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Energy-Efficiency Policy Opportunities for Electric Motor-Driven Systems

INTERNATIONAL ENERGY AGENCY

PAUL WAIDE AND
CONRAD U. BRUNNER

WORKING PAPER

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- Promote sustainable energy policies that spur economic growth and environmental protection in a global context – particularly in terms of reducing greenhouse-gas emissions that contribute to climate change.
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Table of Contents

List of figures

List of tables

List of equations

Acknowledgments

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Executive Summary

The global assessment

This paper presents the findings of the first global analysis of energy consumption in electric motor- driven systems (EMDS)[1] and the options to reduce it. It assesses the energy currently used by EMDS and the potential for energy savings, examines market barriers to the adoption of energy-efficient solutions, and reviews current policy settings and outcomes. The report then proposes a comprehensive package of policy recommendations to help governments tap the huge potential for energy savings in EDMS.

Electric motors convert electrical power into mechanical power within a motor-driven system. The vast majority of the electricity used by an EMSD is consumed by the electric motor itself. Only a very small amount is used to power control functions or other ancillary circuits.

Electric motors and the systems they drive are the single largest electrical end-use, consuming more than twice as much as lighting, the next largest end-use. It is estimated that EMDS account for between 43% and 46% of all global electricity consumption, giving rise to about 6 040 Mt of CO_2 emissions. By 2030, without comprehensive and effective energy-efficiency policy measures, energy consumption from electric motors is expected to rise to 13 360 TWh per year and CO_2 emissions to 8 570 Mt per year. End-users now spend USD 565 billion per year on electricity used in EDMS; by 2030, that could rise to almost USD 900 billion.

Table 1: EDMS electricity consumption by sector

Sector	Electricity consumption	% of all EMDS electricity	% of sector electricity
Industrial	4 488 TWh/year	64%	69%
Commercial	1 412 TWh/year	20%	38%
Residential	948 TWh/year	13%	22%
Transport and agriculture	260 TWh/year	3 %	39%

Source: IEA statistics, 2006 (national electricity demand); A+B International, 2009 (motors calculations).

These daunting figures are the aggregate of the energy consumed by an array of different types of motors operating within a wide set of applications in every sector of energy use, with the greatest opportunity for savings in the industrial sector (Table 1).

Motor systems used widely across all sectors

The majority of electric motors in use draw less than 0.75 kW of power in a variety of small applications, mostly in the residential and commercial sectors. These motors account for only about 9% of all electric motor power consumption. In general, they are integrated into mass-produced packaged applications such as refrigerator compressors, extractor fans, computer hard drives, etc. Many of these applications are subject to policies that apply to the level of the packaged system, rather than the electric motor component, but many are still not subject to any policy requirements. In the European Union, for example, at the beginning of 2010, only about 38% of motor electricity consumption in the combined residential and commercial sectors was used in systems subject to minimum energy performance standards (MEPS).

[1] Throughout this report, the acronym EMDS is used to refer to electric motors and motor systems.

The largest proportion of motor electricity consumption is attributable to **mid-size motors with output power of 0.75 kW to 375 kW**. Many different motor technologies and design types are available, but asynchronous alternating current (AC) induction motors are most frequently used and consume the most energy. These motors are either sold to original equipment manufacturers (OEMs) and integrated into pre-packaged electromechanical products (such as pumps, fans, compressors, etc.) or sold as stand-alone motors that final customers then integrate into a specific application on site. Such stand-alone motors are produced in large volumes, according to standardised input power and size specifications, with varying channels to market and integration into electromechanical systems. This has a significant impact on the type of barriers to adoption of energy-efficient solutions for EMDS and, hence, on the most appropriate policy packages to overcome such barriers.

Motors in the mid-size range are most commonly found in industrial applications, but they are also widely used in commercial applications, infrastructure systems and, less often, in the residential sector. In general, their main applications are mechanical movement, compressors, pumps and fans, which in turn have many types of sub-application. At present, most OECD and many non-OECD economies impose MEPS on asynchronous mid-size AC motors sold as separate components. Very few countries have set such requirements for other types of electric motors, and the requirements are rarely applied specifically to motors integrated directly into a packaged system prior to sale.

Large electric motors with more than 375 kW output power are usually high-voltage AC motors that are custom-designed, built to order and assembled within an electromechanical system on site. They comprise just 0.03% of the electric motor stock in terms of numbers, but account for about 23% of all motor power consumption, making them very significant consumers of global power (about 10.4%). These motors are not currently subject to MEPS in any part of the world.

In electric motor-driven systems, some energy losses occur in the motor itself, but energy losses are greater in the rest of the mechanical system to which the motor is coupled. A typical electromechanical system involves a motor, an electrical control system, a variable-speed drive (VSD) and a mechanical load. The magnitude of energy losses depends on the application and the degree to which an advanced technical solution is used. For any given power rating, there is a difference of only a few percentage points in energy efficiency between average motors and the most efficient motors on the market.

Small motors are less efficient than higher-powered motors. Large losses can occur due to mismatches between the output power of fixed-speed motors and the mechanical power demands of the electromechanical system. This is especially true when motors are used in mechanical applications with variable mechanical power needs, which have a highly non-linear relationship between input power and mechanical load (torque and speed) and an exponential relationship between input power and mechanical power (*e.g.* pumps, fans and compressors). In this case, there can be very significant savings from using variable-frequency drives (VFDs) with intelligent control, which regulate the output torque and speed of the motor to match the system mechanical loads. However, such control systems need a significant amount of power to operate and should not be used in fixed output power applications. In such applications, they will incur more energy losses and impose higher costs than a properly sized fixed-speed system.

For any given output power rating, there is currently a spread of several percent in efficiency between the most and least efficient motors on the market. Despite being slightly more costly to purchase than standard motors, higher-efficiency motors (HEMs) with over 1 000 hours of operation per year are more cost-effective over the system life for end-users in all applications, because motor-energy costs typically account for over 95% of a motor's life-cycle cost. The internal rate of return (IRR) from the use of a HEM compared to a standard motor is often well over 100%, but end-users rarely demand HEM applications, due to a host of market barriers. Mandatory regulations are usually the best way to ensure significant and timely market penetration of HEMs.

Policy intervention can stimulate significant savings

Overall, this analysis finds that using the best available motors will typically save about 4% to 5% of all electric motor energy consumption. Linking these motors with electromechanical solutions that are cost-optimised for the end-user will typically save another 15% to 25%. The potential exists to cost-effectively improve energy efficiency of motor systems by roughly 20% to 30%, which would reduce total global electricity demand by about 10%.

The three major routes to achieving these savings are:

- Use of properly sized and energy-efficient motors.
- Use of adjustable-speed drives (ASDs)[2], where appropriate, to match motor speed and torque to the system mechanical load requirements. This makes it possible to replace inefficient throttling devices and, in some cases with "direct-drive", to avoid wasteful mechanical transmissions and gears.
- Optimisation of the complete system, including correctly sized motor, pipes and ducts, efficient gears and transmissions, and efficient end-use equipment (fans, pumps, compressors, traction, and industrial handling and processing systems) to deliver the required energy service with minimal energy losses.

Without policy intervention, many barriers make it difficult or impossible to realise these savings in the current market environment. In unregulated markets, purchasers tend to underinvest in higher-efficiency options and choose electric motor systems with a low first cost. This occurs for a variety of reasons, including:

- Lack of awareness among motor purchasers of the potential for energy and cost savings by using more efficient motors within energy-efficient EMDS.
- Company organisational structures that manage their equipment procurement budget separately from operations and maintenance budgets.
- The fact that motors are often integrated into equipment produced by OEMs before sale to the final end-user.

To overcome these barriers, many countries (now comprising over one-third of the world's population) have adopted MEPS for the main class of industrial electric motors. More countries are in the process of developing such requirements. This policy instrument has been shown to be practicable to implement and a cost-effective means of saving energy. The average energy efficiency of new motors in countries applying MEPS is notably higher than in countries without such requirements. It is estimated that if all countries adopted best practice MEPS for industrial electric motors, by 2030 approximately 322 TWh of annual electricity demand would be saved, giving rise to corresponding savings of 206 Mt of CO_2 emissions.

[2] An **adjustable speed drive (ASD)** or **variable-speed drive (VSD)** is equipment used to control the speed of machinery. Many industrial processes such as assembly lines must operate at different speeds for different products. Where process conditions demand adjustment of flow from a pump or fan, varying the speed of the drive may save energy compared with other techniques for flow control. Where speeds may be selected from several different pre-set ranges, usually the drive is said to be "adjustable" speed. If the output speed can be changed without steps over a range, the drive is usually referred to as "variable speed". A **variable-frequency drive (VFD)** is a system for controlling the rotational speed of an alternating current (AC) electric motor by controlling the frequency of the electrical power supplied to the motor.

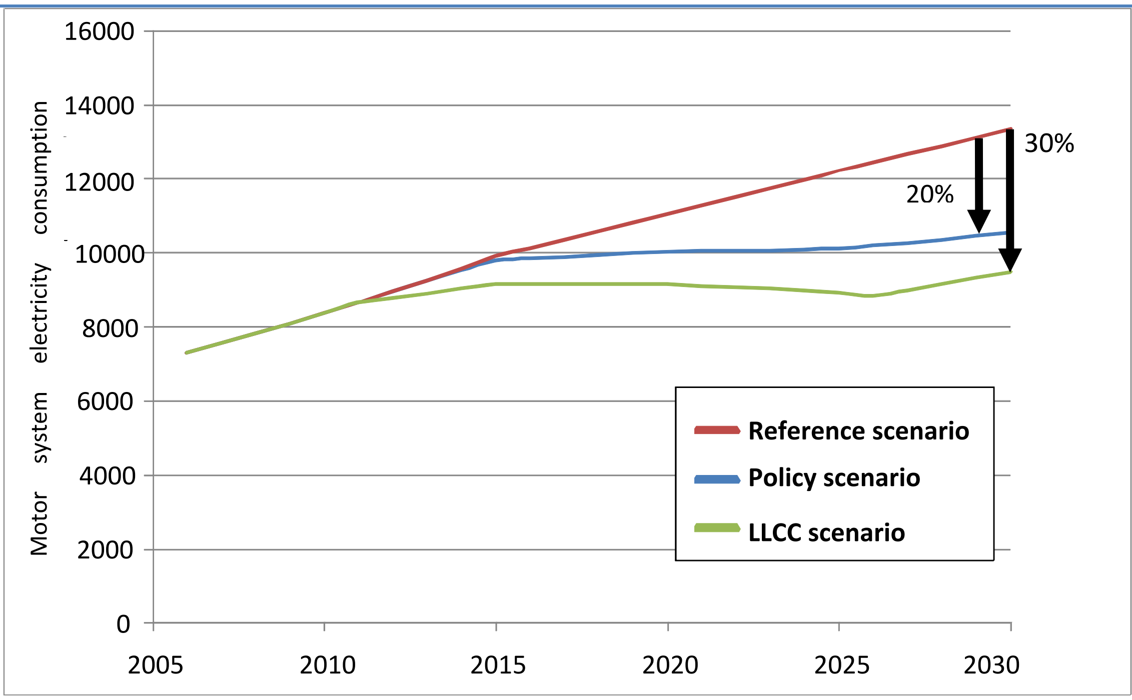
Policies needed for optimising packaged systems

Important as these savings are, much larger savings would accrue if all EMDS were properly optimised. Realising this objective is less straightforward from a policy perspective, but it is possible to make headway in the more complex domain of EMDS by carefully segmenting the applications in which motors are used, and by targeting regulatory policies at packaged motor systems applications with large savings potentials (*e.g.* certain kinds of pumps, fans and compressors). It is practicable to set MEPS and energy labelling requirements for a range of core motor-driven systems, including fans, pumps and compressors. In some cases, similar MEPS can be applied to entire motor-driven system applications (*e.g.* for municipal water pumping, elevators and escalators).

Regulatory measures should not necessarily be confined to devices and components that directly consume power; policies could also eventually target the large potential energy savings from improved energy performance of mechanical components (such as gears and drive belts). Certain common technologies (such as worm drives and V-belts) are fundamentally inefficient and could potentially be regulated out of the market in favour of more efficient options.

As some aspects of motor-system energy use do not lend themselves to simple regulatory approaches, softer policy measures can be beneficial. It is especially important to strengthen market awareness through educational efforts targeting multiple decision-making levels (OEM, system specifier, plant manager, energy manager and senior manager/executive level). This would include user-friendly technical assistance through enhanced technical standards, system specification and operational/energy management tools and services. There is also a need to better align fiscal and financial incentives throughout the value chain, which could be complemented by well-targeted economic assistance to encourage the uptake of energy-efficient EMDS.

Figure 1: Projected global electric motor-system electricity consumption



Abbreviation: LLCC = least life-cycle cost.

Notes:

Reference scenario: when the current situation is maintained without additional policy measures.

Policy scenario: when all countries adopt a broad-based and rigorous policy package on EMDS.

LLCC scenario: when all EMDS are moved toward the least life-cycle cost level.

Source: IEA estimate.

Above all, it is essential to scale up the operations and resources committed to realising the vast savings potential of optimised EMDS. By comparison with other sustainable energy opportunities, the energy efficiency of EDMS has been relatively neglected, and nowhere do such systems currently benefit from the scale of support that is offered to sustainable supply-side options. While governments are starting to become more proactive on this issue, and many have implemented some useful policy measures, none has yet put in place the resources or policy processes likely to realise substantial savings.

If a broad-based and rigorous policy package were put in place, it is estimated that globally, by 2030, it would save some 24 000 TWh in electricity demand, avoid some 16 Gt of CO_2 emissions, and generate cost savings of about USD 1.7 trillion (Figure 1). These savings would come at less cost than supplying this energy. Annual savings in 2030 would be in the order of 2 800 TWh in electricity demand, 1 790 Mt of CO_2 emissions and USD 190 billion in electricity costs.

If it were possible to move all EMDS towards the least life-cycle cost level as rapidly as technically possible, it is estimated that some 42 000 TWh of electricity demand, 29 Gt of CO_2 emissions and USD 2.8 trillion in electricity costs would be saved globally by 2030. Annual savings in 2030 would be of the order of 3 890 TWh in electricity demand, 2 490 Mt of CO_2 emissions and USD 264 billion in electricity costs.

Comprehensive integrated policy package

To help realise the tremendous potential for cost-effective energy savings in electric motor-driven systems, governments should consider, as a first measure, adopting mandatory MEPS for electric motors, in line with international best practice, subject to due process and cost-effectiveness analysis.

These standards should apply to as many types and sizes of electric motor as it is feasible to address and should not be confined to mid-size asynchronous AC motors sold as separate components. The level of these standards should be set at no lower than the least life-cycle cost, which is generally at IE3[3] or higher for mid-size asynchronous AC induction motors. Even larger energy savings can be achieved by using VFDs, which dynamically match the output power of motor systems to the power demanded by the drive train. Further savings can be achieved by using efficient transmission and gear systems, and through better sizing and management of electric motor-driven systems.

Overall it is estimated that it is cost-effective to save about 20% to 30% of total global electric motor demand (*i.e.* roughly 10% of all global electricity consumption) through the use of more efficient electric motors and drives. Achieving such savings will require individual and concerted action on the part of all players, including regulators, policy makers and standards development agencies.

It is proposed that IEA member countries and non-member economies apply a market-transformation package based on the portfolio of energy performance policies set out in the following package of policy recommendations:

Regulatory policy measures

1. **MEPS** should be introduced in IEA member countries in line with international best practice for all major classes of electric motors. They should not be set at levels less than IE3 for asynchronous motors. These requirements should apply to motors sold individually or integrated into pre-packaged electric motor-driven systems, and should apply to motors with as wide a range of output power as is practicable (100 W to 1 000 kW).

[3] Premium efficiency level as defined within IEC60034-30 and IEC 60034-31.

2. Regulatory measures, such as **MEPS and energy labelling**, should be introduced for packaged integrated motor-driven energy end-uses between 100 W and 1 000 kW, including fans, pumps, circulation pumps and compressors that are produced in sufficiently large volumes to have significant energy consumption.
3. Regulators, policy makers and standards development agencies should ensure that **energy performance test procedures are developed for all motor types** that use significant amounts of electricity and are not covered by existing internationally agreed test procedures.
4. Regulators, policy makers and standards development agencies should commission the development and application of **energy-performance test procedures to cover other essential components** of electric motor-driven systems, including transmissions, gears and system control devices (*e.g.* VFDs). In addition, efforts should be made to develop energy-performance test procedures and guidelines that apply to whole electric motor system applications, such as utility water-pumping, lifts (elevators), escalators, conveyors, etc.
5. Regulators should explore the feasibility of developing **minimum energy performance standards for certain classes of gears and transmissions** to discourage (and later prohibit) the use of inefficient solutions such as worm gears and V-belts.

Non-regulatory policy measures

6. Large-scale **awareness programmes** should be developed and put in place to inform industrial and commercial electricity users of the significant savings potentials possible through the use of efficient electric motor-driven systems. These programmes should target those responsible for procurement of electric motors and motor-driven systems, including operations and maintenance managers, production and plant managers, and company executives and decision makers responsible for overall company policy on energy, carbon and cost reduction.
7. **Incentive schemes** should be developed and applied to encourage adoption and use of best practice motor sizing, management and integration, including the appropriate use of VFDs. These should be targeted at the systems producing the highest benefit, namely for pumps, fans and other applications with variable mechanical loads (where torque increases nearly as the square of the rotational speed of the motor). In most cases, cost-effective savings can also be achieved when VFDs are used for conveyors, hoists, escalators and similar applications (where torque is more or less independent of the motor speed). Incentive schemes are also likely to be beneficial for these applications.
8. **International capacity-building efforts** should be substantially expanded to create permanent support structures, at a scale sufficient to support ongoing needs in the domain of energy-efficient electric motor-driven systems.
9. **Global market monitoring** should be established at defined intervals, to support national regulation and incentive programmes with market-transformation data.

