. cap. [MW]	9% [15.5]	Neij et al. (2003), p. 30
		1987 – 2000	Germany	sp. price [€/kW]	sp. price [€/kW]	6% [11.0]	Neij et al. (2003), p. 28 f.
		1992 – 2001	United Kingdom	inv. costs [€/kW]	cum. cap. [MW]	19% [n.a.]	Junginger (2005), p. 65 ff.
		2006 – 2020	World	sp. inv. costs [€/kW]	cum. cap. [GW]	15% – 19% [n.a]	Uyterlinde et al. (2007), p. 4080
		2006 – 2030	World	capital costs [$/W]	cum. cap. [MW]	11% [n.a.]	Vattenfall (2007). p. 33
	Photovoltaic	1979 – 2002	World	sp. price [$/W]	cum. cap. [MW]	19% [9.4]	Swanson (2006), p. 444
		1976 – 2001	EU	sp. price [€/W_p]	cum. prod. [MW]	20% – 23% [10.5]	IEA (2007)
		1988 – 2001	World	sp. price [€/W_p]	cum. cap. [MW_p]	26% [n.a.]	Schaeffer (2004), p.20
		2006 – 2020	World	sp. inv. costs[€/kW]	cum. cap. [GW]	20% – 23% [n.a.]	Uyterlinde et al. (2007), p. 4080
	Biomass	1990 – 2002	Sweden	costs of electricity	costs of electricity	8% – 9% [n.a.]	Junginger et al. (2006), p. 4039
		2006 – 2020	World	sp. inv. costs [€/kW]	cum. cap. [GW]	7% – 9% [n.a.]	Uyterlinde et al. (2007), p. 4080
Buildings	Double-glazed windows	1985 – 2001	Switzerland	costs in CHF/kWh	cum. cap. in Mio. m²	12% – 17% [n.a.]	Jakob, Madlener (2004), p. 170
	Facades with insulation (1.25 W/m²K)	1975 – 2001				18% – 21% [n.a.]	Jakob, Madlener (2004), p. 170
Products and household appliances	Condensing boilers	1988 – 2006	World	real price [€/kW]	cum. installed cap. [MW]	8% – 14% [n.a.]	Weiss et al. (2007)
	CFLs (Compact Fluorescent Lamps)	1988 – 2006		price [€/W]	cum. worldwide sales in million units	18% [5.2]	
	Washing machines	1988 – 2006		price [€ per kg washing capacity]	cum. worldwide prod. in million units	30% [n.a.]	
	Tumble dryers	1988 – 2006		price [€ per kg capacity]	cum. worldwide prod. in million units	13% [n.a.]	
	Refrigerators and freezers	1988 – 2006		price in €	cum. worldwide prod. in million units	7% – 16.5% [n.a.]	
Industrial cross-cutting technologies	Electric motors (IE1)	1995 – 2006	Germany	derived from the statistical development of the production value	cum. production of units	9% [5.0]	This study

sp. = specific; cum. = cumulative; cap. = capacity; prod. = production

Source: own table referring to McDonald, Schrattenholzer (2000)

Conclusion

By analyzing the detailed structure of the GPV for energy-efficient electric motors, it was possible to identify cost reductions in the reference category amounting to approximately 20% between 1995 and 2006, corresponding to a LR of around 9%. The decreasing costs refer to the realization of EOS (decrease in material costs: 15%) and EOE (decrease in labor costs: 43%). EOE are especially noticeable in cost structures concerning labor because absolute wages have decreased due to lower workforce numbers despite a constantly increasing wage level. The methodology was based on a statistical analysis of cost structures for the production of electric motors, but the analysis only revealed a cost reduction regarding "IE1" motors during the period in which "eff3" motors were substituted by more efficient "eff2" (IE1) motors. Hence, it was not possible to show that the cost differential between standard and energy-efficient motors decreased. However, some arguments were put forward to support this hypothesis. The consideration of a future scenario until 2013 is based on assumptions in cost reductions of about 7% caused by EOS and EOE (material: 6%, labor: 45%).

Finally, in consideration of the current climate discussion, both efficiency improvements and an increasing market penetration of efficient electric motors are essential. If manufacturers offered efficient electric motors at reasonable prices from the beginning, demand would increase in the future. This process could be accelerated through the introduction of minimum efficiency standards by prohibiting the sale of inefficient motors. Another policy support measure is the promotion of highly efficient motors in order to stimulate a large market at an early phase which then contributes to cost reductions through EOS and EOE. Detailed empirical analyses of energy-efficient electric motors are important because they can contribute to better understanding the innovation effects triggered by strong policies to improve energy efficiency on the demand side. Furthermore, the outcomes can be integrated into energy system models used for policy recommendations or into the advice given to market actors. For the first time, this study presents evidence of cost reductions occurring for efficient electric motors while these penetrate the market.

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