Energy efficiency in electric motor systems: Technical potentials and policy approaches for developing countries
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Summary

Electric motor systems account for about 60 percent of global industrial electricity consumption. Electric motors drive both core industrial processes, like presses or rolls, and auxiliary systems, like compressed air generation, ventilation or water pumping. They are utilized throughout all industrial branches, though the main applications vary.

Studies showed a high potential for energy efficiency improvement in motor systems in developing as well as in developed countries. Particularly system optimization approaches that consider the whole motor system's efficiency show great potential. Many of the energy efficiency investments show payback times of only a few years only. Still, market failures and barriers like lack of capital, higher initial costs, lack of attention by plant managers and principal agent dilemmas hamper the investment in energy efficient motor systems.

To overcome these barriers, policies were established in several countries. Examples include minimum energy performance standards (MEPS) that require a minimum efficiency level for electric motors to allow them to enter the national market. These have been implemented in many countries worldwide. Although MEPS can be a very effective measure to improve the market share of energy efficient motors, they are not designed to address system optimization aspects of whole compressed air or pump systems, for example. Policies using a system optimization approach combined with capacity development were implemented by China or Brazil.
1. Introduction

Electric motor systems account for about 60 percent of industrial electricity consumption and about 15 percent of final energy use in industry worldwide (IEA 2007). It is estimated that a full implementation of efficiency improvement options could reduce worldwide electricity demand by about 7 percent (IEA 2008). Electric motors drive both core industrial processes, like presses or rolls, and auxiliary systems, like compressed air generation, ventilation or water pumping. They are utilised throughout all industrial branches, though the main applications vary. With only some exceptions, electric motors are the main source for the provision of mechanical energy in industry. Size classes vary between motors with less than one kW and large industrial motors with several MW rated power. In recent years, many studies identified large energy efficiency potentials in electric motors and motor systems with many saving options showing very short payback times and high cost-effectiveness.

Still, investments in improving the energy efficiency of electric motor systems are often delayed or rejected in favour of alternative investments. Different barriers and market failures were found to be responsible for that. Among them are a lack of attention of the plant manager, principal agent dilemmas, higher initial cost for efficient motors and many more. Particularly in developing countries, access to capital and initial higher costs of energy efficient motors are a very relevant barrier. In many cases, broken motors are rewound and reused even though motor rewinding often reduces its efficiency.

This opportunity of high energy efficiency potential has also been recognised by policy makers, who have worked toward overcoming the barriers since the 1990s. As a consequence, policies, like minimum standards and motor labelling schemes, were introduced in many countries around the world. In addition, energy audit schemes and capacity development programmes that focus on system optimization were established.

However, after more than a decade of energy efficiency policy on motor systems, considerable energy efficiency potential can still be observed, e.g., by investing in more efficient motors or installing inverters to better control the motor. Market transformation programmes showed they successfully transformed the motor market towards higher efficiency, while new emerging motors with even higher efficiency are just about to enter the market.

Although, this report focuses on developing countries, it is in some parts unavoidable to use literature and data from developed countries, due to data constraints. In these cases however, the
conclusions are also valid for developing countries, as they mostly concern technical descriptions. In other cases, data from developed countries was intentionally added for comparison, especially in the policy chapter. This report does neither describe the situation in the least developed countries nor give policy conclusions for these countries.

2. **Motor system technology and options for energy efficiency**

Electric motors are used in most industrial systems where mechanical energy is needed. They convert electrical energy into rotary mechanical energy, which then is further converted to finally provide the needed use-energy.

![Figure 1](image)

**Figure 1**  
Share of different motor systems of total electricity use by industrial motor systems in the US

*Source: IEA 2007*

Depending on the industrial structure, electric motor systems account for about 60 to 70% of industrial electricity consumption. A typical classification of motor systems is shown in Figure 1, which shows the share of each motor system in the total electricity consumption of all motor systems in the US. Although the figures vary slightly by country, the general pattern is comparable to most countries. Pumping, compressed air and fan systems are some of the most electricity-consuming motor systems. Furthermore, material handling and processing consume a great deal of electricity, although these systems are more heterogeneous and rather different from each other.
While most of the electric motors used are induction motors\(^1\) and thus relatively comparable, the systems in which they are used vary strongly – in terms of complexity as well as efficiency. Pumping, compressed air and ventilation systems often enjoy special attention, as they represent a huge share of industrial electricity consumption and at the same time relatively high saving potential. The importance of each motor system differs among industries. For example, in the metal processing industry, most motors are used for material processing and handling, while in the pulp and paper industry, the share of motors used in pumping systems is remarkably high and the food industry shows high shares of motors used for cooling appliances.

Consequently, the system perspective is essential for the exploitation of energy savings in motor systems. In this document, the system definition by Brunner (2007) et al. will be used. They distinguish between three kinds of motor systems:

1. The (fully functioning) electric motor itself.
2. The core motor system, which can comprise a variable speed drive, the driven equipment, like a fan, pump or compressor, and the connection like a gear or a belt.
3. The total motor system, which also includes a ducting or piping system and all possible end-use equipment, like compressed air tools. An uninterruptible power supply could also be included.