Putting ideas into practice

Realising these savings opportunities by 2030 will require a clear a plan of action and rapid implementation of an effective set of structural and consensus-building endeavours. It is proposed that IEA member countries establish a timetable for implementation of the nine policy recommendations. To aid that process, the authors have identified timelines for completion of the steps necessary to progress EMDS toward the identified energy-savings goals by 2030 (Table 2).

Table 2: Proposed timetable for implementation of recommendations

Recommendations	Phase 1 In 2011	Phase 2 2012-15	Phase 3 2016-20	Phase 4 2021-25	Phase 5 2026-30
Regulatory policy measures					
Implementation of MEPS for all major classes of electric motors.	COMMENCE	COMPLETED			
Regulatory measures for packaged integrated motor-driven energy end-uses.	COMMENCE	COMPLETED			
Development of international test procedures for other electric motor types.	COMMENCE	CONTINUE	COMPLETED		
Development of international test procedures for other electric motor system components.		COMMENCE	COMPLETED		
Regulatory measures for gears and transmissions.		COMMENCE	COMPLETED		
Non-regulatory policy measures					
Development of large-scale awareness programmes.		DEVELOP	ROLL-OUT	ROLL-OUT	ROLL-OUT
Development of incentive schemes.		DEVELOP	IMPLEMENT		
International capacity-building efforts and creation of a permanent support structure.	COMMENCE	COMPLETE	ROLL-OUT	ROLL-OUT	ROLL-OUT
Global market monitoring (to support national regulation and incentive programmes with market-transformational data).	COMMENCE	REPORT 2015	REPORT 2020	REPORT 2025	REPORT 2030

To support the underpinning recommendation regarding the adoption of mandatory minimum energy performance standards for electric motors, it is proposed that IEA member countries adopt a policy position as quickly as possible, with an IEA report on it before 2015. IEA member countries can then be positioned as lead actors in a push for globally co-ordinated action on motors, with supporting project work to engage with major motor-manufacturing countries (such as China, Brazil, India and others).

In addition, it is proposed that the IEA immediately undertake a comprehensive study, completed in 2011, to assist member countries in their efforts to implement these measures within the proposed timeframes. As binding policy decisions are taken by IEA member countries, this study should evolve into a regular update on implementation plans.

The IEA Secretariat should also work with the non-member economies that produce and export significant volumes of electric motors and electric motor-driven components to ensure that this co-ordinated plan will gain their support.

1. Introduction

This report explores the complex and challenging world of electric motor-driven systems (EDMS) and makes recommendations for future policy settings to reduce electricity demand for EMDS in a timely and cost-effective manner.

Electric motors are used in a wide range of industrial applications, but also in many types of applications in the commercial, residential, agricultural and transportation sectors. Typically electric motors are a component in a motor system, responsible for converting electrical power into mechanical power. Consumption of a motor system corresponds to electricity consumption of its motors plus a small additional quantity to power system controls.

Prior to the analysis presented in this report, there have been very few attempts to estimate the overall electricity consumption of electric motors and no systematic attempt to produce global estimates. However, "back-of-the-envelope" calculations have typically estimated that motors use over 40% of all electricity (in 2005, more than 6 000 TWh at the global level). In fact, electric motor-driven systems appear to be the largest source of electricity use, far exceeding lighting, the next largest end-use (about 19% of global electricity demand).

It is surprising how few concerted studies have been directed at quantifying the energy use of EMDS. This report attempts to provide a sounder basis for these estimates, using both top-down and bottom-up analyses to increase confidence in the findings. It builds upon important regional studies such as the European Union's Lot 11 studies for the Eco-design Directive (De Almeida *et al.*, 2008a [motors]; Falkner, 2008a [pumps]; Falkner, 2008b [circulator pumps]; Radgen, 2008 [fans]), US Department of Energy-sponsored investigations (DOE, 2002), other North American sources (Elliot, 2007; Boteler, 2007; NRCan, 2009), Japanese studies (JWG, 2007), Chinese studies (Zhao, 2007) and other regional data sources.

Electric motors are found in the industrial, commercial, residential, agricultural and transportation sectors.

- In the **residential sector**, motors are used for compression (in refrigerators and air conditioners), ventilation (to power fans); pumping (to power central heating system circulation and hot and cold water pumps); cooking appliances (food mixers, whisks, oven fans, extractor hoods); laundry; cleaning; ICT (hard disks and fans) and garden appliances. Some less widespread residential applications (such as automatic gates and shutters) also use motors.
- In the **commercial building sector**, motors are used for heating, ventilating and air conditioning (HVAC); pumping; ICT (hard drives and fans); escalators; lifts (elevators) and hoists; laundry; cleaning and cooking.
- In the **agricultural sector**, motors are used for pumping and conveyance activities.
- In **transportation**, motors are used for motive power for electric trains, trucks, cars and motorbikes and related cooling; ventilation and auxiliary devices; fluid pumping in vehicles shipping and planes; HVAC applications; servo-mechanisms in aviation and several other applications.
- Yet it is in **industry** that electric motors dominate and account for the largest amount of total electricity consumption. In industrial applications, motors are used for pumping; fans; air and liquid compression; conveyance; and other forms of mechanical handling and processing. Electric motor-driven systems (EMDS) are by far the most important type of electric load in industry. In the European Union, for example, they are estimated to account for about 70% of all industrial electricity consumption.

In each of the applications mentioned above, the electric motor is only one part of the whole electromechanical system. The motor (together with the controller) is the only part that uses electricity, but the amount of electricity required to fulfil its function is determined by the amount of mechanical power required and the magnitude of the losses that occur in the delivery of that power. Those losses occur not only within the motor itself but also – and usually more significantly – in the mechanical system that distributes power from the motor to the final mechanical application.

This report examines markets and use of electric motor-driven systems and estimates their electricity consumption by sector, application and country as well as at a global level. It reviews the types of EDMS and analyses the different technologies in use and the potential to save energy through better design, configuration and operation. It presents estimates of potential energy savings and reduction of CO_2 emissions and explores cost-efficiency issues associated with different motor-system choices. It also examines barriers to the adoption and use of more efficient EMDS and the various standards that have been developed to measure and improve motor-system electricity demand. It reviews existing and pending policy settings for motors and motor-driven systems and makes recommendations for future policy settings.

The findings of the report are consistent with and build upon the findings of earlier regional studies. By drawing attention to the wide variety of means to increase efficiency of EMDS, the study attempts to set out practicable pathways to increase energy savings and exploit opportunities more effectively than under current policy settings. It proposes policy measures to stimulate energy-efficiency improvements in motor-system components, core motor systems and dedicated motor-system applications and future activities to build international capacity to identify and access significant savings in EDMS.

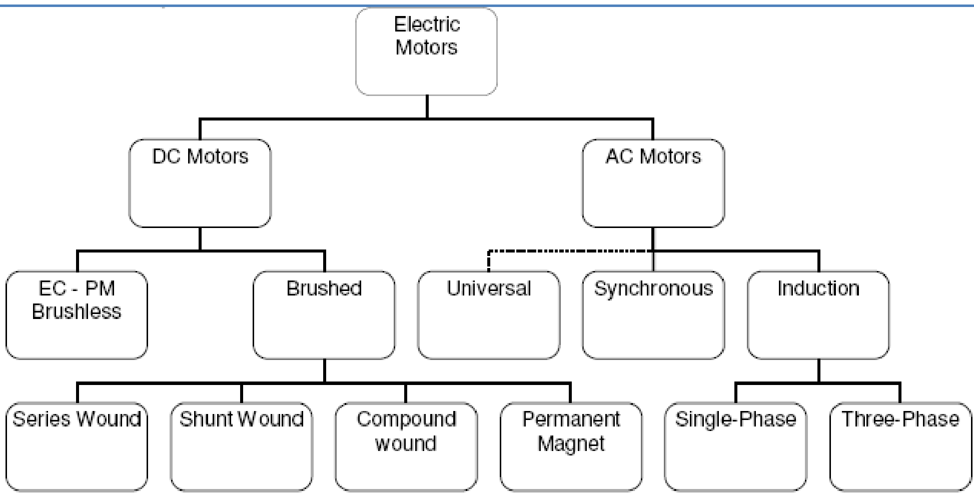
2. Electric Motor-Driven Systems and Applications

This chapter describes technologies and applications of electric motor-driven systems (EMDS), summarises available market data (including information on sales and stocks of motors and motor-driven systems as a function of their efficiency), and explores the adoption of controllers that match output to load, such as variable-speed drives (VSDs).

Motor system types and definitions

An electric motor is a device that converts electrical energy into mechanical energy. Motors come in output power ranging from a few watts up to many hundreds of kilowatts. In the recent EU study under the Directive on Eco-design of Energy-Using Products, the product group is described as electric motors in the output power range of 1 kW to 150 kW. However, the study considered a lower bound of 0.75 kW and an upper bound of 200 kW to take into account standard power sizes and the new proposed International Electrotechnical Commission (IEC) 60034-30 efficiency classification standard on motor efficiency. Almost all motors in this power range are of low voltage. Medium-voltage motors are typically used in very high power applications of >500 kW; as they are of non-standard design, they are sold in very small numbers and are not yet included in any targeted energy-efficiency policies. Electric motors are classified according to type of power supply and other criteria (De Almeida *et al.,*2008a) (Figure 2).

Figure 2: Electric motor categories



Abbreviations: AC – alternating current; DC – direct current; EC – electronically commutated; PM – permanent magnet.
Source: De Almeida *et al*., 2008a.

EMDS Applications

Motors are used in a myriad of applications, which are broadly categorised as follows:

- **Industrial applications:** pumps, fans, compressed air delivery, conveyors, motive power for other machinery, etc.
- **Building applications:** pumps, fans, conveyors, lifts, compressors in heating, ventilation and air-conditioning systems, etc.
- **Appliance applications:** refrigerators, air conditioners, personal computer and laptop fans, hard drives, cooking appliances, oven fans, extractor fans, garden appliances, pool pumps, etc.

Table 3: EMDS applications showing relationships between systems and service

Electric motors		**Pumps**	**Drinking water**	**Water/refrigerant**	**Sewage**	**Oil**
Rotating machines	Application	Closed loop	Closed water supply system	Heating, cooling and chilling system	Pressure sewage system	Hydraulic pumps
		Open pipe	Water supply system	Irrigation, cooling tower	Sewage system	Pipeline
		Fans	**Air**	**Gas**		
			Room air supply and exhaust, blowers	Natural gas systems		
		Compressors	**Refrigerant**	**Air**	**Gas**	
			Cooling machines for air conditioning and commercial freezers, refrigerators and freezers	Compressed-air storage and distribution system, pneumatic systems	Liquification systems	
		Rotating/mix/ stir	**Roller, rotors**	**Extruder**	**Textile handling**	**Mixers, stirring**
		Solid	Metal, stone, plastics	Aluminium, plastics	Weaving, washing, drying	Food, colour, plastics
		Liquid				Food colour, plastics
		Transport	**People**	**Goods**	**Vehicles**	
		Vertical	Passenger elevator	Goods elevator, cranes, hoists		
		Inclined	Escalator	Conveyor	Cog wheel train, cable car, ropeway	
		Horizont al	Conveyor	Conveyor	Train, tram, trolley, cars, buses, electric cars, bikes and bicycles	
Linear motors			**Open/close**	**Sort**	**Grab and place**	
Back and forth movement			Valve		Robot	
Stepper motor			**Open/close**	**Position**		
Angular position			Valve	Servo		

Source: A+B International, 2009.

Motor market data

Following a review of data on motor sales, efficiency and stocks, this report considers motor usage by end-use system applications and examines market penetration of adjustable-speed drives (ASD) and variable-frequency drives (VFD). Although few sources are available to determine distribution of electric motors by end-use application, data from the United States and the European Union on different motor applications are included. Literature about different applications is rarely available for other countries, except for some sales data for Japan and Taiwan. Regional data sets are not easily comparable, as they have different scopes of study and apply different definitions (for example, definitions may vary regarding whether a compressor is used for cooling or compressed air applications).

Market volumes by application

The share of motor sales by end-use application in the United States appears quite different from the situation in the European Union (Tables 4 and 5). Figures for US pump sales include only pumps and vacuum pumps used in industry, and do not cover pumps used in commercial or building sectors. Compressor data applies only to stationary compressors. The total is the sum of these three applications. No data for any other applications is presented.

Table 4: Motor systems sales in the United States (2003)

	Pumps	Vacuum pumps	Compressors	Total
No. of units (thousands)	12 143	200	1 301	13 645
Sales value (USD millions)	2 637	103	1 534	4 275

Note: Numbers may not sum to total due to rounding.

Source: US Census Bureau.

Table 5: Motor systems sales in the European Union (2005)[4]

	Pumps	Circulators	Fans	Total
No. of units (millions)	1 800	14 000	8 927	24 727
Market share	7%	57%	36%	100%

Sources: Falkner, 2008a (pumps); Falkner, 2008b (circulator pumps); Radgen, 2008 (fans).

In the United States, more than 40% of general-purpose industrial motors are used to drive material processes, representing the largest share of motor applications. Other large groups are pumps and material-handling applications; compressors (compressed air, refrigeration) and fans represent only minor shares (Table 7).

Table 6: Distribution of motor applications in the US industry sector (1997)

	Pumps	Fans	Compressed air	Refrigeration	Material handling	Material process	Other	All
Share of stock	19.7%	11.2%	5.1%	0.8%	16.8%	42.2%	4.2%	100.0%

Source: DOE, 2002.

Table 7: Stock data for three applications in the European Union (2005)

	Pumps	Fans	Circulators	Total
No. of units (millions)	17	104	10	131
Share of stock	13%	79%	8%	100%

Sources: Falkner, 2008a (pumps); Falkner, 2008b (circulator pumps); Radgen, 2008 (fans).

In the case of the European Union, the figure for circulators includes only large stand-alone circulators, and the figure for fans includes only building ventilation (no fans for process ventilation etc. are included). In this limited context, fans account for the largest share – almost 80% – of the installed motor base (Table 7). Significant differences in the scope of available stock data on motor applications make it difficult to draw direct comparisons between the United States and the European Union.

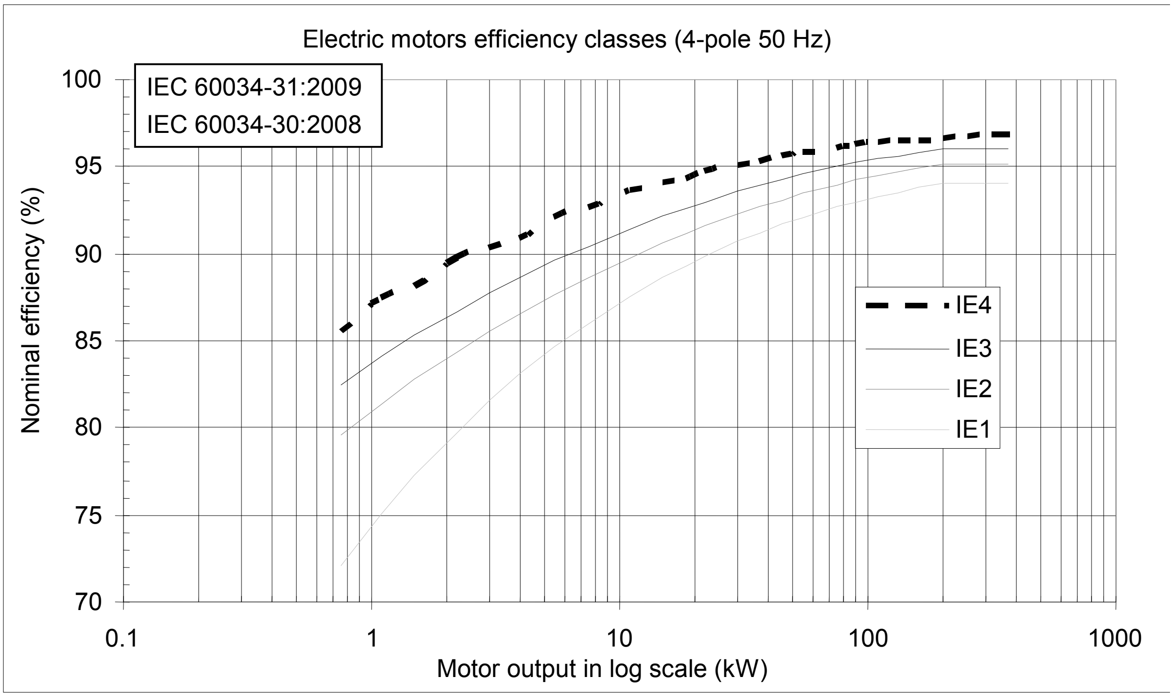
[4] On 1 January 2007, the European Union expanded from 25 to 27 member states. Data up to 2006 is for EU-25; starting in 2007, data is for EU-27.

Market share by efficiency

Electric motor efficiency is the ratio of mechanical output power to electrical input power. The weighted average efficiency of the running electric motor stock depends on:

- size distribution of the motor stock;
- relative shares of energy-efficiency classes;
- mandatory energy performance standards (MEPS) and other policy measures in place (*e.g.* voluntary agreements) and their period of introduction/reinforcement.

Figure 3: Efficiency classes for four-pole motors of standard IE3, IE2 and IE1 classes, and the new IE4 class



Source: IEC 60034-30 and IEC 60034-31, draft 2009.

The efficiency of motors depends both on their size and their efficiency quality, which can be characterised by efficiency classes. For small motors, size is the most important factor in determining efficiency; for large motors, efficiency classes are relatively more important. In 2008, in IEC 60034-30, the International Electrotechnical Commission introduced the precisely defined and open-ended international efficiency-classification scheme using IE1, IE2, IE3 and IE4[5] as the classification system (Figure 3).

In recent years, market share of more efficient motors has been increasing in many regions and countries (Borg and Brunner, 2009). This was particularly the case for the United States, China and other countries, and, to a certain extent, for Europe. To understand this diffusion pattern, it is useful to relate different efficiency-classification systems to each other, and to relate diffusion to MEPS and other policy measures. Four standardised efficiency classes are currently recognised, although definitions and classification schemes vary slightly from country to country (Table 8).

[5] Super premium efficiency level as defined within IEC 60034-30 and IEC 60034-31.

Table 8: Motor efficiency classes in different countries and the corresponding international standard

Motor efficiency class	International	United States	European Union (old system 1998[1])	European Union (new system 2009)	China	Australia
Premium	IE3	NEMA Premium	–	IE3	–	–
High	IE2	EPAct	Eff1	IE2	Grade 1 (under consideration)	AU2006 MEPS
Standard	IE1	–	Eff2	IE1	Grade 2	AU2002 MEPS
Below standard	IE0 (used only in this paper)	–	Eff3	–	Grade 3 (current minimum)	–

Abbreviations: EPAct – US Energy Policy Act, 1992; MEPS – minimum energy performance standard;

NEMA – US National Electrical Manufacturers Association.

Source: A+B International, 2009.

Note: 1. With the backing of the European Commission, manufacturers representing 80% of the European production of standard motors, agreed to establish three efficiency bands or classes designated EFF1, EFF2, and EFF3, with EFF1 being the highest band.

When a new and higher motor-efficiency class is introduced, it diffuses slowly into the national market. The rate of diffusion depends on national motor producers, additional price, electricity cost, financial incentives, MEPS, etc.

Table 9: Timeline for electric-motor efficiency classes, testing standards and minimum energy performance standards

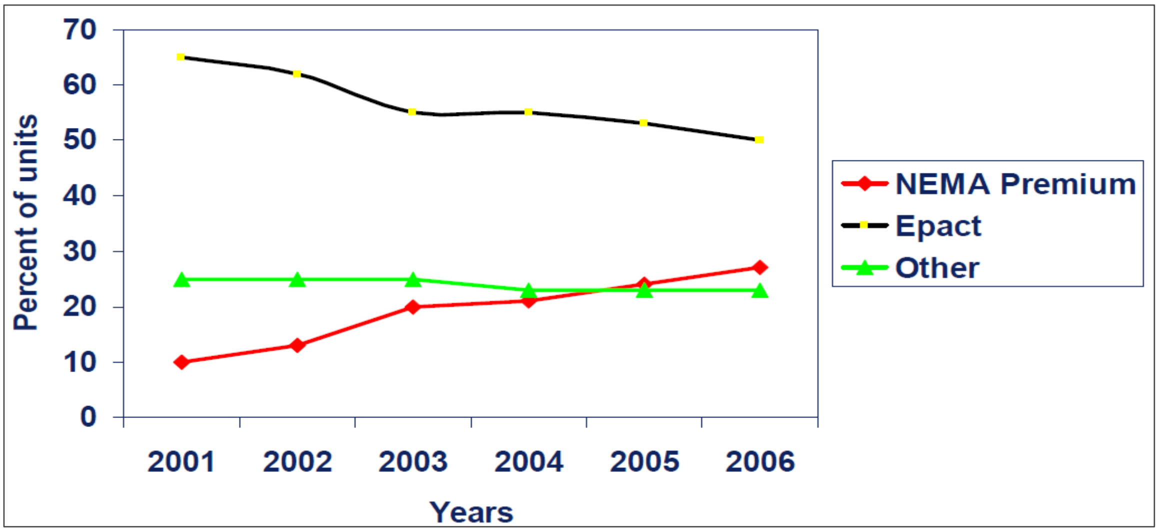
Efficiency levels	Efficiency classes	Testing standard	Performance standard
	IEC 60034-30	IEC 60034-2-1	Mandatory MEPS
	Global definition of motor efficiency classes, IEC, 2008	Including stray load losses 2007	Policy goal
Premium efficiency*	IE3	Low uncertainty	United States 2001
			Europe 2011
High efficiency	IE2		United States
			Canada
			Mexico
			Australia
			New Zealand
			Korea
			Brazil
			China 2011
			Switzerland 2011
			Europe 2011 with VSD
Standard efficiency	IE1	Medium uncertainty	China
			Brazil
			Costa Rica
			Israel
			Taiwan
			Switzerland 2010
Below standard			

Source: A+B International, 2009.

The United States and Canada are international leaders in terms of setting motor energy-efficiency standards, as they introduced regulations for motors in the late 1990s. As early as 2002, China defined MEPS for electric motors. The European Union passed MEPS legislation for electric motors in 2009 as an implementing measure under the Eco-design Directive; these will replace the previous industrial voluntary agreement. Australia, Korea, Brazil, Mexico, Taiwan and some other countries with large electricity consumption from motors have already adopted MEPS, as have some smaller economies such as Costa Rica, Israel and New Zealand (Table 9). However, some large motor-using economies, such as India, Japan and Russia, have not yet adopted MEPS (such measures are understood to be under consideration).

In the **United States,** market penetration of energy-efficient motors has been increasing since the late 1990s – particularly since 1998 when MEPS were enforced. In 2001, EPAct motors (equivalent to IE2) reached a market share of about two-thirds; this figure has since steadily declined, as the US National Electrical Manufacturers Association (NEMA) Premium motors started gaining market share (Figure 4).

Figure 4: Market share of efficiency classes in the United States (2001-06)



Source: Boteler, 2007.

In Canada, the energy efficiency of motors is the responsibility of the ministry of Natural Resources Canada (NRCan). In 1994, the Energy Efficiency Act was implemented and in 1997 Canada's Energy-Efficiency Regulations for General Purpose Industrial Motors came into effect (Figure 5). In 1999, explosion-proof and integral-gear motors (which are not covered in the United States) were also included. For motors in the range of 0.75 kW to 150 kW (1 hp to 200 hp), regulation in Canada corresponds in principle to the MEPS of EPAct of the United States. However, Canada also has some specific regulations, such as allowing the use of 75% load to pass MEPS.

In the United States, market introduction of the most efficient class IE3 (NEMA Premium) started in 2002 and market share has grown steadily (Table 10). It was introduced as a voluntary product but has been supported since 2006 by a federal procurement decision (the Federal Energy Management Program [FEMP]).

Market penetration of different efficiency classes varies considerably between countries. The share of the most efficient class (IE3) has reached 20% in the United States, but it is virtually zero in the European Union. In the United States, the share of efficiency classes generally increases with motor size (Table 11). The share of the most efficient class (IE3) reached 75% of sales for the largest motor class; it was only about 10% for smaller motors. The diffusion of motors with higher efficiency starts earlier for larger motors than for smaller ones, since more engineering time and money is usually spent in the search for the best-matching motor when a large motor has to be renewed.

Figure 5: Motor efficiencies in Canada before and after introduction in 1997 of Energy-Efficiency Regulations for General Purpose Industrial Motors

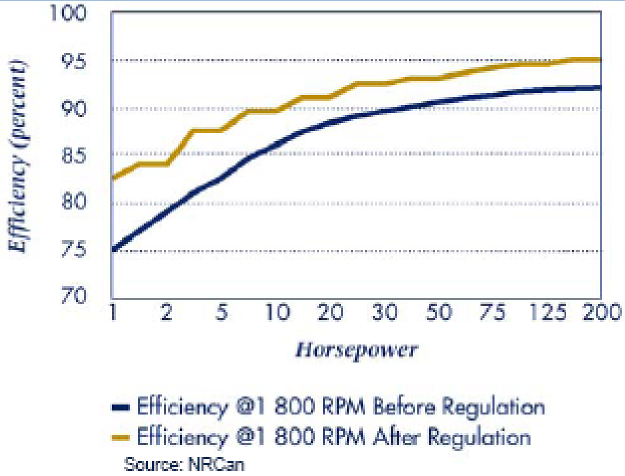


Table 10: Share of motor efficiency class IE3 sales in the United States (2001–06) and Canada (2007)

	2001	2002	2003	2004	2005	2006	2007
United States	10%	13%	20%	21%	24%	27%	
Canada							39%

Sources: Boteler, 2007; NRCan, 2009.

In **Europe**, electric motors between 1.1 kW and 90 kW are included in a voluntary agreement between the European Committee of Manufacturers of Electrical Machines and Power Electronics (CEMEP) and the European Union. Since this agreement was initiated in 1999, the market share of the class Eff3 has been falling due to increasing market penetration of the more efficient class Eff2 (IE1) (Figure 6). The even more efficient class Eff1 (IE2) has also been gaining market share, albeit at a much slower rate.

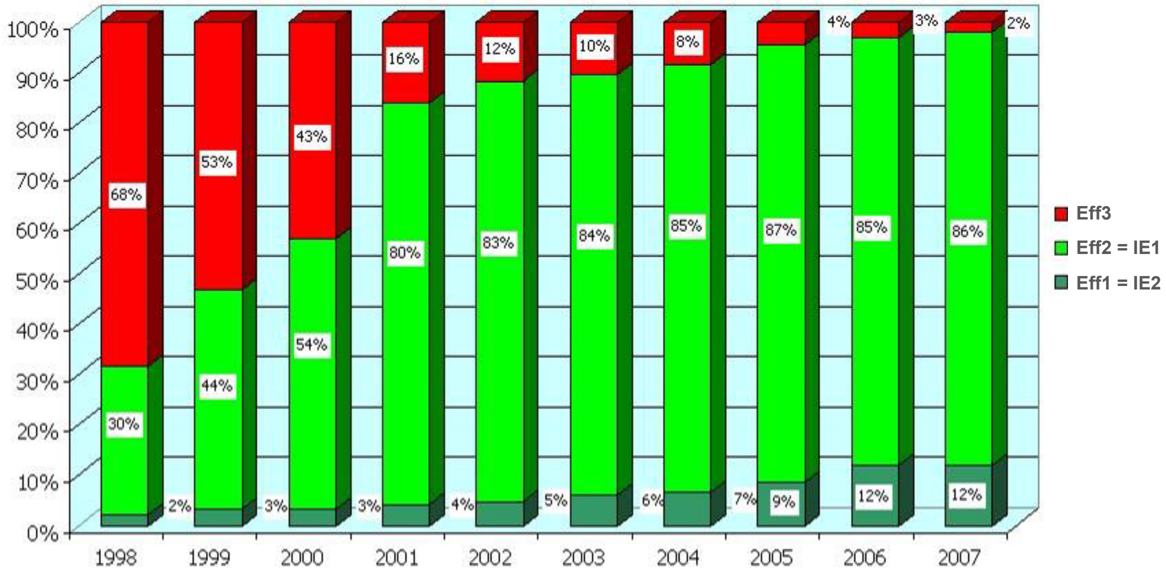
Table 11: Share of efficiency class IE3 in electric motor sales by size, United States (2003)

Motor size (kW)	Horsepower	Sales (thousands)	Market share of IE3 (%)
0.75 - 3.75	1 - 5	932	9.8
4.5 - 15.0	6 - 20	410	27.6
15.0 - 37.5	21 - 50	116	48.1
37.5 - 75.0	51 - 100	41	55.1
75 - 150	101 - 200	22	69.2
150 - 375	201 - 500	11	75.0
Total		1 532	20.0

Source: US Census Bureau as cited by Elliott, 2007.

In **Australia** since October 2001, manufactured or imported three-phase electric motors from 0.73 kW to <185 kW must comply with MEPS requirements. However, these MEPS were characterised as quite modest compared to the United States version of 1997 (Australian Government, 2007). A high efficiency level came into force in 2001 and was then revised in April 2005. MEPS levels for three-phase electric motors were then revised to become more stringent in 2006, with the 2001 high efficiency level becoming the MEPS level. In 2005, premium efficiency reached a market share of 10% and high efficiency a share of 32%, leaving 58% to the standard efficiency (De Almeida *et al.,* 2008a, citing the SEEEM Harmonization Initiative).

Figure 6: Market share of efficiency classes in Europe under the CEMEP voluntary agreement



Source: CEMEP, 2008.

Brazil launched its first regulation of the Energy Efficient Act for electric motors in 2002. This act established two sets of MEPS, for standard (mandatory) and high efficiency (voluntary) motors. An updated regulation from the end of 2005 (Edict 553/2005), established the previous high-efficiency MEPS as mandatory for all motors in the Brazilian market. These new Brazilian MEPS are compatible with those implemented in other countries. Brazilian motor manufacturers had already set a high-efficiency line in 2006, accounting for about 10% of total production. Nevertheless, it is expected that the expansion of this share to 100% would have a large impact on manufacturers and their pre-suppliers, mainly for technical reasons (Garcia *et al.*, 2007).

South Korean data on the market share of highly efficient motors were reported by Huseok (2007). After cross-checking with relevant experts, it has been determined that the term "highly efficient" was used to refer to motors at the IE2 efficiency level.

Market penetration of VFD technology

Motors are sometimes sold together or later matched with a variable-frequency drive (VFD) to enable greater efficiency when operating at partial loads. The fraction of motors sold with a VFD is increasing, but is not clearly reported because motors and VFDs are often manufactured, and mostly sold, by different manufacturers, and are integrated after purchase at the place of use. Data on VFD use is very sparse.

A market overview of VFD use in EU-15 in 1998 estimated that 1.3 million VFDs were sold, with a market value of EUR 1.05 billion (De Almeida *et al.,* 2000), The VFDs were mainly 0.75 kW to 4 kW in output size. More recent industry-based estimates in Germany show that 30% of electric motors are now sold together with a VFD. Small pumps and fans are also increasingly sold in integrated packages that include a VFD.

Europe and Japan are the major centres of motor production in the OECD. Japan produces over 15 million electric motors per year of which about 8 million are in the integral motor power range (the rest are very small motors). The energy efficiency of the Japanese new motor market is slightly lower than in the European Union, and significantly lower than in the United States and Canada. However, Japan is the global leader in production and use of inverters (VSDs/VFDs), and thus may well be using electromotive power more efficiently on average than other OECD economies. Sales of inverters in Japan began in the 1980s and by the mid-1990s accounted for about 75% of the sales volume of electric motors, which implies that a high proportion of applications were using inverters. Prices of inverters dropped by 60% from 1990 to 2002. Japan has been using tax incentives to encourage the uptake of inverters since the late 1980s; it has been estimated that these may have led to power savings of >1 GW, *i.e.* the output of a nuclear power plant (JWG, 2007).

In non-OECD economies, VSD/VFD (inverter) use is thought to be quite low due to the higher initial cost of inverter-based technologies.

3. Global Electricity Consumption and CO_2 Emissions of Electric Motor-Driven Systems

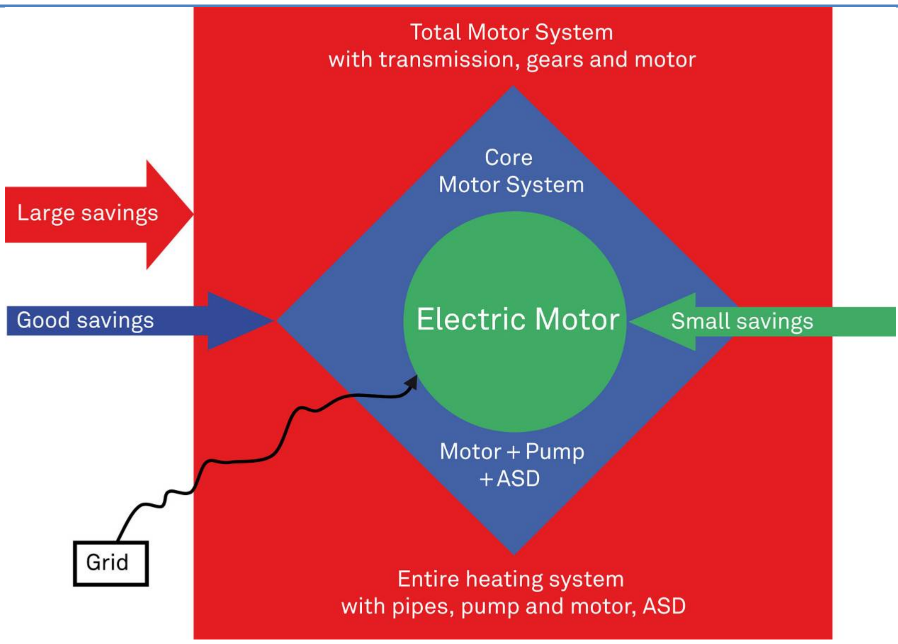
The global electricity consumption by electric motor-driven systems (EMDS) has not previously been measured or estimated in a consistent way, and few reliable data exist on which to base such estimates. The authors used alternate top-down and bottom-up methodological approaches to develop estimates of global electricity consumption and CO_2 emissions from EMDS. These analyses draw on dispersed and inconsistent data on stock and sales of electric motors, electric motor power and electricity demand, and attempt to organise the available data within a consistent analytical framework. A comparison of the estimates of energy and CO_2 emissions produced by these two methodologies determines the degree of agreement between the disparate data sets and serves as a measure of uncertainty in overall estimates. Global energy demand and CO_2 estimates are reported by efficiency classes, motor size, application and sector.

Scope and methodology

An electric motor system comprises three layers of equipment (Figure 7):

1. **Electric motor:** a fully functioning electric motor run from the electric grid.
2. **Core motor system:** the electric motor and its driven piece of mechanical equipment (fan or pump wheel, compressor, etc.) plus the necessary interconnection (clutch, gear, transmission belt) and a variable-speed drive (VSD) system between the grid and the motor to control torque and speed.
3. **Total motor system:** the core motor system plus the eventual application of power (a water heating piping system, an air ventilation ducting system, a cooling system with its cold water network and the cooling tower, a compressed air pipe system and the storage tank, a conveyor belt installation, an elevator for people or goods, etc.), as well as electric equipment between the grid and the motor (such as uninterruptible power supply, transformers, power factor compensation, etc.).