By going from 1 to 3, the system boundaries are systematically expanded, which consequently increases the complexity as well as the potential for energy efficiency improvements. While the choice of high efficiency components may also improve the system’s efficiency, only a system-wide optimization with regard to control equipment and choosing components that fit together in terms of load and size can realize the full potential of energy efficiency improvements.

### 2.1 System efficiency improvement

**Pump systems** account for the highest share of industrial electricity consumption. They represent about one quarter of total electricity consumption of all motor systems in industry in the US. In Europe, they account for about 20 percent of industrial electricity demand (ETSU et al. 2001). The use of pumps is highest in the petrochemical (51 percent), the pulp and paper (28 percent) and the chemicals industry (18 percent), while the share of pumps of total electricity consumption is well below 10 percent in many other industries (Elliot, Nadel 2003). Figure 2

\(^{1}\) There is a great variety of motors available on the market, however, induction motors account for the large part of electricity consumption. The majority of other motors are used for distinctive applications.
presents a comparison between a typical pump system and an energy efficient one. The efficient pump system uses a variable speed drive instead of a throttle, more efficient components like motor and pump, and shows reduced friction loss in motor and pump coupling as well as in the pipe network.

Figure 2  Comparison of a typical and an energy efficient pump system

Source: De Keulenaer H. et al. 2004

Over time, pumps deteriorate and their efficiency can fall by up to 10–15 percent (ETSU et al. 2001). Gudbjerg (2007) mentions possible efficiency losses in centrifugal water pumps of around 5 percent after the first five years of operation. If the fluid contains solids or if temperature or speed is increased, deterioration will accelerate. The drop in efficiency is strongest in the first years of utilization. Besides regular maintenance, coatings, e.g., with glass or resin, can improve long-term durability as well as the efficiency of the pump (Gudbjerg, Andersen 2007).
Fans are mostly used in heating, ventilation and air-conditioning systems to provide the necessary air exchange, but they are also applied in other processes like material handling and cleaning, drying or painting. Fans account for about 9.5 to 17.5 percent of the industrial sectors’ total electricity consumption with the highest share of 17.5 percent in the pulp and paper industry (Radgen 2002).

Fans can typically be distinguished into centrifugal and axial fans, which then have further sub-categories. Among these sub-categories, the fan’s efficiency can vary between 55 percent and 88 percent, which implies that great potentials for efficiency improvement exist simply by choosing the right fan, although not all fans are applicable for all purposes (Radgen et al. 2007). As for other cross-cutting technologies, including the efficiency of fans, the system perspective is essential and most of the potential savings can only be realized by extending the system borders beyond the optimization of single components.

Refrigeration accounts for a high share of electricity use in the food industry as well as in the chemicals industry. For food processing, many raw materials, intermediate products and final products need to be refrigerated to ensure product quality, lifetime and to comply with hygienic standards. The chemical industry mostly needs very low temperature cooling for the liquefaction of gases, often down to several Kelvin only. Options for energy efficiency
improvement exist along the entire cold chain, from better insulated cold storage houses in the food industry to more efficient compressors and cold generation systems.

**Compressed air systems** consume about 10 percent of industrial electricity consumption in the EU as well as in the US (Radgen, Blaustein 2001; XEnergy 2001). They range in size from several kW to several hundred kW. In comparison to electric motor-driven systems, compressed air tools can often be designed smaller, lighter and more flexible. They allow for speed and torque control and show security advantages, because no electricity is used where the pneumatic tools are used. Consequently, compressed air systems are found in all industries, although they are considerably less energy efficient than direct motor-driven systems. While compressed air is used in the food industry for purposes like bottling, spraying coatings, cleaning or vacuum packaging, typical uses in the textiles industry are loom jet weaving, spinning or texturizing. In most industries, compressed air is used for conveying and controls and actors.

**Figure 4    Typical compressed air system**

![Typical compressed air system](Source: The Carbon Trust 2005)

In a typical compressed air system a supply and demand side can be distinguished. The supply side consists of compressors and air treatments and provides pressurized air, while the demand side consists of an air distribution system, storage tanks and mostly several end-uses like different pneumatic tools (see Figure 4). Controls adjust the compressed air supply to the actual demand. The compressor is often driven by an electric motor, but particularly in plants with high electricity costs or a high risk of blackouts, alternative drives like diesel or natural gas
engines or steam turbines are used to drive the compressor. A variety of different types and designs is available for the compressor, which converts mechanical energy into pressure. Many compressors are sold packaged with the motor already included and the design of the core motor system is thus already determined by the compressor producer. Before being transported to the place of use, the air is treated to improve its quality by drying or filtering. These many energy conversion, storage and transportation steps lead to significant energy losses and inefficiencies. With a typical system efficiency of 10–15 percent, compressed air systems are among the least efficient industrial motor systems (IEA 2007). Efficiency improvements are practically available everywhere in the system.