Figure 7: Total motor system, core motor system and electric motor



Source: A+B International, 2008.

In an EMDS, the motor itself is the only part that directly consumes energy; however, when considering the energy efficiency of the system, the total or at least the core system is relevant. This study considers the energy used by all types of electric motors around the world, but parts of the analysis focus differently on some motor types as a function of type and application.

There is no commonly accepted definition of an electric motor system. The authors believe that a more precise definition should be the subject of future research. The current lack of clarity makes it difficult to account for sales, installed base and running stock of electric motor systems. In principal, the sum of all electric motors within the scope of the study should be equivalent to the sum of all those in end-use applications (pumps, fans, compressors, material handling and processing, and traction). In practice, data on motor stocks and sales does not always add up this way because there are three ways to manufacture, sell and install an electric motor:

a) An electric motor may be manufactured integrally with its pump, fan or compressor wheel. In this case, it cannot be separated and counted as a single piece. This is typically the case for motors of up to 2 kW used in small packaged applications.

b) An electric motor may be manufactured in parallel with a piece of application equipment, either in the same manufacturing plant or in a different plant. An eventual match is preconceived by standardised hardware interconnection and software compatibility.

c) A standard electric motor (as based on IEC classifications for frame-type and size, output size and performance categories) may be manufactured by a company, advertised in catalogues and made available on short notice from stock without the eventual user and application being known. Related components to be used with the motor in the final application (such as fans, pump wheels, etc.) may be manufactured by other specialised companies without their knowing what type and size of motor they will eventually be driven by. Similarly, the motor may be directly integrated by an original equipment manufacturer (OEM) into a larger machine or product before being sold to an end-user. In this case, the motor will no longer be separately visible from the machine as a whole and can no longer be treated or tested as such.

Scope and definitions

Small motors with a power rating of up to 0.75 kW account for about 90% of all electric motors in the global stock, but for only about 9% of the total electricity used by electric motors. They are used in appliances, small pumps and fans. These motors are often single-phase and are induction, shaded-pole, or shunt-wound motor types, which are typically custom-made in large series to be integrated into specific machines or appliances. They often operate at, or at less than, mains voltage.

About 68% of the electricity consumed by electric motors is used by **medium-size motors**, those in the 0.75 kW to 375 kW input power range. For the most part, these are asynchronous AC induction motors of 2, 4, 6 or 8 poles, but some are special motors (*e.g.* direct current, permanent magnet [PM], switched reluctance, stepper and servo motors). They are polyphase motors operating at voltages of 200 V to 1 000 V, manufactured in large series, usually with short delivery lead times, according to standard specifications that can be ordered from catalogues. These motors account for about 10% of all motors and are used in pumps, fans, compressors, conveyors, and industrial handling and processing applications.

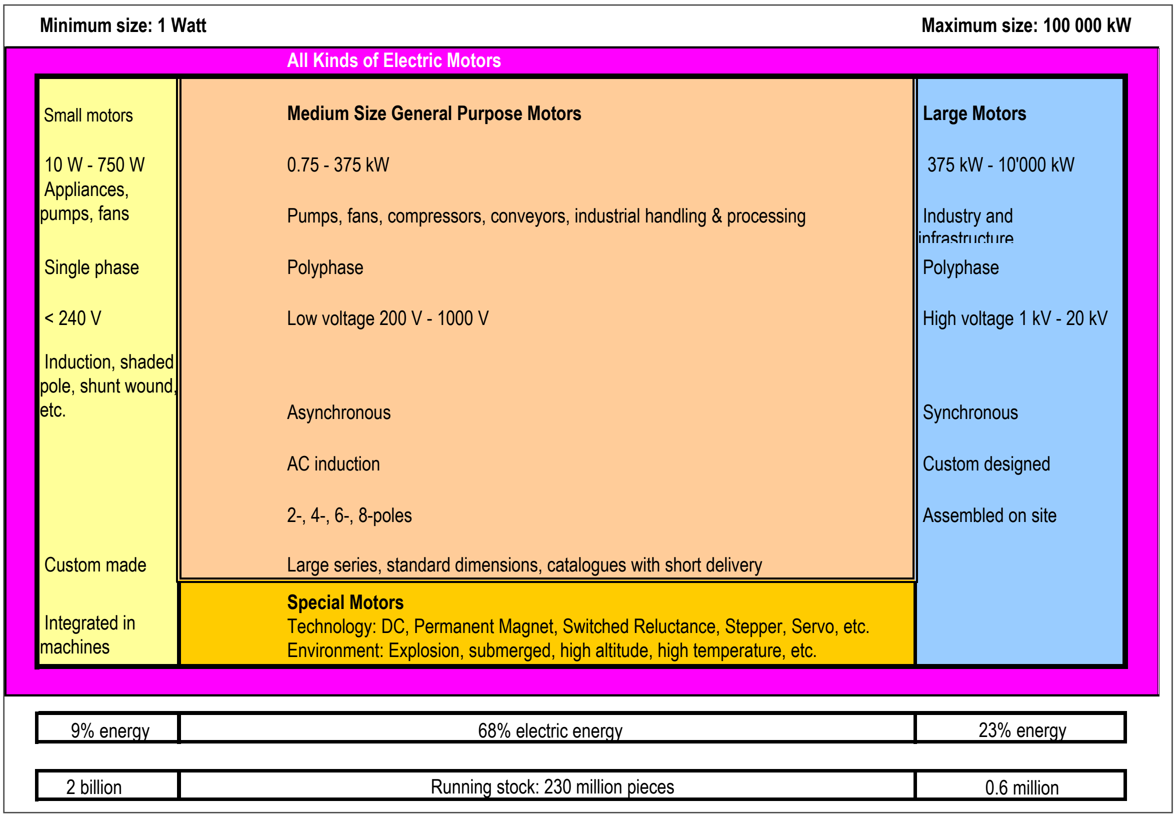
Large motors with a rated power of 375 kW to 100 000 kW are polyphase, high-voltage motors operating in the 1 kV to 20 kV range. They are custom-designed, synchronous and assembled on site. They account for only about 0.03% of the stock of all electric motors but about 23% of energy use. Most and are used in industrial and infrastructural applications.

The association of the input power ranges with motor-size definitions given above corresponds to those used in international technical standards. Specifically, the IEC 60034-30 Standard for rotating electrical machines - Part 30: Efficiency classes of single-speed, three-phase, cage-induction motors applies to:

Low voltage (<1000 V) three-phase electric motor systems in industry, infrastructure, commercial buildings and agriculture used for pumps, fans, compressors, material handling and processing from 0.75 kW to 375 kW output size that are able to run continuously for an important part of the year.

This corresponds to the input power range used here to refer to medium-size, general-purpose industrial electric motors. In fact, the IEC standard focuses on AC induction squirrel-cage motors, which are the most common motor type in this size range. However, in this study, the term medium-size motor includes any electric motor within the specified input power range.

Figure 8: Main types of electric motors as a function of power and associated characteristics



Source: A+B International, 2009.

Most of the detailed analysis in this study focuses on general-purpose, medium-size industrial motors, *i.e.* the AC induction squirrel-cage motors and the less commonly used DC, synchronous and PM motors. Less attention is focused on:

- Larger motors (>375 kW), generally run at mid and high voltage, which are manufactured on demand in relatively small quantities according to specific requirements of industrial users.
- Smaller motors (<0.75 kW), often single-phase and – although manufactured in millions – usually tailor-made for a specific purpose and thus integrated into a packaged machine. There are currently no definitive standards for testing, sizing or making efficiency classifications of such motors. Many of these motors have low running hours, but in some applications (such as pumps and fans), they can have long hours of operation.

- Electric motors in vehicles (trains, trams, cable cars, motor cars and airplanes). They serve either as main traction systems (electric trains, trams, trolley buses, etc.) or as auxiliary motors within fuel systems (cars, trucks, buses, diesel trains, airplanes) to operate all kinds of devices (windshield wipers, window motors, servo motors for brakes and steering, air conditioning, etc.).

- Electric motors integrated in household appliances, consumer goods and office equipment. These small motors typically have low operating hours and are treated as components in systems that often already have test standards, energy-efficiency classes and labelling schemes applying at the whole system level.

The analysis focuses on electricity delivered directly from the grid to the motor, excluding special applications run from fossil-driven generators or batteries.

Methodology

Currently there are few reliable statistics or information about the global electricity use of electric motors. Neither data from individual countries nor data available on a global level are based on harmonised and consistent methods, or on published data. Therefore, it has been necessary to develop and apply a methodology to make a best estimate of electric motor electricity use from the available data sets. Two different approaches to estimate global electricity demand of electric motors are applied to examine the uncertainty in the overall estimates:

- A **top-down** approach: The methodology applied involves estimating all non-motor electricity uses and assuming the residual part of total electricity consumption is that used by electric motors. Explicitly, the approach looks at sector-level electricity use in some 55 large countries and assumes an average fraction of electric motor usage in each sector.
- A **bottom-up** approach: The national energy use of electric motors is calculated based on available data (annual sales, running stock) and estimates of the average size, efficiency, running hours and load factor of the motor stock, which is then used to calculate motor-system power and electricity demand.

The authors of the study compared the results of the two approaches to ascertain their plausibility and robustness and determine the level of uncertainty.

Top-down estimates of electricity use

Demand by end-use

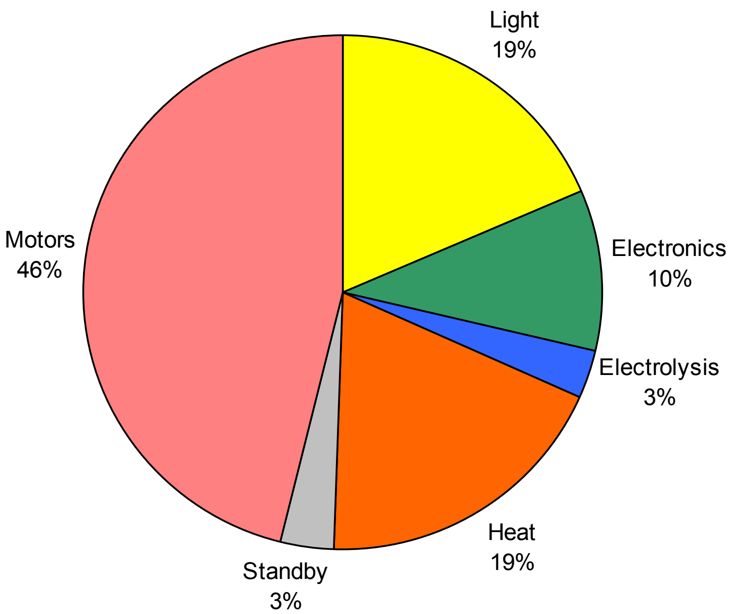
According to IEA statistics, global electricity production was 19 000 TWh in 2006 and annual electricity consumption for all end-use sectors was 15 600 TWh. Information about non-motor electricity consumption is available from several other studies: lighting (Waide, 2006); residential consumer electronics (Ellis, 2009); office electronics ICT (The Climate Group, 2008); space heat and process heat (A+B International estimates based on global industry process heat); and rail transport (UIC, 2008). Deducting these figures from total electricity consumption results in an estimate of total electricity use for electric motors in all sectors (industry, commercial [including vehicles]), small refrigeration and household appliances) of 7 200 TWh per year. This represents 46% of all end-use electricity consumption (Table 12 and Figure 9).

Table 12: Estimate of global electricity demand (TWh) by sector and end-use (2006)

Sector	All	Light	Electronics	Electrolysis	Heat	Standby	Motors
Industry	6 500	500	200	500	800	100	4 400
Transport	300	100	0	0	0	0	200
Residential	4 300	900	700	0	1 600	200	900
Commercial and public services	3 700	1 300	500	0	300	200	1 500
Agriculture, forestry and fishing	400	0	100	0	200	0	100
Others	500	100	100	0	200	0	200
Total	15 700	2 900	1 600	500	2 900	500	7 200
Share of total (%)		18.6%	10.0%	3.2%	18.7%	3.3%	46.2%

Source: A+B International, 2009.

Figure 9: Estimated share of global electricity demand by end-use (2006)



Source: A+B International, 2009.

Demand by motor sector

The IEA maintains a well-established database of national electricity consumption by major end-use sectors, but does not differentiate electricity consumption by application or electric motor application.

Global electricity demand for every type of electric motor can be estimated via a top-down calculation.

Equation 1

$$E_m\ [TWh] = (E_{ind} * f_{ind}) + (E_{tra} * f_{tra}) + (E_{res} * f_{res}) + (E_{com} * f_{com}) + (E_{agr} * f_{agr})$$

E_m	TWh	Electricity consumption in electric motor systems
E_{ind}, E_{tra}, E_{res}, E_{com}, E_{agr},	TWh	Global electricity consumption in the industrial, transport, residential, commercial and agricultural sectors

Table 13: Estimated global electricity consumption by sector in 2006

Sector	Electricity consumption (TWh)
Industry	6 510
Transport	270
Residential	4 310
Commercial and public services	3 690
Agriculture and forestry and fishing	410
Others	480
Total	**15 650**

Source: IEA statistics, 2006.

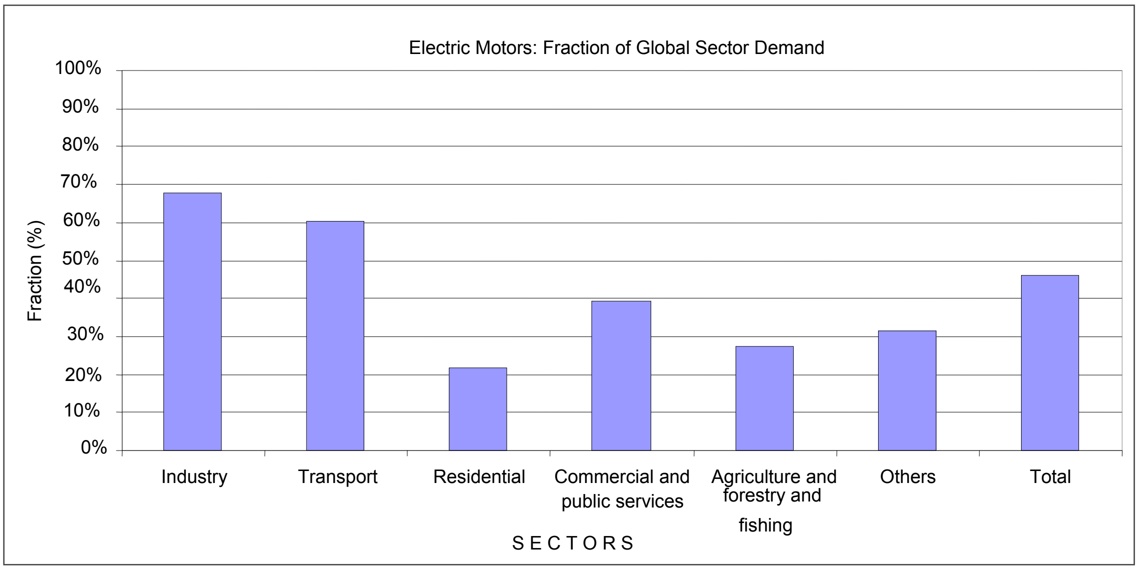
Figures for typical shares of electric energy use by motors in specific sectors are available from research results based on surveys. The authors have estimated the share of other sectors (Figure 10).

- **Industrial:** 68.9% (mostly industrial handling and processing);
- **Commercial:** 38.3% (mostly HVAC);
- **Agricultural:** 20% to 25% (mostly pumps and fans);
- **Residential:** 20% to 25% (mostly in refrigerators/freezers and HVAC);
- **Transport:** 60% (mostly in electric railways) (UIC, 2008).

Clearly, the relevance of motors and motor systems is largest in the industrial sector (about 70% in the European Union, about 60% in South Africa [Mthombeni and Sebitosi, 2008]), but also in the commercial sector, where its share of energy use reaches almost 40% (De Almeida *et al.,* 2008a). Note that this top-down analysis does not discriminate between motor types and uses; it includes all kinds of electric motors operated on the electricity grid. Some types of motors (*e.g.* those used in vehicles, very small and very large motors, and motors included in appliances, etc.) are not the focus of the current study; their energy consumption must be deducted in order to compare the top-down results to the bottom-up analysis.

The estimated electricity consumption of motors is based on average sector use for motors, using Equation 1. For each country, the electricity demand of each sector is multiplied by a factor representing the fraction of motor-electricity use in the given sector. Due to data limitations, the same sector-specific factor is applied to all the countries. The countries in Table 14 were selected by the magnitude of their electricity demand in 2006; some smaller countries were added because they have motor MEPS.

Figure 10: Assumed share of motor electricity use by end-user sector



Sources: De Almeida *et al.*, 2008a; A+B International, 2009.

The results represent a rough top-down estimate, but they do give a first indication of the relevance of motor-electricity use by country:

- With a share of 64%, industry consumes the most power for electric motorised applications (Figure 11). The next most important sectors are the commercial sector (accounting for 20% of all motor-electricity consumption) and the residential sector (accounting for 13%). The transport and agricultural sectors contribute only marginally to global motor-electricity demand.
- The residential sector accounts for a large number of small electric motors used in appliances (refrigerators/freezers, room air conditioners, washing machines), in building technologies (pumps and fans), and in central heating, ventilating and air conditioning (HVAC) systems.
- The electricity consumed by motors was greatest in China, the European Union and the United States. These three economies account for about 50% of total global motor-electricity consumption. If Canada, India, Japan and Russia are included, these economies account for about two-thirds of the worldwide motor electricity demand.
- Globally, the combination of all kinds of motor electricity demand is estimated to be about 45%. Among the countries considered, the respective share varies between 38% and 54% (China) with one exception of 31% (Saudi Arabia).