Hence, replacing compressed air-driven tools by motor-driven ones can improve energy efficiency considerably. This option is, of course, not applicable to all compressed air systems. However, due to the continuous improvement of electric motor drives the applications in which they can deliver the same services and quality at lower costs increase as well. In fact, compressed air is considered the most expensive energy carrier available at a plant and its replacement can result in significant economic benefits, and it is particularly important for new plants to determine whether compressed air is the appropriate energy carrier if they are to achieve the highest energy efficiency levels.

A large improvement potential also exists in cases in which compressed air is still the most appropriate energy carrier. Radgen and Blaustain (2001) found a technically and economically feasible savings potential of about 33 percent of the electricity consumption of all compressed air systems in Europe – exploitable within a period of 15 years. They identified 11 distinct measures that improve the energy efficiency of compressed air systems. Among these, the reduction of air leaks is by far the single most influential measure. Other measures with a comparably high impact include the use of multi-pressure systems, variable speed drives or the recovery of waste heat. Many of the improvement options can be implemented by replacing only select components and some, like the prevention of air leaks, require no system change at all. Case studies in the US showed average energy savings of 15 percent of the compressed air system electricity use with payback times less than two years (XEnergy 2001). In Germany, the assessment of 40 compressed air plants revealed high saving potentials of mostly between 20 and 50 percent of total electricity consumption of the compressed air system (Radgen 2004). As energy costs account for the

Already small air leaks in compressed air systems can cause several thousand dollars of additional annual costs. Leak prevention programmes can avoid these unnecessary expenses and increase energy efficiency.
highest cost share of compressed air systems, many energy efficiency options show very short payback periods (see Figure 5).

Figure 5 Costs of a compressed air system with a 10-year lifetime

![Pie chart showing costs of a compressed air system with a 10-year lifetime.]

Source: The Carbon Trust 2005

Material handling and material processing differ strongly between industries and processes. For example, in the paper industry they are mostly rolls and conveyors, while in the cement industry mills account for a substantial amount of electricity consumption. They are too heterogeneous to be described here and their improvement options are closely linked to the industrial process to which they are applied. Some of the general options that are applicable in most cases, like high efficiency motors, are described in the following section.

Optimization of the entire motor system goes a lot further than applying high efficiency components and avoiding stand-by time. System optimization assures that the chosen components work together effectively and that saving potentials along the entire energy flow chain within a system are considered. This, e.g., means that the first and highest ranked energy efficiency option for compressed air systems should be to determine whether the amount of compressed air provided is actually needed in the process. As a next step, the compressed air system itself has to be optimized by choosing high efficiency components, but also by making the components fit together and by efficiently controlling and monitoring the entire system. As a final step of system optimization, the possibilities for energy recovery, like the use of low temperature waste heat from air compressors, should be considered.
In contrast to the replacement of components by energy efficient ones, many of the system optimization options involve fairly low investment costs, which make them particularly attractive in developing countries where companies are exposed to even stronger capital restrictions. However, system optimization which goes beyond switching off appliances if they are not needed is complex and requires in-depth knowledge about the installed processes. Therefore, the success of improved system optimization initiatives is closely bound to the capacity development of highly skilled system optimization experts (McKane et al. 2007).

2.2 Component efficiency improvement

Due to the considerable heterogeneity of motor systems, production systems and firms in industry, the options to improve energy efficiency are manifold and diverse. However, certain cross-cutting improvement possibilities are observable among the majority of motor systems. These options also have the highest savings potential at industry level, although system-specific options might provide for higher energy savings at the individual firm-level. Some of the options that have the highest potentials for efficiency improvement relate to the motor itself, the motor control and the core motor system like the use of high efficiency pumps or fans or the correct sizing of these appliances. The following options relate to the electric motor itself and the core motor system.

Depending on the age and efficiency of the motor in place, the replacement of a less efficient motor with a high efficiency motor can have considerable saving potentials with payback times of a few years only. For applications which have high annual running hours, in particular – mostly in firms with multi-shift operations – replacement can be very profitable. Case studies reveal that motors which are older than 20 years are still being used in many companies – in developing as well as in developed countries. Even shorter payback times are achieved if, following the breakdown of a motor, high efficiency motors are chosen rather than standard ones. The price premium of a high efficiency motor of about 20 percent often pays off after several months. A direct comparison of the lifecycle costs of an energy efficient permanent magnet motor with a standard asynchronous motor in Figure 6 shows that investment in the energy efficient motor is cost-effective above 2000 h annual running time (Almeida et al. 2008). For motors with very high annual running hours, the lifecycle costs can be reduced by more than 10 percent.

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2 The assumptions were the following. Motor lifetime was assumed to be 12 years. The standard motor had an efficiency of 75.1 percent and a price of EUR 160, while the permanent magnet motor had an
In case of a motor breakdown, companies often decide to **rewind** the broken motor and to thus avoid higher investments in a new one. The main steps in motor rewinding are the dismantling of the motor and checking for damages, removal of the old windings as well as insulation and cleaning of the stator core and, finally, rewinding with new wire and efficiency testing. According to Meyers et al. (1993) rewinding is even more common in developing countries due to the relatively low labour costs and the high price of a new motor. Some motors are rewound 5 to 6 times before they are finally scrapped.