These data illustrate that the 55 countries on the list account for 93% of global motor-electricity demand, but the three largest countries/regions, China, the European Union and the United States account for the majority of this.

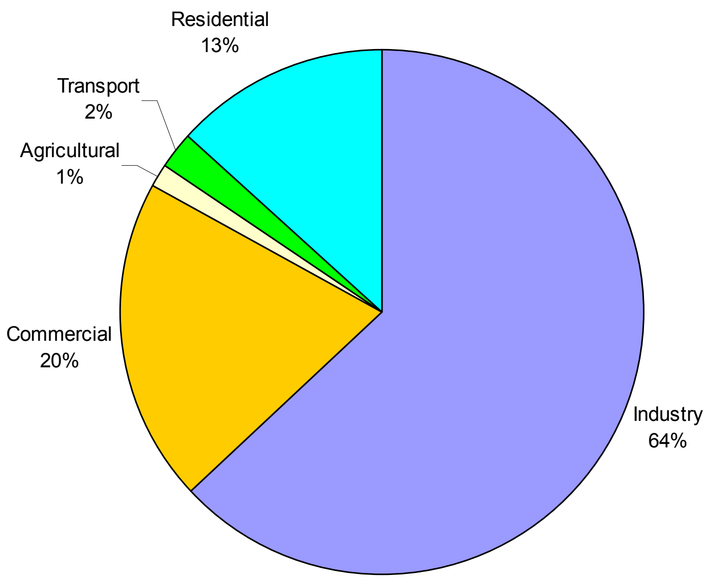
Table 14: Electricity end-use by sector, country and estimated demand for all electric motors (2006)

	Country	National electricity demand (TWh/year)	Electricity demand for all kinds of electric motors by sector (TWh/year)						
\			Industry	Commercial	Agricultural	Transport	Residential	Total motors	Motor's share of national total
1	United States	3 722	632	498	0	4	297	1 431	38.4%
2	EU-27	2 813	787	282	13	44	177	1 303	46.3%
3	China	2 317	1 092	50	24	13	72	1 251	54.0%
4	Japan	981	221	138	0	11	62	432	44.1%
5	Russia	681	244	43	4	52	25	367	53.9%
6	Canada	499	141	51	2	3	33	229	45.9%
7	India	506	157	15	24	6	24	226	44.7%
8	Korea, South	371	131	46	1	2	12	191	51.4%
9	Brazil	375	126	34	4	1	19	184	49.0%
10	South Africa	198	78	11	1	3	8	102	51.4%
11	Australia	210	65	19	0	2	14	99	47.3%
12	Mexico	199	77	8	2	1	11	98	49.4%
13	Taiwan	207	70	11	1	1	9	92	44.4%
14	Ukraine	130	47	8	1	6	6	68	52.3%
15	Turkey	141	46	14	1	0	8	68	48.4%
16	Thailand	128	41	16	0	0	6	62	48.8%
17	Iran	151	36	10	4	0	11	62	41.1%
18	Norway	108	34	8	0	1	7	51	47.3%
19	Indonesia	113	30	10	0	0	10	49	43.8%
20	Argentina	99	33	9	0	0	6	48	48.6%
21	Saudi Arabia	143	9	16	1	0	19	44	31.0%
22	Venezuela	81	28	7	0	0	5	40	49.7%
23	Pakistan	73	15	4	2	0	7	28	38.2%
24	Switzerland	58	13	6	0	2	4	26	44.3%
25	Vietnam	49	16	2	0	0	5	22	45.9%
26	Israel	46	8	6	1	0	3	18	38.6%

	Country	National electricity demand (TWh/year)	Electricity demand for all kinds of electric motors by sector (TWh/year)						
27	New Zealand	38	10	3	0	0	3	17	43.2%
28	Bangladesh	22	6	1	0	0	2	9	42.8%
29	Costa Rica	8	1	1	0	0	1	3	38.1%
	Total (55 countries)	**14 465**	**4 193**	**1 324**	**89**	**153**	**862**	**6 621**	**45.8%**
	Share of motor electricity	100%	29%	9%	1%	1%	6%	46%	
	Rest of World	1 195	295	88	12	6	86	487	
	World	15 660	4 488	1 412	101	159	948	7 108	45.4%
	55 countries share of world	92%	93%	94%	88%	96%	91%	93%	
	Sector share of total		**68.9%**	**38.3%**	**25.0%**	**60.0%**	**22.0%**		

Sources: IEA statistics, 2006 (national electricity demand); A+B International, 2009 (motors calculations).

Figure 11: Estimated electricity demand for all electric motors by sector



Sources: IEA statistics, 2006; A+B International, 2009 (motors).

Demand by motor size

In terms of numbers of running motors (installed stock), small motors are the most common: 2 billion out of an estimated global total of 2.23 billion are rated at less than 0.75 kW. The relatively few large motors account for a considerable share of overall motor electricity consumption (Wikström, 2009). However, it is estimated that medium-size motors consume almost three-quarters of the global electricity demand of all motors (Table 15).

Demand by motor application

In these estimates of electricity demand disaggregated by motor application, the term motor application refers to the kind of machine that is driven by the shaft of the electric m otor. Several layers of definitions exist, with the largest segment being rotating machines (Table 16).

Table 15: Estimated electricity demand for the three major groups of electric motors (2009)

Motor size	Output size, P_m (kW)				Operation		Number of running stock (millions)	Life-time (years)	Sales (millions/year)	Motor efficiency		Power (P_e)	Electricity demand (TWh/year)
	Min	Max.	Median	Total GW_m	Hours/year	Load factor				Nominal	Mean	Total GW_e	
Small	0.001	0.75	0.16	316	1 500	40%	2 000	6.7	300	40%	30%	422	632 (9.1%)
Medium	0.75	375	9.5	2 182	3 000	60%	230	7.7	30	86%	84%	1 559	4 676 (67.6%)
Large	375	100 000	750	450	4 500	70%	0.6	15.0	0.04	90%	88%	358	1 611 (23.3%)
Total				**2 948**			**2 231**	**6.8**	**330**		**79%**	**2 338**	**6 919 (100%)**

Abbreviations: $_e$ = electrical; $_m$ = mechanical; P = power.

Source: A+B International, 2009.

Table 16: Applications of all kinds of electric motors

Electric motors	**Applications**	**Pumps**		**Drinking Water**	**Water/refrigerant**	**Sewage**	**Oil**
Rotating machines			**Closed loop**	Closed water supply system	Heating, cooling and chilling system	Pressure sewage system	Hydraulik pumps
			Open pipe	Water supply system	Irrigation, cooling tower	Sewage system	Pipeline
		Fans		**Air**	**Gas**		
				Room air supply and exhaust, blowers	Natural gas systems		
		Compressors		**Refrigerant**	**Air**	**Gas**	
				Cooling machines for AC and commercial freezers, refrigerators and freezers	Compressed air storage and distribution system, pneumatic systems	Liquification systems	
		Rotating/mix/stir		**Roller, rotors**	**Extruder**	**Textil handling**	**Mixers, stirring**
			Solid	Metall, stone, plastics	Aluminium, plastics	Weaving, washing, drying	Food, colour, plastics
			Liquid				Food, colour, plastics
		Transport		**People**	**Goods**	**Vehicles**	
			Vertical	Passenger elevator	Goods elevator, cranes, hoists		
			Inclinded	Escalator	Conveyor	Cog wheel train, cable car, ropeway	
			Horizontal	Conveyor	Conveyor	Train, tram, trolley, cars, busses, electric cars, bikes and bicycles	
Linear motors				**Open/close**	**Sort**	**Grab & Place**	
Back & forth movement				Valve		Robot	
Stepper motor				**Open/close**	**Position**		
Angular position				Valve	Servo		

Source: A+B International, 2009.

Motor use in the sectors by application and complementing assumptions on motor electricity demand is broken down in the sector-application matrix (Table 17). Motor electricity demand for mechanical movement (transport of people and goods) and compressors (compressed air and cooling) account for about 30% of total global electricity motor demand. The remaining part, of less than 40%, is consumed in equal amounts by fans and pumps (Figure 12).

Conclusions from top-down estimates

The top-down analysis provides several preliminary results:

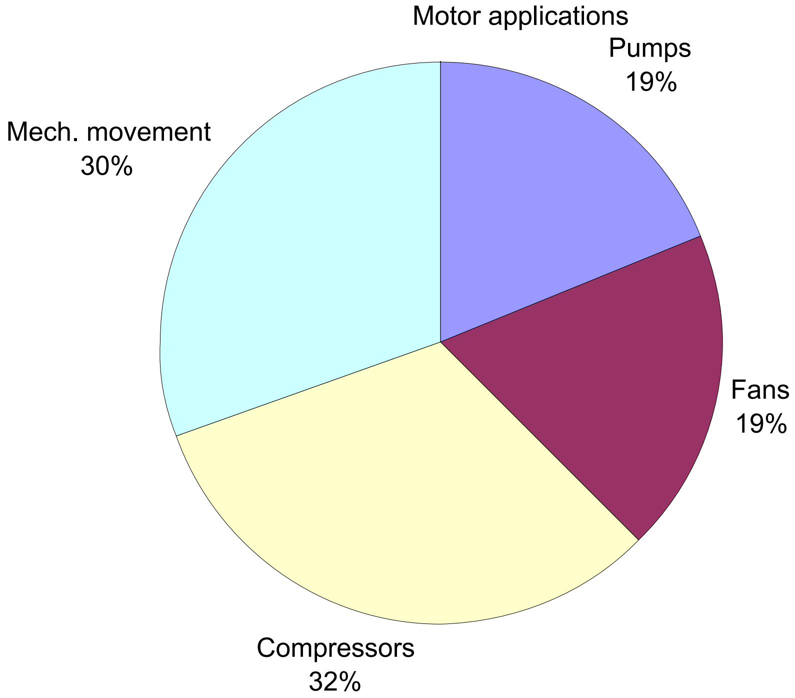
- The estimated total global electricity use of all electric motors in 2006 was between 6 900 TWh and 7 200 TWh.
- Electric motors account for between 44% and 46% of total global electricity consumption; industry accounts for 64% of this, the commercial sector for 20% and the residential sector 13%.
- General purpose industrial electric motors of between 0.75 kW and 375 kW consumed 4 700 TWh (68% of the total for all motors); their share of global electricity demand is 30%.
- The three economies with the highest electricity consumption for motors are China, the United States and the European Union, which collectively consumed 4 000 TWh (56% of global electricity demand for motors); the addition of four more countries (Japan, Russia, Canada and India) adds another 1 200 TWh (18%), which makes a total of 5 200 TWh (74%).
- Four major motor applications dominate the electricity demand of motors: compressors (32%), mechanical movement (30%), pumps (19%) and fans (19%).
- The net mechanical energy used in motor applications is estimated to be roughly 50% of the electrical energy input into motors (*e.g.* on average it is thought electric motor systems operate at an efficiency of about 50%). The losses occur in the motors themselves as well as in throttles and dampers, gears, transmissions, clutches, brakes, VFDs, etc. (Figure 13).

Table 17: Estimated global motor electricity demand by sector and application (2006)

Sectors	Total demand of electric motors (TWh/year)	Pumps		Fans		Compressors		Mechanical movement	
		Demand (TWh/yr)	Sector motor share	Demand (TWh/yr)	Sector motor share	Deman d (TWh/yr)	Sector motor share	Demand (TWh/yr)	Sector motor share
Industry	4 488	942	21%	718	16%	1 122	25%	1 705	38%
Commercial	1 412	223	16%	339	24%	603	43%	247	18%
Agricultural	101	20	20%	20	20%	20	20%	40	40%
Transport	159	16	10%	16	10%	48	30%	80	50%
Residential	**948**	**142**	**15%**	**237**	**25%**	**474**	**50%**	**95**	**10%**
Total	**7 108**	**1 344**	**18.9%**	**1 330**	**18.7%**	**2 267**	**31.9%**	**2 167**	**30.5%**

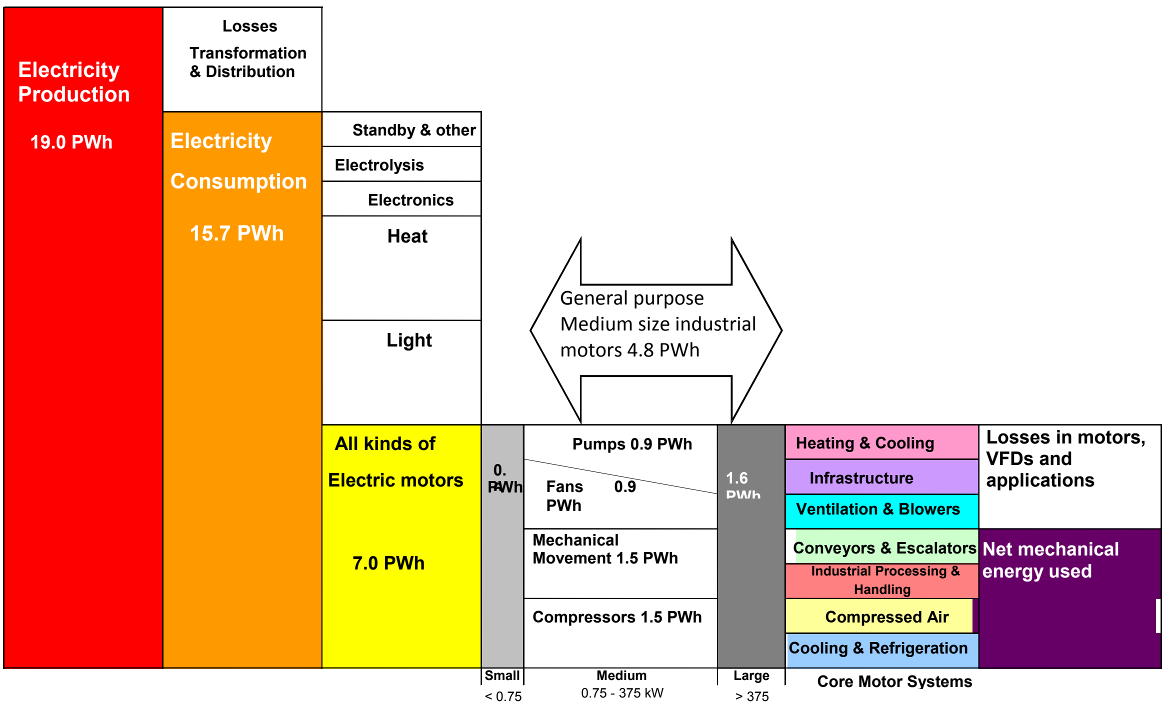
Sources: De Almeida *et al*, 2008b; A+B International, 2009.

Figure 12: Estimated share of global motor electricity demand by application (2009)



Sources: De Almeida *et al.* 2008b; A+B International, 2009.

Figure 13: Estimated overall efficiency and electricity use for all types of electric motor systems



Source: A+B International, 2009.

Bottom-up model of motor electricity use

Methodology

Estimating the global electricity consumption for electric motors is challenging due to limited data available and incomplete coverage from one economy and sector to another. To tackle this challenge, the analysis presented uses existing data gathered by the consultants (Brunner, 2008) and/or information in the public domain. It also makes use of newly collected evidence and data for 2009 gathered through direct contacts with market actors in several countries.

Electric energy consumption of the global stock of electric motors can be estimated from the bottom-up by multiplying the electric power of the installed motor stock by the number of full-load hours per year. The electric power is determined from the installed mechanical output power divided by the nominal efficiency of the motors. Full-load hours are decomposed by operation time and load factor. Each of these factors may be differentiated by end-use sector, application, motor size, efficiency class or other factors denominated by the index *k*.

Equation 2

$$E = \sum_k n_{r,k} \cdot Pm_k \,/\, eta_{p,k} \cdot h_k \cdot LF_k$$

With:

E_m	TWh	Electricity use by motors
P_m	kW	Nominal mechanical output power* (by *k* or weighted average over all sizes)
P_e	kW	Average nominal electric input power (by *k* or weighted average over all sizes)
n_r	number	Running stock of electric motors in installed base
h	hours	Average annual operation time* (by *k* or weighted average over all sizes)
LF	percent	Average load factor during operation time (by *k* or weighted average over all sizes)
eta_p	percent	Average annual effective motor efficiency in partial load* (by *k* or weighted average over all sizes)
K		Index for the size classes

* Data for the number of running motors (n_r) is quite limited or even non-existent in many countries. For this reason, a stock model was developed to derive stock data from sales data.

The motor stock model

Since data on motor sales are generally more available than data on motor stock, a stock model was developed to derive the installed stock from motor sales data. Generally, new motors sold in a given country originate from either domestically manufactured or imported products. This means that national motor sales are:

Equation 3

$$n_s = n_{pro} - n_{ex} + n_{imp}$$

with:

$n_{s\text{-}i\text{-}x}$	number	Electric motors **sold** in year *i* in country *x*
$n_{pro\text{-}i\text{-}x}$	number	Electric motors **produced** in year *i* in country *x*
$n_{ex\text{-}i\text{-}x}$	number	Electric motors **exported** in year *i* in country *x*
$n_{imp\text{-}i\text{-}x}$	number	Electric motors **imported** in year *i* in country *x*

Note that motors are imported and exported not only in terms of motors as such, but also in terms of integrated and packaged motor applications and core motor systems (such as pumps, fans, compressors, machines and others). Motors sold nationally [n_s] are used for replacement installations, building up replacement stock or new installations.

To estimate the installed base, the following assumptions are made:

- Replacement is usually made after a normal life cycle.
- Earlier replacements are possible when a motor fails prematurely and repair is not feasible or when a machine is renewed before the lifetime is reached.
- If no specific data are available from the literature, assumptions on the average lifetime and the annual replacement are made based on figures from De Almeida (2008a).

Motors have an average operating life of 12 to 15 years; thus 7% to 8% of the installed base is replaced each year. In general, the volume of new installations is directly related to the development of the industrial sector, which is measurable through industrial GDP, electricity use and investments. In industrialised parts of the world, such as Europe and the United States, the annual growth rate of new motor installations is 1% to 3% of the installed base. In developing economies (such as China, India, Brazil and Russia), it can be in the range of 3% to 6% of the installed base. The total motor market in any country is therefore somewhere between 9% and 14% of the installed base. Put another way, the installed base is typically 7 to 11 times the annual domestic sales volume.

Estimates from bottom-up model

Motor electricity demand (derived from stock data and the other factors in Equation 2) is largest in China, followed by the United States and the European Union. The five largest motor-electricity consuming economies are China, the European Union, Japan, Russia and the United States, which collectively account for about 84% of motor electricity consumption in the countries covered in Table 18 and about 45% of worldwide motor-electricity demand.

The bottom-up estimates (Table 18) indicate that:

- Average motor size varies considerably between countries (by more than a factor of 3).
- Economy-wide average motor efficiency varies between 87% and 93%.
- Annual operation times are similar between countries, mostly between 2 500 and 3 000 hours.
- Average load factors are almost the same among countries.

Table 18: Estimated motor electricity demand with particular factors from the bottom-up model for 13 countries with highest electricity consumption

	Base year sales	Sales (tsd. pieces)	Base year stock	Stock (Million pieces)	Avg. Pm (kW)[1]	Avg. Pm (kW)[2]	National Pm (GW)	Efficiency (%)[2]	Annual op. time (h/a)[2]	Load factor[2]	Full load hours (h/a)	El. cons. bottom-up (TWh/a)
USA	2003	1 532	2007	24.0	12.9	23.5	309	92.7%	3 654	0.63	2 302	758
EU25	2007	10 395	2007	89.0	5.5	8.2	493	87.8%	2 528	0.58	1 478	824
China	2006	6 152	2006	35.6	15.9	24.5	566	90.9%	2 858	0.62	1 764	1 090
Japan	2008	1 081	2008	16.4	8.8	14.5	144	89.5%	2 769	[5] 0.60	1 670	268
Russia[3]	2007	1 282	2008	12.5	10.3		128	85.0%	2 698	0.60	1 619	244
Canada[3]	ca. 2004	147	ca. 2004	2.6	12.9		33	91.4%	2 402	0.60	1 441	53
India	2003	1 244 [6]	2003	12.2 [6]	4.3 [4]	5.8	53	85.5%	2 863	0.57	1 634	102
S. Korea[3]	2005	384	2005	4.2	5.5		23	84.6%	2 410	0.60	1 446	64
Brazil	2002	936	2002	9.1	8.2 [4]	14.5	128	89.6%	3 059	0.68	2 068	169
Australia	2004	236	2004	2.6	12.9	26.9	34	92.3%	3 787	0.63	2 403	86
Mexico[7]	2005	198	2005	1.9	4.1 [4]	5.2	7.7	80.3%	2 581	0.56	1 443	15
Taiwan[3]	2008	1 147	2008	6.9	5.5		38	84.6%	2 740	0.60	1 644	74
Total		24 734		192.9	9.9		1 648	89.8%	2 899	0.61	1 775	3 747

Notes:
1. Weighted by sales.
2. Weighted by use.
3. No differentiation by size classes available.
4. Standard value.
5. Lower value due to data from literature for China for industry.
6. Based on average sales data 2000-07.
7. Mexico, consumption is for 300 hp to 500 hp motors.
8. Source: TEP Energy, 2009.

Consolidated top-down and bottom-up estimates of electricity consumption and CO_2 emissions

The study compares the results of top-down and bottom-up estimates with each other and with other evidence from technical literature for large economies (Table 19). Results of the top-down approach reported in Table 14 are reduced by over 30% for this comparison because the bottom-up analysis does not include motors smaller than 0.75 kW or larger than 375 kW, and only considers multiphase AC motors. Overall, the results of the top-down and bottom-up estimates are found to be reasonably close (*e.g.* within about 5%). However, for some economies, the difference can be up to 80%.

The greatest consistency in these estimates was for the European Union, because the bottom-up model is calibrated with motor stock data from a recent EU regulatory study and complemented by a time series of sales data. Results for Japan and Russia were also in good agreement.

For Australia and Brazil, bottom-up estimates were clearly higher than top-down estimations (about 30%). For China it was 19% and Taiwan 14%. Conversely, in the cases of Canada, South Korea and Mexico, top-down results exceeded bottom-up estimates by over 50%. For India and the United States, top-down results exceeded bottom-up estimates by 26% and 16% respectively. The explanation for these differences is as follows.

Table 19: Comparison of motor electricity demand in bottom-up and top-down models and figures from the literature of 12 economies

Economy	Motor electricity demand (TWh/year) (0.75kW to 375kW)				Difference between top-down and bottom-up
	Top-down estimate	Bottom-up estimate	Literature	Year of literature estimate	(Top-down – 100%)
United States	904	758	944	2007	-16%
EU-25	856	824	519	2000	-4%
China	914	1 090	–	–	19%
Japan	287	268	–	–	-7%
Russia	229	244	–	–	7%
Canada	153	53	–	–	-65%
India	138	102	–	–	-26%
South Korea	141	64	–	–	-55%
Brazil	128	169	85	2003	32%
Australia	67	86	72	2000	29%
Mexico	68	15	50	2006	-78%
Taiwan	65	74	–	-	14%
Total	**3 949**	**3 747**	**1 670**		**-5%**

Cases where bottom-up results significantly exceed top-down estimates:

- For **China**, the share of motors in electricity demand, especially in the industrial sector, is above the global average (a constant sector-specific fraction of motor electricity was assumed across all countries). Hence, the simplified top-down approach presumably underestimates motor electricity demand.
- For **Brazil**, the top-down estimate is about one-third greater than the bottom-up estimate, for which model input data are taken from the literature (Garcia *et al.*, 2007) and are not adjusted for international trade. There is some evidence of significant OEM exports, but further research is needed to explain the difference with confidence.
- **Australia**'s industrial final electricity consumption is heavily affected by the non-ferrous metal sector (54% in 2005, mainly aluminium production). This would lead to an overestimation of motor electricity demand via the top-down approach, since electricity in this sector is mostly used for non-motor purposes (see the case of Canada below). However, bottom-up estimates are higher than top-down estimates, which could be due to an overestimation of sales or full-load hours or due to an underestimation of net exports (*e.g.* of OEMs).

Cases where top-down estimates significantly exceed bottom-up results:

- For the **United States**, the bottom-up model provides results that are slightly lower than the top-down estimate if no trade adjustments are made. Including adjustments regarding trade (which is known in terms of value but not in terms of numbers) might lead to an overestimation via the bottom-up model.
- For **Canada**, the share of motors per unit of electricity consumption is presumably below the global average since Canada's electricity demand includes a significant share from non-motor

energy-intensive industries such as aluminium production. Thus the top-down approach will tend to overestimate motor electricity demand. Moreover, Canada may be a net importer of motors or OEM equipment containing motors; this is not taken into account owing to a lack of data.

- For **Mexico**, it is assumed that available motor sales data underestimate the total number of electric motors, since OEM sales in several applications are not included. Note that the bottom-up estimate from the literature is more consistent than the top-down estimate.

- Further research is needed in the case of **South Korea**; however, it is likely to be a large net importer of OEM equipment and/or motors.

Causes of uncertainty

Top-down estimates

Uncertainties in the top-down estimates are related to structural differences among countries in activity in industrial, commercial, residential and other sectors. For instance, in some countries, electricity consumption in the industrial sectors is dominated by bulk applications such as electrolysis, electro-steel production and aluminium electrolysis, which include a significant share of electricity for thermal (non-motorised) applications. Such electricity demand should be subtracted from industrial electricity consumption before multiplying it by the factor representing the share of motor electricity demand. Also, factors representing shares of motor electricity demand might depend on the developing state of the different countries. To some extent, developed economies are characterised by manufacturing industries whereas developing economies have a larger share of primary industries. Moreover, the share of electricity consumption attributable to motors may depend on the climate, particularly in the commercial sector (as a result of the penetration of air conditioning).

Bottom-up estimates

The uncertainty of the bottom-up estimates is dependent on the availability and quality of the data used to make the estimates, namely information on:

- motor sales and stock
- import and export of motors
- average motor annual running hours
- average motor load factor
- average motor efficiency

4. Energy-Savings Technologies and Savings Potentials Applicable to Electric Motor-Driven Systems

The efficiency of an electric motor-driven system (EMDS) (such as a pump, fan, compressor or industrial handling and processing) is determined by the total motor system, *i.e.* the multiplication of efficiencies for each component. Within the various electric motor technologies described, energy-savings options are available for both components and integrated systems.

Improving component efficiency

The following analysis examines key electrical and mechanical components and how they interact, and identifies state-of-the-art efficiency, beginning with the electric motor itself.

Standard AC squirrel-cage induction motor

AC induction motors are a cheap and cost-effective means of converting electrical energy into rotational mechanical power, and are an effective way to continuously operate pumps, fans, compressors and conveyors, etc. at fixed speed. These motors are mass-produced by many manufacturers around the globe and sold in standard catalogue types and sizes. They are easy to replace because manufacturers, wholesalers and industrial end-users keep them in stock. These products are internationally traded like commodities, and have the advantage of standardised features (such as frame size, output power or torque, rotational speed, insulation, and protective coatings).

AC induction motors now have a clear international energy-efficiency testing standard (IEC 60034-2-1, September 2007), which allows minimum energy performance standards (MEPS) to be compared and checked and for industry to compete internationally on the basis of the energy efficiency of their products. The past controversy on US testing standards based on IEEE 112 B (including a full account of stray load losses) has now been settled with the new IEC standard that offers a variety of testing methods, all of which account for stray load losses.

The energy efficiency of the AC motor is classified by IEC 60034-30 (October 2008) into three commercially available energy-efficiency classes:

- IE3 Premium Efficiency (equivalent to 60 Hz operation with NEMA Premium)
- IE2 High Efficiency (equivalent to 60 Hz operation with EPAct, similar to 50 Hz operation with Eff1)
- IE1 Standard Efficiency (similar in 50 Hz operation with Eff2)

To initiate a competition for even higher motor efficiency in future, the IEC standard indicated a Super Premium class with 15% lower losses than the IE3. General understanding is that this will be not a standard AC induction squirrel-cage motor, but either an electrically commutated or copper rotor motor. These efficiency classes cover motors from 0.75 kW to 375 kW, 2-pole, 4-pole and 6-pole, and in 60 Hz or 50 Hz operation with a supply voltage of 200 V to 700 V. This efficiency classification asks for IE2 and IE3 motors to be tested with a method of “low uncertainty” among the various testing methods provided by IEC 60034-2-1.

The three-phase asynchronous AC induction motor is the global standard for general-purpose medium-size industrial motors. It consists of two major elements:

- A fixed **stator,** with feet to the ground or with flanges to the machine, with copper coils inside that produce a rotating magnetic field.
- An inside **rotor,** separated by a slot and attached to the output machine, that receives a torque via the rotating magnetic field.

There is only a very limited potential for further efficiency improvement in the state-of-the-art electric motors on the market today (Table 20).

Table 20: Nominal load efficiencies in IE3 Premium Efficiency AC induction motors

IE3	50 Hz (4-pole)	60 Hz (4-pole)
0.75 kW	82.5%	85.5%
200 kW	96.0%	96.2%

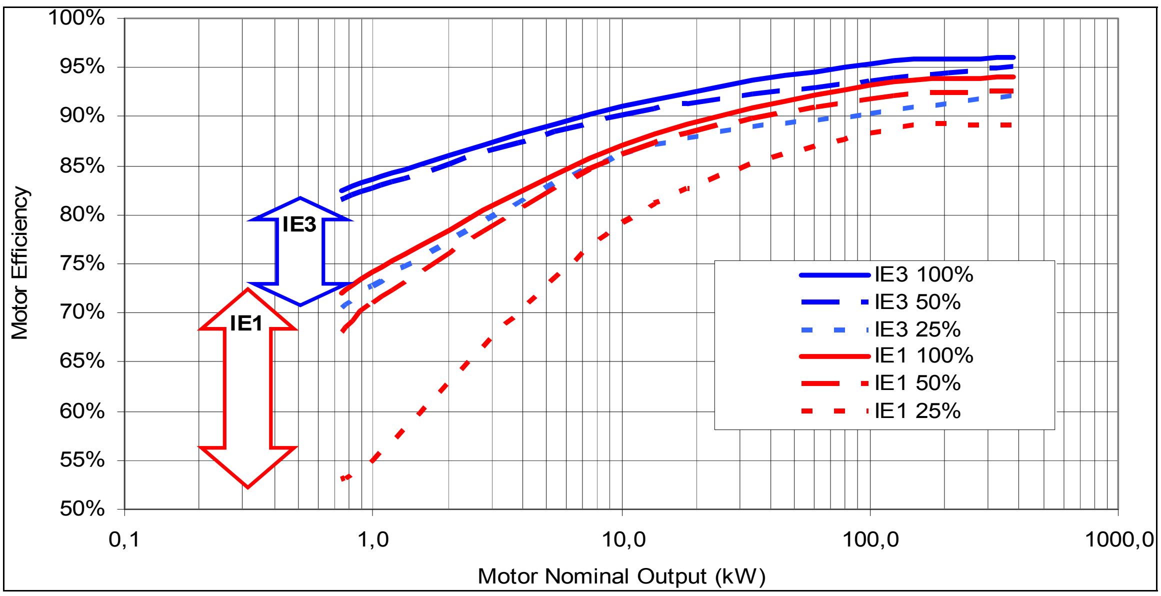
Abbreviation: AC = alternating-current.
Source: IEC 60034-30.

Assessments of the theoretical zero-loss performance of an electric motor at 100% efficiency are very close to the values in Table 20. Especially in larger motors, 100% efficiency can only be further approached through extremely high marginal effort and cost with decreasing additional benefit. The remaining efficiency potential in motors lies mainly with:

- Improved smaller motors (<10 kW) because their spread IE1/IE3 is larger than in bigger motors.
- Increased partial-load efficiency because both IE1 and IE3 produce large losses at between 25% and 50% load (Figure 14).

In order to further reduce electricity losses in motors, their respective type and size must be analysed in detail (Table 21). Stator losses in small motors significantly dominate over other losses.

Figure 14: Partial-load efficiency of IE3 and IE1 motors (4-pole)



Source: A+B International, 2009.

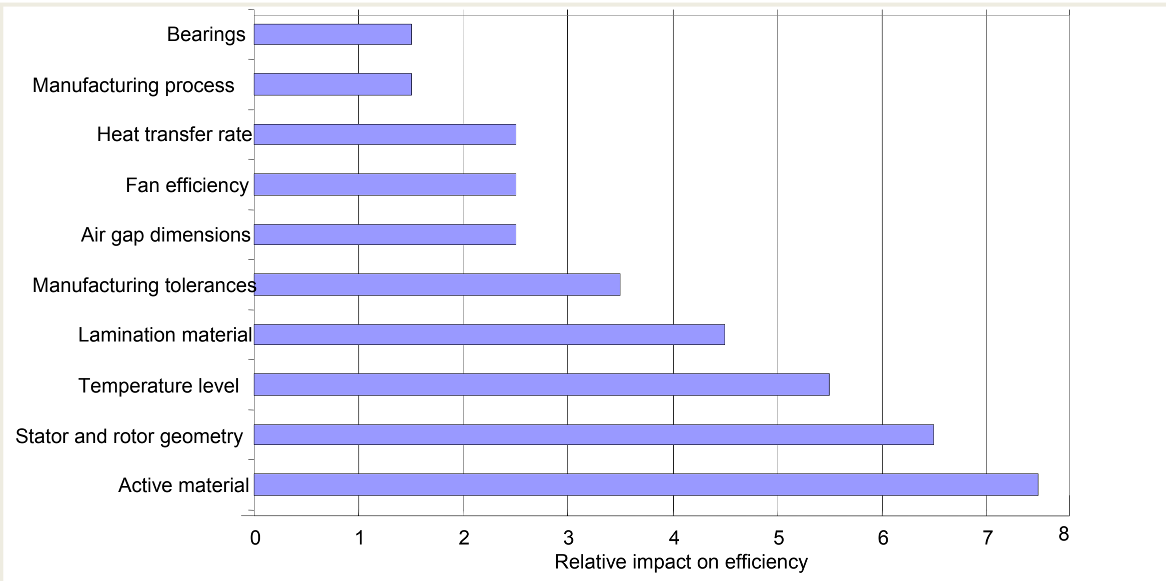
Table 21: Typical losses in an AC induction motor

	Typical losses in 4-pole motors	Factors affecting these losses
Stator losses	30 - 50%	Stator conductor size and material
Rotor losses	20 - 25%	Rotor conductor size and material
Core losses	20 - 25%	Type and quantity of magnetic material
Additional load losses	5 - 15%	Primarily manufacturing and design methods
Friction and windage	5 - 10%	Selection/design of fan and bearings

Abbreviation: AC = alternating-current.
Source: IEC 60034-31, draft 2009.

Further research has been undertaken to systematically evaluate the components of losses, and the technical and economical means to reduce them. Each step has been rated according to impact (Figure 15). A combination of the most effective means delivers the highest overall feasibility. In addition to energy efficiency in different motor classes and partial loads, the power factor must be monitored. Unbalanced voltage or voltage magnitude deviation lowers the power factor. This means a heavier load on the internal electric distribution network (requiring larger copper wires to avoid overload) or larger power-factor correction equipment. The manner in which the motor is integrated into the system is critical to the overall efficiency of the EMDS. In particular, it is important that the motor be sized correctly; in practice, there is a tendency to oversize motors based on a misguided belief that larger motors will operate more reliably for a given application.