From an efficiency point of view, rewinding can be a bad decision for two reasons. The older less efficient motor will continue to be used for a decade or two and, furthermore, rewinding often comes with a loss of motor efficiency of 1 to 3 percent, which is substantial for electric motors. Others argue that rewinding can actually increase motor efficiency, if, for instance, the copper content of the windings is increased during rewinding by using a copper wire with a greater diameter (EASA, AEMT 2003). Still, if motor efficiency is low and can be improved through rewinding (through increased copper content), the motor might just be very inefficient and buying a new one might significantly improve efficiency. Furthermore, good rewinding needs reliable repair shops that use low temperature bake out ovens, high quality materials and a efficiency of 88.75 percent and a price of EUR 288. The underlying electricity price was 0.0754 euros/kWh
quality assurance programme to ensure that motor efficiency is tested after rewinding and that the motor was not damaged during the process (EnerWise Africa 2005).

Rewinding broken motors is a common practice, particularly in developing countries, but the rewound motors often lose efficiency by 1 to 3 percent. Consequently, rewinding should only be used for motors with low annual running hours (below 2,000 hours per year).

Therefore, (high quality) rewinding may be used for motors in applications with low annual running hours (less than 2,000 hours per year), where motor efficiency is not as crucial. Quality assurance and capacity development for proper motor rewinding is an effective measure to improve the efficiency of the motor stock, particularly in developing countries.

Another option to considerably improve motor system efficiency is the application of frequency converters to adjust motor speed in accordance with the use-energy needed. These variable speed drives have the highest saving potentials in flow systems, like pumping or ventilation systems with high output variations. Pumping systems are traditionally controlled by valves. These reduce output flow while the motor is still running in full load and thus waste an enormous amount of energy, which is released as friction. Variable speed drives, in contrast, control motor input frequency and voltage in order to adjust the motor rotation speed to the requirements. As a consequence, pump load or water flow are adjusted – without the use of an inefficient valve. Depending on system design, the efficiency improvement can be higher than 30 percent. These high savings are achieved because in pumping or ventilation systems, the power consumed is proportional to the cube of the flow.

Variable speed drives have increasingly attracted attention since the 1990s. However, their application and market diffusion still lags behind what is energetically and economically feasible, also in newly installed systems.

Considerable efficiency differences exist for the electric motor as well as for the pump, the fan or the compressor. Radgen and Oberschmidt (2007) show that the efficiency of today’s fans varies by up to 25 percent within one fan class. They found an improvement potential of 8 percent (centrifugal backward curved fans) to 33 percent (axial fans) in comparison to the typical product of each product type. This shows that by focusing on energy efficiency when designing a product, large efficiency gains can be realized.
Similar observations are made for pumps (AEA Energy and Environment 2008). Consequently, when choosing a pump or fan, its energy efficiency should be an important decision factor which it often is not.

2.3 Future technology

Although electric motors are a mature technology, certain improvements of energy efficiency are still expected. Currently, a new generation of motors with copper die cast rotors is being produced which will increase efficiency by some percentage points in comparison to standard technology (Doppelbauer et al. 2005). The permanent magnet motor shows potential for even higher efficiencies, particularly for smaller motors up to several kW.

Compared to electric motors, electronic motor controls that allow for variable speed drives (VSD) are a fairly new technology, which still have considerable market potential in the coming years. As the cost of power controls production is mainly determined by processing and packaging costs, further substantial declines in VSD costs are expected (Mecrow, Jack 2008). Together with the tendency towards more integrated and smaller motor controls, the application of VSD is expected to increase significantly.

In the very long-term, superconductivity may reduce losses in electric motors even more and thus reach efficiency levels of around 99 percent. However, this technology will only be cost-effective for very large motors (or generators) in applications with high annual running hours.