Figure 15: Impact of possible areas of improvement for induction motor performance



Source: Fuchsloch and Brush, 2007.

Other motor technologies

In addition to the standard AC induction motor, there are many other types of motors with applications in specific fields:

- **Single-phase AC induction motors:** Mass-produced shaded-pole or split-phase motors below 1 kW with generally low efficiency, used in household appliances, etc.

- **Synchronous AC motors:** Running at exactly the supply frequency (or multiples of it) without slip at a constant speed, independent of torque, generally used for larger medium- and high-voltage machines.
- **Universal AC motors:** Able to run on both AC and DC with low efficiency up to 1 kW, used for low-cost applications.
- **Brushed DC motors:** Industrial motors that apply AC/DC-converter technology to be able to adjust speed to the necessary load. This traditional version of DC motor with brushes is less used today because of their higher maintenance costs and adoption of VFD.
- **Brushless DC motors:** New motor technology that is permanently magnetic and electronically commutated.
- **Linear motors:** Motors that produce a precisely controlled linear force used by on/off switches and actions (10 to 1000 times per minute) that can also substitute for pneumatic systems. This type of motor can be extended along a track for the propulsion of a Maglev/Transrapid magnetic levitation train system.
- **Servo motors:** A motor system that is insensitive to changes in the load torque, with a very fast response to recover against torque disturbance. A servo motor is connected in a regulation loop and designed and manufactured to achieve high dynamic performance. It is characterised by low rotor inertia for high acceleration, high over-load capacity, smooth rotation, low torque ripple and wide operating speed ranges. Servo motors may be DC motors, induction motors or synchronous motors. They are much more expensive than regular fixed-speed induction motors, making them unfeasible for general purposes.
- **Stepper motors:** The rotor turns in discrete angular increments when its stator windings are energised in a programme. These motors are used for servo-controlled positioning systems that can accelerate and stop at a very precise angle. They are used in printers and disk drives etc., but are not used for continuous operation.

Only motors running continuously for more than 500 hours to 1 000 hours per year use significant amounts of energy. It is only at this level of operation that the cost of more efficient technologies can be fully offset by reduced energy use and operational expenses.

New motor technologies

The energy-efficiency potential for new motor technologies includes:

- Improvements on the continuously operated fixed-speed motor.
- Variable-speed motors that adapt to changing loads and also eliminate gears and transmissions.

The AC induction motor has been continuously improved by optimising stator and rotor design (size), and electric material properties and quantity (steel, aluminium and copper). More efficient AC induction motors require longer stacks in stator and longer rotors, amounting to using more and costly active material (Figure 16). With given exterior motor dimensions (frame sizes: European standard EN 50347 [CENELEC, 2001] and United States standard NEMA MG1 [NEMA, 1998]), the potential efficiency gain is limited and costly.

New developments reduce losses by using copper instead of aluminium for the conductor bars and end rings in rotors. Aluminium pressure die-cast rotors (melting temperature 660 °C for aluminium) are now standard in AC motors. It is much more difficult to cast copper in precise forms (with its considerably higher melting temperature of 1 034 °C), but this has been performed successfully (Copper Development Association, 2007). In the United States in 2006, Siemens launched a new series of IE3 (and slightly above) efficient motors with copper rotors.

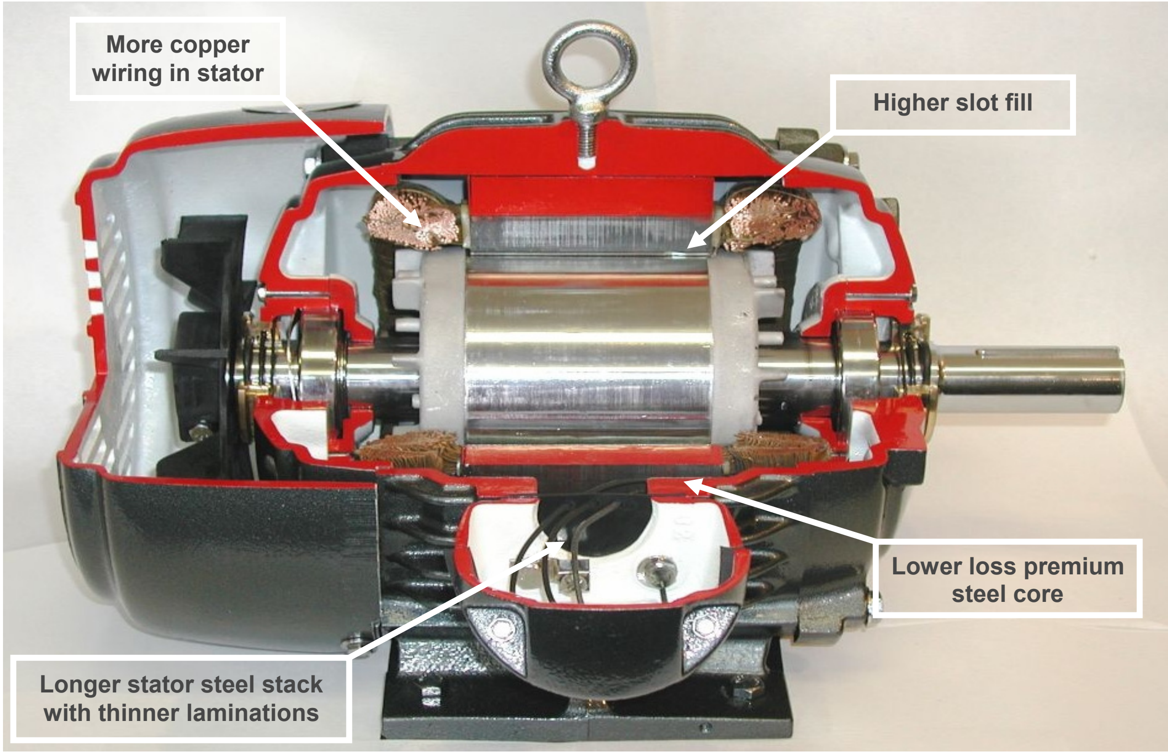
Now copper rotor motors from 0.1 kW to 100 kW are available. The design effort and the advanced production technology add considerable cost to the product, but this allowed a gain of almost one efficiency class within the same frame size. Some manufacturers offer motor-stator combinations with either traditional aluminium rotors or special copper rotors. This is done especially for long-stack motors to avoid larger diameters.

There are a number of advantages to using copper rather than aluminium in AC motors:

- **Lower coefficient of expansion:** aluminium will creep and move approximately 33% more than copper.
- **Tensile strength:** copper is 300% stronger than aluminium and thus able to withstand high centrifugal force and the repeated hammering from current-induced forces during each start.
- **Higher melting point:** copper can better withstand thermal cycling over the life of the motor.

Independent tests show that a copper rotor can reach slightly higher than IE3 performance values, though at a considerable cost premium. In 2007, IEC 60034-30 defined a future efficiency class, IE4 Super Premium efficiency, with 15% lower losses than IE3. Since then, a more precise definition of the eventual performance level has been given in the draft IEC 60034-31 (IEC, 2009) wherein the eventual improvement is dependent on 50 Hz, 60 Hz and the number of poles.

Figure 16: IE3 Premium-Efficiency motor



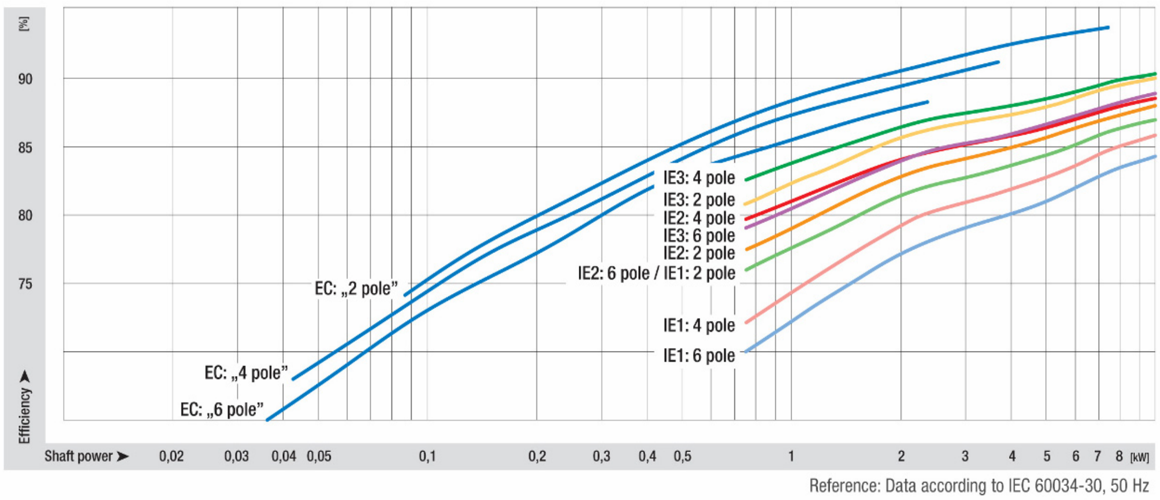
Source: Emerson. Reproduced with permission from US Motors/Emerson.

Motor technology development has also been moving towards DC motors using electronically commutated (EC) or permanent magnet (PM) motors as well as switched reluctance motors (without magnets but dependent on a VFD to start).

Manufacturers now produce brushless DC motors supplied by an AC/DC converter with a permanent rotating magnet and stationary electrical magnets on the motor housing. A brushless EC motor is simpler than a brushed motor because it eliminates the complication of transferring power from outside the motor to the spinning rotor. EC motors have an external rotor with a cup-shaped housing and a radially magnetised permanent magnet. Advantages of brushless motors include longer life spans, little maintenance, smaller sizes and higher efficiency. Disadvantages include high initial cost for magnets and more complicated motor-speed controllers.

Applications of smaller motors in pumps and direct-driven fans have experienced rapid development of high-efficiency products in the marketplace (Figure 17). EC motors are being found increasingly in HVAC systems. Their main advantage is their ability to adapt speed and torque to the necessary flow.

Figure 17: High-efficiency EC motors from 0.1 kW to 10 kW for fans



Source: ebm-papst UK, Ltd.

Many new motor technology ideas are known in miniature laboratory editions of 0.1 W to 10 W (*e.g.* homopolar, ball bearing, ultrasonic, piezo, etc.), which use novel electromagnetic and piezoelectric phenomena. None of the schemes are ready to be developed in industrial sizes or regular factory use, but many special applications of small motors (such as photographic cameras, wrist watches, etc.) use such devices. Future applications of high temperature superconductors include electric motors up to megawatt sizes for vehicle propulsion, as in linear motor Maglev trains, cars or ships (Kalsi *et al.*, 2005) or in wind power generators. Superconductivity is sensitive to moving magnetic fields, so applications that use alternating current (*e.g.* transformers) will be more difficult to develop than those that rely upon direct current.

Gears and transmissions

Motor systems experience losses in other mechanical components. Gears and transmissions are two mechanical elements which offer significant potential for improved efficiency. In motor efficiency of around 100 kW output, just two percentage points separate one motor efficiency class from the next. This means it can be easier or more cost-effective to change transmissions and gears to achieve the same overall performance improvement. In efficient motor systems, artificial flow reducers (such as dampers, throttles, bypasses, etc.) should be avoided; they are not treated here.

Table 22: Gear efficiency

Gear type	Normal ratio range	Pitch line velocity (m/s)	Efficiency range
Spur	1:1 - 6:1	25	98% - 99%
Helical	1:1 - 10:1	50	98% - 99%
Double helical	1:1 - 15:1	150	98% - 99%
Bevel	1:1 - 4:1	20	98% - 99%
Worm	5:1 - 75:1	30	20% - 98%
Crossed helical	1:1 - 6:1	30	70% - 98%

Source: Roymech, 2009.

Gears are used in some applications to convert motor speed to the required speed. Some types of gears (worm gears with very high gear ratios) can be very inefficient: the larger the gear ratio (relationship of the two revolutions per minute [rpm]) and the more gear stages used, the lower the efficiency. Gear losses come from tooth friction and lubrication churning. Losses tend to be between 2% and 12% higher in new gears until the teeth are smoothed. High gear losses can be avoided by using a motor with a pole number and respective speed closer to the desired rpm of the driven equipment. If the gear is not used to provide maximum torque at low speed, a VFD can be used instead. In many newer applications, gears are avoided by an integrated direct-drive, direct coupling of a motor to a machine (pump, fan, compressor, etc.), thereby eliminating any intermediary mechanical element.

Figure 18: Two transmission systems: roller chains and synchronous belts

Source: Gates Corporation, 2006.

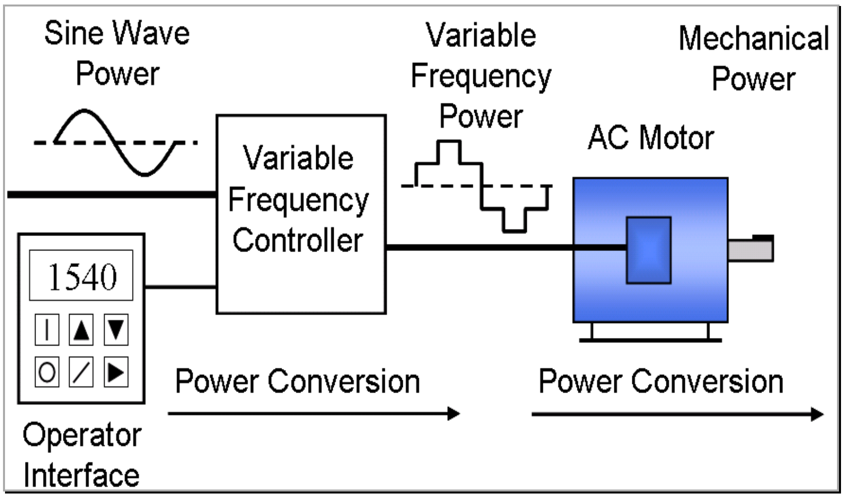
Transmissions are used in some applications to adjust the motor speed to the machine and to allow some soft connection between the two to allow for vibration etc. The traditional V-belt has maximum friction but also high losses. It stretches in use and increases its slip. Its efficiency is around 95% to 98% when new and then drops to 93%. So-called synchronous belts are toothed and require a toothed drive-sprocket. They reach and maintain 98% efficiency. Flat belts can do the job with far lower friction losses and reach 98% to 99% efficiency. Recent developments in flat-belt technology have overcome the drawbacks of high tension and mistracking. New designs and advances in materials have made both low- and high-power transmission practical and cost-efficient, at speeds that usually exceed other belt designs. Roller chains made from steel can make transmissions at around 98% efficiency. As for gears, in many newer applications, transmissions are avoided by an integrated direct-drive, direct coupling of a motor to a machine (pump, fan, compressor, etc.), eliminating any intermediary element.

Motor control technologies

Variable loads and VFDs or ASDs

Many motor applications have high operating hours but variable loads. Even with the relatively flat efficiency curve of larger IE3 motors (between 50% and 125% load), there are still large gains to be made by adapting motor speed and torque to the required load. The largest benefit comes with pumps and fans in closed loops for which power consumption varies as a cubic power of their rotational speed. In traditional equipment, the load adjustment is made by introducing artificial brakes (control valves, dampers, throttles, bypasses, etc.). In air-conditioning systems, the temperature and flow control of pumps and fans can be achieved with VSDs, reducing on/off cycles and providing a more stable indoor climate. In constant torque loads such as air compressors and horizontal conveyors, an adjustable speed control also has efficiency benefits by running the system with modulation more stably than with on/off cycles. Traditional speed and torque control uses either two-speed or multi-speed motors, with several motors working in parallel or with changing gears (step or continuous). Electrical switching (star/triangle) or other methods are also used. Early on, DC motors were used to alter speed continuously, but they are used less nowadays because of increased wear (brushes).

Figure 19: Schematic variable-frequency drive



Source: Wikipedia, 2009.

The control technology used for adjusting motor, voltage and frequency to deliver only and precisely the required torque and speed is an electronic controller known as a “variable-frequency drive” (VFD) (Figure 19). This independent component lies between the grid and the motor and consists of an AC/DC converter, a DC link and filter, and a DC/AC inverter. The VFD is mostly based on pulse width modulation. It has power demand in both standby and subsequent variable operational modes, so additional losses of a VFD have to be over-compensated by reducing losses in partial load.

Many of the new motor technologies operate with variable speeds. This means that they electronically adapt the speed rather than being based on a fixed-speed design with 2, 4, 6 or 8 poles. Advanced adjustable-speed controllers offer two energy-efficiency advantages:

- They can eliminate the major source of partial-load losses, such as mechanical resistance elements (throttles, dampers, bypasses).
- Adjustable-speed and torque systems can be used for direct drive, eliminating unnecessary components such as gears, transmissions and clutches, and reducing cost and losses.

Many mechanical systems in industry, infrastructure and buildings operate with variable load. A key element in improving energy efficiency and system integration is dealing efficiently with variable load, typical of many applications. This means that the motor speed (rpm) and/or torque (Newton metre [Nm]) should be adjustable to the immediate condition as determined by temperature or pressure differences, required flow of volume and mass, process and traction speed, etc. Depending on the application, the adaptation of the motor load to the necessary speed and torque can be made using several traditional or more advanced electronic controller technologies such as VFDs. The addition of a VFD adds considerable potential for improved energy efficiency in many electric motor systems. The VFD has additional costs -- typically equal to or larger than the higher-efficiency motor). It also has some additional losses, depending on size and quality, typically 2% to 5% at nominal torque and speed, and 10% to 30% at 25% torque and speed. The application therefore requires careful analysis.