3. Case studies

This chapter aims to illustrate how energy efficiency improvements can be realized in companies. Although real cases are presented, they cannot be regarded as representative, as they only present a very small sample.
<table>
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<tr>
<th>Project</th>
<th>Country</th>
<th>Energy efficiency improvement</th>
<th>Cost-effectiveness</th>
</tr>
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<tr>
<td><strong>Optimization of the cooling water system</strong> in a pharmaceutical company by installing two new pumps, applying variable speed control and minimizing friction losses in the ductwork system.</td>
<td>China</td>
<td>Reduction of electricity demand of cooling water system by 49 percent</td>
<td>Payback about 1.8 years (investment of USD 145,000 and annual savings of USD 80,000)</td>
</tr>
<tr>
<td><strong>Installation of 34 variable speed drives</strong> in a petrochemical company.</td>
<td>China</td>
<td>28% electricity demand reduction per tonne of crude oil refined</td>
<td>0.48 years static payback time</td>
</tr>
<tr>
<td><strong>Installation of 15 variable speed drives</strong> in a ventilation system in a textile plant</td>
<td>USA</td>
<td>59% reduction of ventilation system's electricity demand</td>
<td>1.3 years static payback time and USD 130,000 investment</td>
</tr>
<tr>
<td><strong>Pump impeller size reduction, throttle replacement and motor replacement</strong></td>
<td>UK</td>
<td>More than 30% of pump electricity consumption</td>
<td>11.5 weeks (investment of GBP 2780)</td>
</tr>
<tr>
<td><strong>Installation of 102 variable speed drives</strong> in one company (Yang 2007)</td>
<td>Mexico</td>
<td>20% reduction of electricity demand of equipped motors</td>
<td>1.5 years static payback and investment of around USD 400,000</td>
</tr>
<tr>
<td><strong>Compressed air system optimization</strong> in textile manufacturing plant</td>
<td>USA</td>
<td>4% reduction of compressed air electricity demand and further reliability benefits</td>
<td>The total investment of USD 529,000 had a payback time of 2.9 years.</td>
</tr>
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Within the scope of the China Motor Systems Energy Conservation Program (collaboration of UNIDO, the US Department of Energy, the Energy Foundation and the Chinese government), energy audits were conducted in Chinese firms to improve the energy efficiency of their motor systems, namely compressed air, fan and pump systems. In total, 41 plants were evaluated and in most cases, investments in system optimization were made. The average estimated payback time was 1.4 years. However, some projects showed payback times of only a few months, while others were about 5 years. The projected savings were between 7 and 50 percent of the systems’
electricity consumption. The projects that had already been realized when the project report was produced showed that the projected savings were achieved or overachieved (Peters, Nadel 2004).

The following energy efficiency project was initially described by Tutterow et al. (2004). It entailed an energy audit which was conducted in a Chinese pharmaceutical company to identify improvement potentials of the plant's pumping system. Before optimization, the cooling system consumed over 2 million kWh per year, which was about 13 percent of the total plant's electricity consumption. The audit revealed several sources of unnecessary energy loss, including the use of a valve to regulate water flow and a drastic change in the diameter of a pipe that caused considerable friction losses. The optimization project which was conducted based on this evaluation included the installation of two new pumps, the use of variable speed control and the cleaning as well as optimization of the ductwork to minimize friction losses. In total, the USD 145,000 investment had a payback time of 1.8 year and reduced the electricity demand for the water cooling system by 49 percent.

Within the same programme, another project was carried out in a petrochemical company to reduce electricity consumption for crude oil refining. 34 variable speed drives were installed resulting in a reduction of specific electricity consumption from 8016 to 5766 kWh/t crude oil refined, with a short payback time of only 0.5 years.

The US Department of Energy (DOE) also published several case studies about the implementation of energy efficiency measures within companies. One of these projects from the textile industry is the installation of 15 variable speed drives in a spinning and weaving plant in the US. The company is a medium-sized company with 300 employees, which operates 24 hours per day, 348 days per year. This high annual operation time makes the investment in energy efficiency measures even more attractive as the payback time tends to be shorter. The plant processes 45,000 lbs of raw cotton per day. As the cotton requires a certain level of temperature and humidity in the production facility, a well-functioning ventilation system is essential. An energy audit of the ventilation system recommended retrofitting 15 of the 18 fans with variable speed drives. The project resulted in a drastic reduction of the ventilation system's electricity demand by 59 percent. These excellent results could be realized because the fans initially ran in part load and the replacement of inefficient dumper control by a variable speed drive enabled a considerable reduction in installed motor power. The investment of USD

130,000 paid back after only 1.3 years and the project showed further co-benefits, including an easier and more precise control of air quality.

Another case study from the UK reveals very short payback times for reducing the size of a pump impeller in a salt production plant. The salt is derived from brine (a salt solution) by evaporating water. To make use of the condensate, the company decided to transport it to a nearby power station where it is used for electricity production. For the condensate pumping, a 110 kW pump is used. An audit revealed that the pump created a pressure that was considerably higher than needed. Reducing the impeller diameter from 320 to 280 mm corrected this inefficiency. As a result, the throttle was made dispensable and the improvements resulted in savings of around 30 percent of the initial pumping energy consumption. After these pump modifications, the old 110 kW motor was oversized and worked in partial load and it was therefore replaced by a smaller motor that could work closer to its peak efficiency. The overall payback time of the two investments of GBP 2780 was 11.5 weeks in total. If only the reduction of the impeller diameter is considered, the payback time was 11 days, while it was 3.5 years for the motor replacement. Reducing the impeller size is such a cost-effective option, because it only requires very low investments and can result in significant energy savings. In this case study, the investment amounted to GBP 260, while the energy savings were around 30 percent.

A case study in a US textile manufacturing plant shows the impacts of compressed air system optimization on energy demand and productivity. The company has around 1,600 employees and manufactures diverse textile products. Compressed air is mainly used for the air jet looms, spinning frames and blowguns. In total, 8 compressors were used, of which 6 were between 800 and 1000 hp. To extend the production by 60 additional air jet looms, the company planned to install an additional 800 hp compressor. Furthermore, to deal with the frequently occurring pressure drops another capacity extension was foreseen. An energy survey revealed several weaknesses in the current system like an enormous pressure drop due to leaking, worn hoses, drains and valves and poorly functioning filters. Also, an excessive compressor blow off was identified, because the centrifugal compressor worked below its minimum stable flow. Bypass valves were not working properly and overheating, and moisture carry-over was found in the compressors. Furthermore, worn end-use components were responsible for substantial air leaks. Many of the recommendations to address all these weaknesses were implemented, such as the installation of a pressure/flow controller, storage, filter, dryer, repair of end-use components, replacement of the smallest compressor by two new 350 hp compressors and some further improvements. The project resulted in energy savings of around 4 percent of the compressed air.
system's electricity use, while production capacity was extended at the same time. Furthermore, the system worked considerably more reliably after project implementation, which directly improved productivity and reduced the system's maintenance costs (due to a 90 percent reduced shutdown rate). These results were achieved with an investment of USD 528,000, which had a payback time of 2.9 years.

4. Barriers

A number of different barriers and market failures can hamper the adoption of energy efficient technologies. Some of the barriers are very prevalent for electric motor systems. Among these are principal agent problems, lack of information, transaction costs or organizational structure.

Electric motor systems like compressed air, pumps and ventilation are mostly auxiliary systems, which are not the focus of the management of firms.

Motor markets often show a principal agent barrier: the majority of electric motors are bought by OEMs and incorporated into pumps or fans. The end-user, who pays the electricity bill, often has no information on the motor incorporated into the pump or fan and thus cannot base the investment decision on the efficiency of the electric motor. On the other hand, pump or fan manufacturers mainly compete on the basis of product price, which means the least costly motor is also the most attractive one.

De Almeida (1998) shows that the procurement process of new electric motors is a fairly standardized process in large firms, which implies the existence of several barriers related to lacking or even opposing incentives. For instance, the department responsible for the procurement of the new motor differs from that department which monitors the motor's electricity bill. In smaller companies, a motor breakdown is an emergency, where the only thing that counts is the time it takes to install a new motor. Furthermore, it is often observed that companies already stock backup motors of the same type to prepare for a breakdown.

The investment decision is often dominated by the initial motor cost and less weight is given to its running costs, which are by far the most important cost component over the motor’s lifetime. Thus, a typical price premium of 20 to 30 percent for high efficiency motors already represents an obstacle for companies with reference to choosing the more efficient motor (Almeida et al. 2008).
The knowledge and capacity of the employees is crucial for the efficient operation of a system. In addition, system optimization is a necessary prerequisite. In developing countries it is even more difficult for companies to find experts in motor system optimization (Nadel et al. 2002).

As motor system optimization also includes the application of high efficiency equipment, the availability of this equipment at reasonable prices is a prerequisite for an investment. However, in developing countries, the most efficient equipment is often not produced locally but has to be imported at relatively high prices. Nadel et al. (2002) describe the case of variable speed drives in China. According to them, imports had a market share of about 90 percent in 2000, mainly because Chinese products lacked the quality or features required by the purchaser.

5. Policy options

Several policy options exist to overcome these barriers and to expand the use of energy efficient equipment. The following section first discusses minimum energy performance standards (MEPS) and product labelling, which aim to increase the efficiency of products on the market, and the subsequent section focuses on ways to go beyond the use of efficient components and improve the entire system's efficiency.

5.1 Minimum standards and labelling

For over a decade, many countries have begun implementing labelling and minimum energy performance standard (MEPS) schemes to improve the efficiency of motors on the market. MEPS aim at phasing out the least efficient motor classes by setting minimum standards for the efficiency of motors being sold in a country. By labelling motors, policymakers seek to overcome the information barrier that made it impossible for company managers to invest in high efficiency motors. Labelling provides the needed information in a transparent way and facilitates comparisons of motor efficiencies among producers. Thus, it reduces transaction costs and contributes to the transformation of the motor market towards high efficiency motors. Therefore, MEPS and labelling often go hand in hand. While MEPS reduce the market share of least efficient motors, labelling promotes the use of very efficient motors, most likely in applications where they are most cost-effective.

As a necessary prerequisite of both labelling and MEPS, motor efficiency classes have to be defined. This has been done in many countries individually resulting in several different national standards. But because the established varying definitions of efficiency classes in different countries turned out to be a considerable trade barrier and made comparisons of motor
markets difficult, the International Electrotechnical Commission (IEC) developed an international efficiency classification, test standards and labels for electric motors (Boteler et al. 2009). The IEC classification distinguishes four efficiency levels with the label IE1 for the least efficient motors and IE4 for the highest efficiency motors. These classes are increasingly being used as a basis for national labelling and MEPS schemes. The scope of the IEC scheme covers AC, three-phase induction motors between 0.75 and 375 kW\(^4\). Although this definition only covers a specific type of the many different motors on the market, this general purpose motor accounts for the largest share of global electricity consumption by electric motors (around 70 percent). Smaller motors are mostly integrated into other products, like refrigerators or circulation pumps, which itself can be addressed by standards or labelling schemes. The defined efficiency classes are shown in Figure 7 for 50 Hz motors. The IE4 class is not yet defined, but expected to entail a further 15 percent reduction of losses in comparison to IE3. Figure 7 illustrates that the efficiency differences – and the expected savings – are particularly high for smaller motors and that the gap closes with increasing motor size to only about 2 percent difference from IE1 to IE3 for 375 kW motors.

**Figure 7** Efficiency classes for 50 Hz 4-pole motors according to IEC 60034-30

![Efficiency classes for 50 Hz 4-pole motors according to IEC 60034-30](image)

*Source: Boteler et al. 2009*

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\(^4\) Further requirements of the cited standard IEC 60034-30 are 2-, 4- or 6-poles, a voltage below 1,000 V, 50 or 60 Hz, and the motor should be a general purpose motor. Motors which are fully integrated into, e.g., pumps or fans and motors exclusively built for converter operation are explicitly excluded.
Several countries already have MEPS for motors in force or plan to introduce them. Among these are large electricity consumers like Brazil, China, USA, Europe, Mexico, Australia or Taiwan.

The first country to introduce ambitious MEPS for electric motors was the US. MEPS were passed into law as early as 1992, but it was not until 1997 when the standards were applied. This gave motor manufacturers a five-year period to adapt to the standards and redesign their motors. This so-called EPAct 92 standard is comparable to the international IE2 definition of the IEC. More ambitious MEPS were introduced in 2007 and entered into force in December 2010. By 2010, the US together with Canada were the first countries to set MEPS on IE3 (Boteler 2009).

Figure 8 provides an overview of the implementation dates of the different standards by country. It should be noted that the implemented standards do not, in most cases, precisely match the IEC testing and classification standards. For example, the standard in Taiwan, effective since 2003, is considerably better than IE1 for smaller motors and relatively close to IE1 for larger motors (Yang et al. 2009). Also, large developing countries like Brazil, Mexico and China have implemented MEPS.

Figure 8  Implementation of mandatory MEPS for electric motors worldwide (simplified illustration; not all countries included)


A look at the historic motor market data reveals that market transformation towards more efficient motors has taken place in the past (see Figure 9). In Europe, the labelling has contributed to the reduction of the market share of least efficient (Eff3) motors. Their market share has dropped from about 68 percent in 1998 to 16 percent in 2001 and only 2 percent in...
2007. However, the motor labelling could not significantly improve the diffusion of high efficient IE2 (former Eff1) motors. This was often explained by a higher price premium for IE2 motors.

In the US, the numbers of NEMA premium motors, which are equivalent to IE3 motors, have constantly increased since 2001 and accounted for close to 30 percent in 2006. In 2006, motors with IE2 or better comprised about 80 percent of the market share in comparison to only 12 percent in the EU.

In Canada, motors with IE3 or higher even accounted for 39 percent of the market in 2007. In Korea, IE1 motors had a market share of 10 percent in 2005, while 90 percent of motors were less efficient.

**Figure 9  Market share of motors by efficiency class in the US (left) and the EU (right)**

According to Garcia (2007), Brazilian motor manufacturers were easily convinced by the first MEPS introduced in 2002, because they already produced motors with a comparably high efficiency level and hoped to dispose of competing foreign motor manufacturers. For South Africa which imports almost all electric motors, it is crucial to develop standards in line with the international development in order not to negatively affect local distributors (Mthombeni, Sebitosi 2008). But at the same time, the scheme has to ensure that the local manufacturers are able to meet the standards.

The introduction of MEPS for electric motors in Brazil prevented the construction of 350 MW hydro power plants (Garcia et al. 2007). Electricity was saved at a cost of around 22 US$/MWh, which is far below market prices.
Besides electric motors, MEPS and labelling are applied for several energy using products, of which many contain electric motors. Examples are the MEPS in force in China since 1990 (Zhou 2008). Preparatory studies for the EU’s Ecodesign Directive also proposed future MEPS for fans and pumps (AEA Energy and Environment 2008; Radgen et al. 2007).

Although MEPS and labelling are an effective way to accelerate the diffusion of energy efficient electric motors, they only allow addressing a smaller part of the saving potentials of the entire motor system. Large parts of the core motor system can also be addressed by product-specific MEPS, similar to motor MEPS. The core motor system can be a circulation pump, a refrigerator or a fan for ventilation with an integrated motor. Thus, the product MEPS also consider motor efficiency. The larger variety of different products and types of products is challenging for policymakers. Nonetheless, the large saving potentials justify MEPS for many products. However, the largest savings can be gained by optimizing the entire motor system. Yet from a policy point of view, this is also more difficult to tackle because motor systems and their integration into the production process varies among processes as well as plants, and their optimization requires substantial knowledge about the relevant process. Consequently, the required policies are also more diverse and the involvement of experts is necessary. Some possible approaches are presented in the following section. They include energy audits and information and capacity building programmes for system optimization.

5.2 Energy audits and capacity development programmes

As shown in Chapter 3, to address the huge saving potential by optimizing the entire motor system (in contrast to the use of single high efficient components), a plant by plant approach is inevitable. As industrial plants differ considerably from one another, so does the compressed air, pump or fan system and a system optimization is not possible without evaluating individual plants. Consequently, system optimization is closely related to capacity development and energy management practices of companies. Many different policy options were proposed and implemented to address motor system efficiency. Among these are schemes that financially support external energy audits or energy management regulations.

The success of auditing schemes is closely linked to the training of the energy experts conducting the audit. Therefore, particularly in developing countries, audit schemes should be accompanied by capacity development programmes. An illustrative example for such a combination is China’s Motor Systems Energy Conservation Program, which was implemented
by UNIDO between 2001 and 2004\(^5\) (Williams et al. 2005). It was designed as a pilot programme and was implemented in two Chinese provinces (Jiangsu and Shainghai). The results provided a foundation for a later nationwide implementation. The main aspects of the programme included the training of experts in motor system optimization and conducting of energy audits in industrial plants where trainees and teachers jointly evaluated the pump, fan and compressed air systems of chosen companies. Two groups of experts were trained, namely factory staff and external experts. The external experts continued working in the two energy centres that were chosen for the pilot programme. The centres planned to offer motor system optimization audits and training programmes as a service.

The programme resulted in 22 engineers trained as system optimization experts, 38 plant assessments conducted which revealed an annual saving potential of 40 GWh, which translates to about 23 percent of electricity consumption per system. Most of the proposed energy efficiency investments showed very short payback times of one to two years. Moreover, more than 10 demonstration projects were implemented and close to 1,000 factory staff trained. Some of the case studies are described in Chapter 4. Thus, the programme not only trained many experts but also achieved considerable energy efficiency improvements in several companies.

The Brazilian Industrial Energy Efficiency Programme entered into force in 2003. Its primary focus area was industrial motor systems optimization. It has three objectives with regard to motor systems: optimizing already installed motor systems, accelerating the market penetration of high efficiency induction motors and strengthening technical support. To increase the commitment from industry, the National Confederation of Industry was involved in programme design and implementation. The programme is strongly based on capacity development. In the first phase, multipliers like university professors and consultants were trained during a 176 hour course in motor system optimization. Furthermore, motor system laboratories and education centres were established in different universities. The next step was the training of industry staff by these multipliers in order for them to be able to conduct energy audits within their own companies. The goal was to train representatives from 2,000 companies in motor system optimization. By 2005, 766 companies participated and 906 company representatives were trained who planned to conduct 1,140 motor system audits in their companies (Perrone, Soares 2005). Furthermore, a total of 123 multipliers from universities and consulting companies were involved in the training. After four years, several lessons could be drawn about the programme.

\(^5\) The programme was implemented in cooperation with the Lawrence Berkeley National Laboratory (LBNL) and the American Council for an Energy Efficiency Economy (ACEEE).
Besides the successful training of motor system experts, the programme succeeded in reducing the gap between university and industry by integrating university professors as multipliers. After the initial energy audits, the majority of optimization recommendations focused on motor replacement and less on system optimization aspects. As a result, many audits had to be repeated. Also, the initial training for the university and consultant multipliers turned out to lack practical aspects. Thus, it was extended by a practical in-company training that also better prepared the multipliers to support companies with their motor system audits (Soares 2008).

In Germany, an energy efficiency fund was introduced in 2008, which combines subsidized energy audits for small and medium-sized enterprises (SME) with low interest loans for investment in energy efficiency. This combination helps overcome barriers like lack of capital for project financing as well as lack of internal knowledge and capacity to evaluate the systems. Although it does not specifically focus on motor systems, many of the proposed and realized improvement projects are implemented in this field.

These examples demonstrate different successful approaches for addressing the tremendous energy efficiency potential motor system optimization offers. They also demonstrate the need to combine motor system optimization programmes with capacity development, because system optimization is a complex task and a plant by plant assessment is indispensable.

6. Conclusions

It has been shown that there is substantial energy efficiency potential in industrial motor systems, particularly when a system optimization approach is followed. Further, many of the energy efficiency investments have payback times of a few years only.

Developing countries with high growth rates and a fast growing industry can, in particular, benefit from policies for energy efficient motor systems. Using system optimization tools and high efficiency components for the construction of new production plants is the least costly and most efficient way to improve energy efficiency. Many of the components have lifetimes of up to 20 years and not choosing energy efficient components would manifest an inefficient production for a long period of time and make future optimizations more costly. This is an advantage developing countries have in comparison to developed countries, where a – sometimes several decades old and less efficient – technological production structure is established and energy efficiency improvements are often more expensive, because they require
substantial system changes or cannot be realized because they would require an interruption of the production process.

Policies to improve motor system efficiency are in place in many countries worldwide. Also, the BRIC countries like China or Brazil have implemented policies like minimum energy performance standards for electric motors on the market as well as audit and capacity development programmes. The latter are particularly useful for addressing the huge saving potentials that lies in system optimization.

Still, in both, developed and developing countries, the policies in place are not sufficient to exploit the energy efficiency potentials of motor system optimization.
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