Applications for ASDs

Three basic types of application exist for ASDs (De Almeida *et al.*, 2009):

- **Pumps, fans and similar equipment with changing loads**, for which torque increases approximately with the square of the change in rotational speed of the motor. Many of these applications are controlled with mechanical dampers, throttles and bypasses. The mechanical load on the motor will change with approximately the cube of the change in rotational speed. The VFD (or an EC motor) can adjust the electric power input smoothly and continuously to the required flow volume, which reduces the losses in partial load accordingly. Traditional load control with multi-speed motors, parallel-operated multi-motor schemes (pump, fan, etc.) or mechanically adjustable fan propeller blades are to be considered – if they can do the job with lower costs and fewer losses.

  The cost and energy-efficiency benefits of a VFD in this group are high because the electric power increases with speed and a smooth adaptation to the real need is possible.

- **Escalators, hoists, cranes and similar types of equipment,** where torque is more or less independent from speed. The VFD (or an EC motor) can continuously adjust the speed from almost standstill to full speed without steps and can thus minimise required power at all times. Some of these applications can include regenerative braking phases in their operating cycles (*e.g.* hoists, elevators and cranes). In these cases, VFDs with active front ends may be beneficial and produce much less harmonic distortion. It must be noted, however, that active front ends produce additional losses and may require high-frequency filters to avoid electromagnetic compatibility (EMC) problems in the grid.

  The cost and energy-efficiency benefits of this second group of applications are smaller than the first group because the change of input power is only linear to the speed.

- **Equipment that has minimal changes in load and speed** but can benefit from a VFD in other ways, *e.g.* soft starting and stopping, or the requirement of an especially high starting torque. The main benefit is not in energy-efficiency improvements but in less wear of the machinery involved, a higher power factor and a reduced voltage drop in the network close to a large starting motor. Some systems allow a change to a direct drive once the nominal constant operating load is reached, which will then eliminate the VFD losses. Some more traditional technical solutions for soft-starting are less costly, but such methods do not save energy, although they may reduce peak loads and thus save on electricity tariffs.

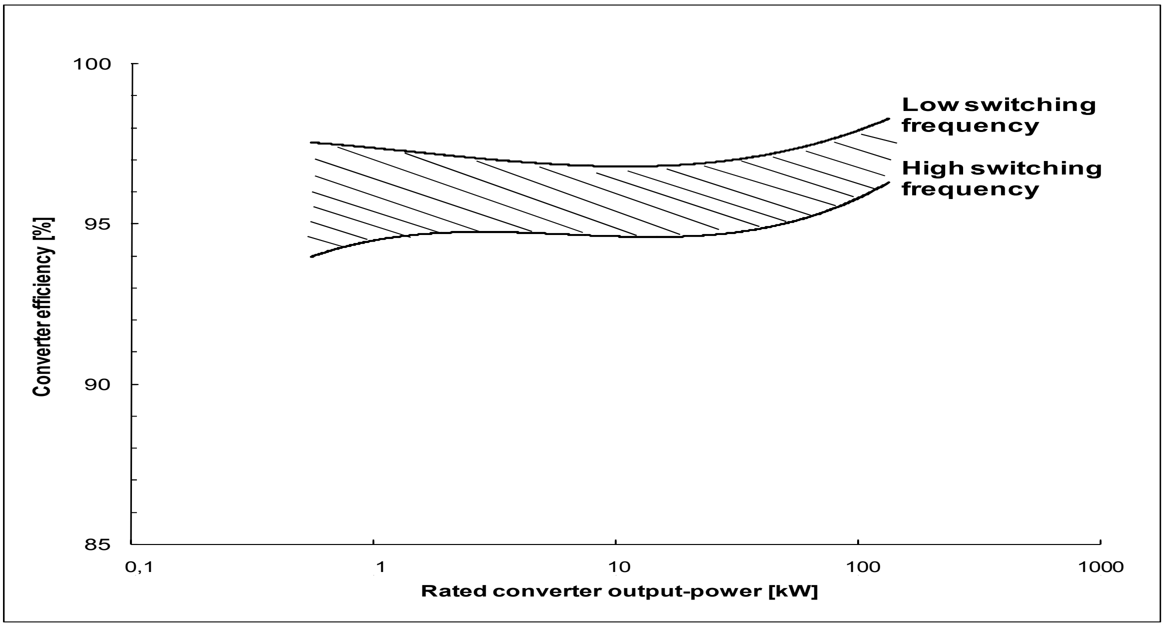
  The cost and energy-efficiency benefits of this third group of applications are small compared to the first two groups. VFDs allow for voltage optimisation to improve motor efficiency if the torque changes (even if the speed needs to remain constant). These savings may be offset by the losses due to the VFD.

In many applications, motors are oversized and run continuously in partial load (*e.g.* 50% or less). Even though a VFD can improve energy efficiency by reducing input voltage to the motor, a better sizing of the motor for the necessary load is much more cost-effective and can save even more energy. Through the use of VSDs, it is possible to avoid oversizing of motors for rarely needed, very high starting torque, which leaves motors running most of the time with low efficiency and very low power factor. The power factor can then be kept at a reasonable level.

Losses in VFDs

VFDs consume energy within their control circuits (motor control, network connection, input/output [I/O] logic controllers, etc.) and lose energy, particularly in the output switches. Today, most VFDs for low voltage (less than 1 000 V) use integrated gate bipolar transistor (IGBT) switches with pulse width modulated signals and switching frequencies between 1 kHz and 20 kHz. The losses of these inverters are relatively low (Figure 20) and their efficiency in partial load is typically better than cage-induction motors. VFDs also induce further losses in the motor due to harmonic distortion and non-sinoidal output-voltage waveform. [6] The main influencing factors on total losses are the switching frequency and the output current (which is basically associated with output power and load).

Figure 20: Typical efficiency of low-voltage, pulse-width modulated frequency converters at full load



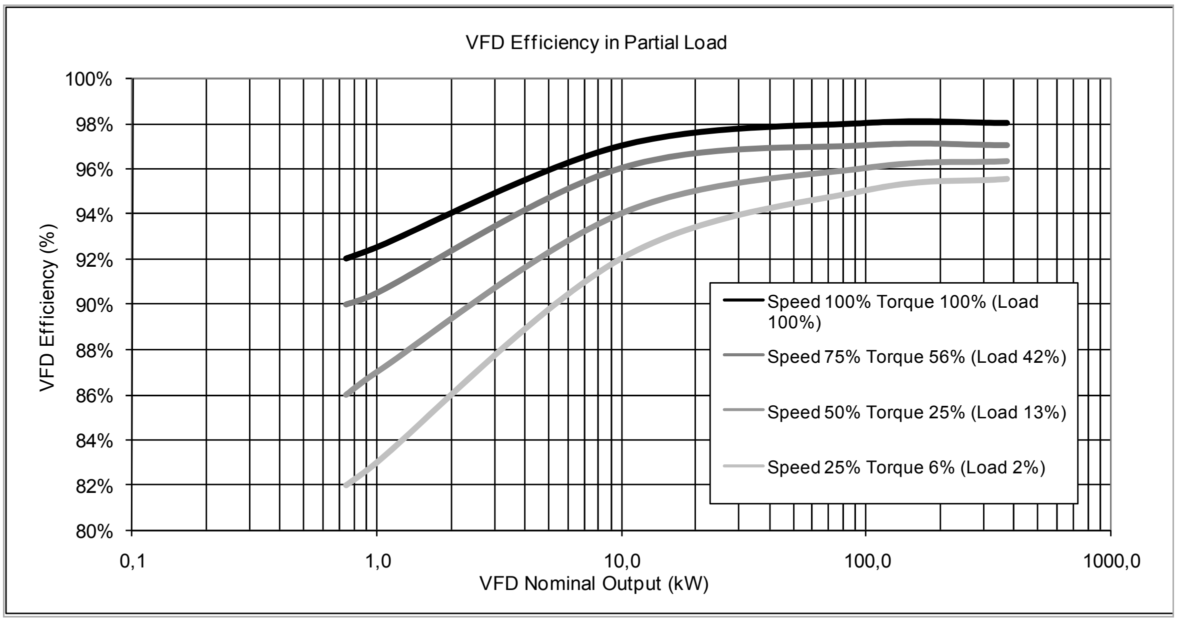
Source: Doppelbauer, 2009.

A new industry standard for VFDs has been proposed in the context of recent regulation (the EU Directive on Eco-design of Energy-Using Products [EuP]) for motors plus VFDs (De Almeida *et al.*, 2009). The goal is to have a better understanding of testing and optimising VFD use in variable load applications with asymmetrical variation of torque and speed. In general though, a VFD used for a considerable amount of time during the year either below 50% speed or below 50% torque has severe additional losses (Figure 21). In a typical application for pumps and fans (indicated with the blue square torque line), a reduction of speed (*e.g.* down to 25%) will invariably reach very low torques (only 6.3%) and thus result in a very low load (1.6%) with severe losses in

[6] I^2R losses: the energy generated or lost as heat due to the internal resistance of the battery, also known as the Joule heating effect.

efficiency: down to <50%. Thus, the correct sizing of square torque machines is still critical in order to avoid many operation hours with speeds <50%.

Figure 21: Variable-frequency drive efficiency at full and partial load



Source: A+B International, 2009.

Efficiency opportunities in different motor applications

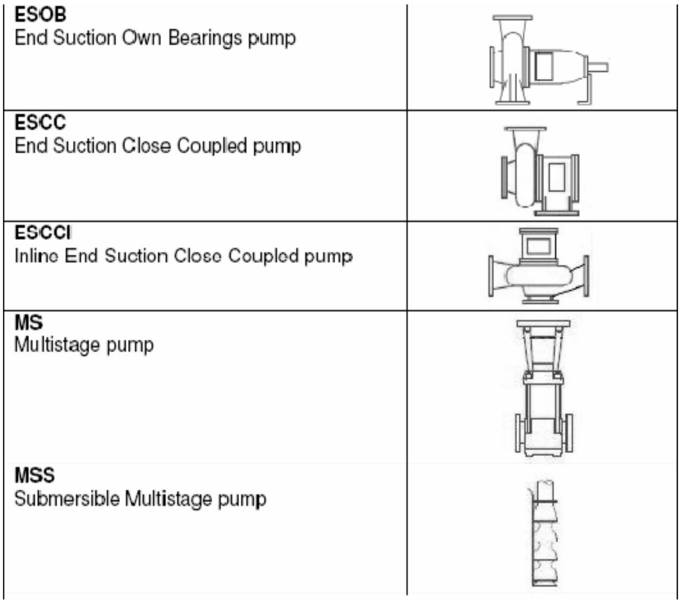
Most electric motor applications use the rotational speed and torque of a motor shaft to drive a piece of equipment. The components can be integrated (or packaged) in one unit or separated and mounted on the same base.

Pumps

Pumps are used for the transport of fluids (mostly water, drinking water, sewage, but also oil etc.) in open and closed loop systems. Pumps are available in integrated sets (size <2 kW) and separately with motors and pump wheels, which are assembled at the place of application. General applications for pumps include:

- **Building technology:** pumps for drinking water, boilers, heating and cooling, sewage pumps and fire water pumps.
- **Infrastructure:** pipelines for oil, urban distribution of drinking water and sewage, district heating and cooling.
- **Industry:** clean and sewage water systems, process fluid pumps (oil, chocolate, etc.), hydraulic pump systems.

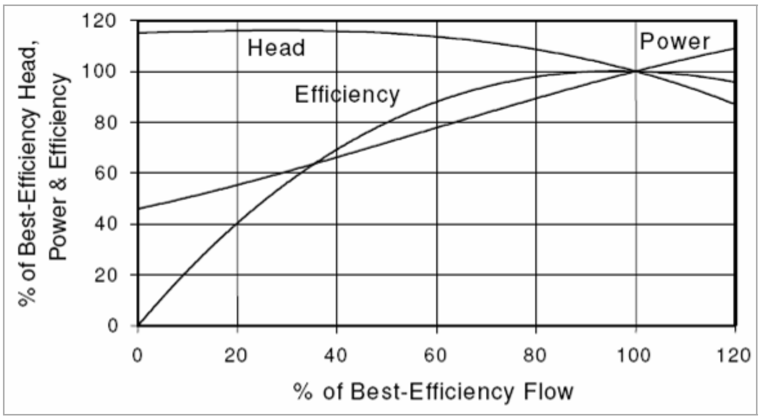
Figure 22: Five major pump types (typical pump configurations)



Source: Falkner, 2008a.

In 2008, in the context of EuP Lot 11, AEA Technology developed a detailed assessment of pump typology, according to transportation system and energy-efficiency potential (Figure 22). The efficiency of pumps varies with size (flow, diameter, power) and type of fluid. A major impact is the operation point versus the optimal point (Figure 23). Constant flow systems can be sized close to the maximum efficiency point. In most applications with variable load, the pump has to work with changing flow and pressure, and therefore moves away from optimal efficiency (Figure 25).

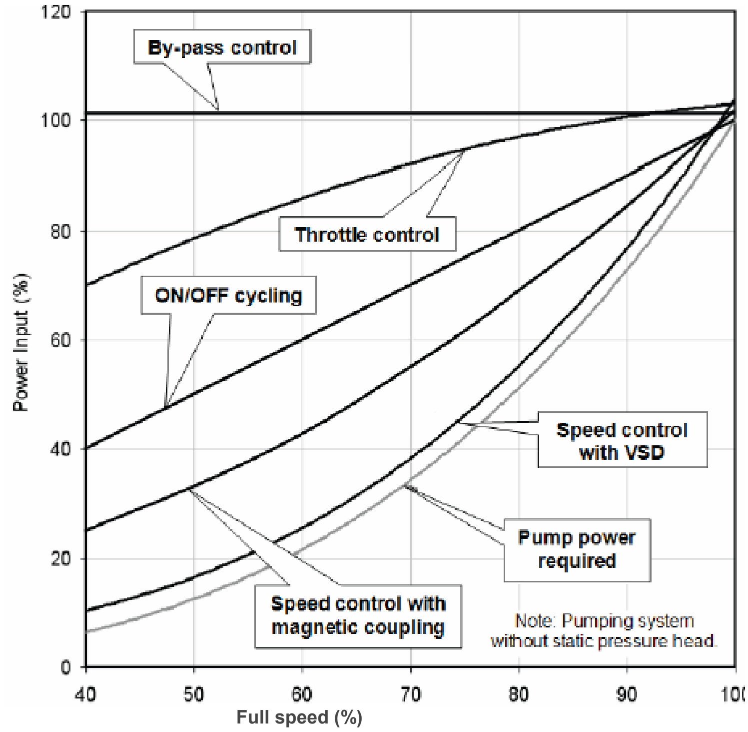
Figure 23: Efficiency of single-stage pumps according to variation of head and flow



Source: EuP Lot 11 pumps, Falkner 2008a.

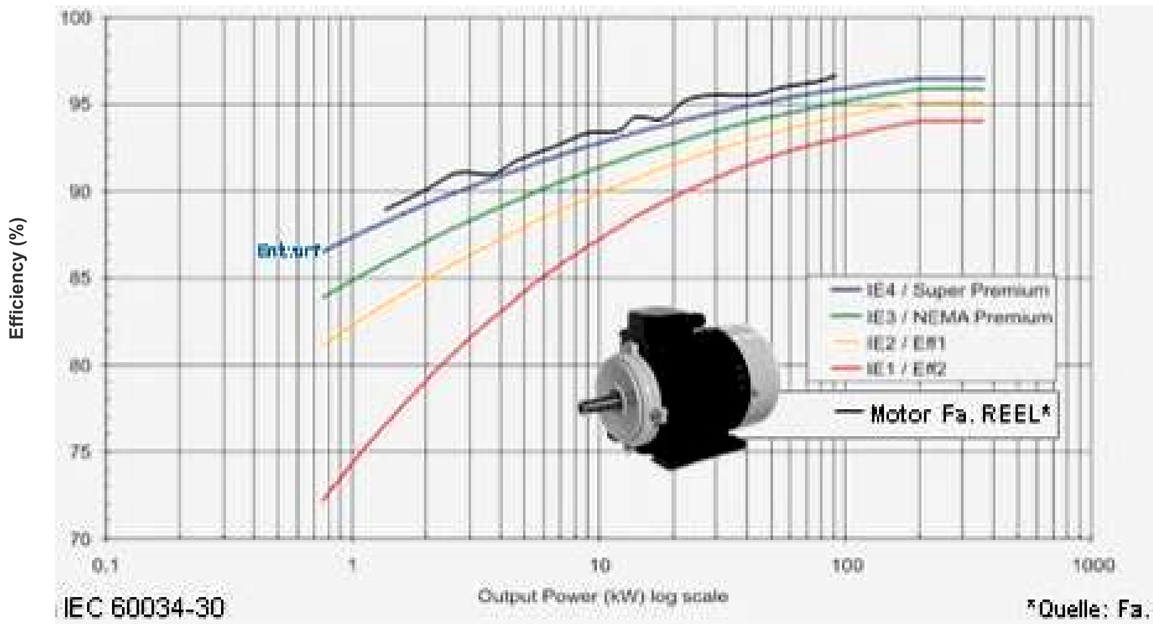
In 2009, a manufacturer of pumps announced Super Premium pumps having a drive rating of up to 45 kW with integrated IE4 EC motors and dynamic pressure set-point compensation technology (Figure 25). The drive is claimed to save considerably more energy under part-load conditions than variable-speed systems that maintain a constant set point. An additional optional module enables the two drives to communicate with each other, allowing the user to operate two pumps at the same time with integrated sequencing control. A display permanently shows the actual speed and allows the user to adjust speed and other set points locally. A proportional-integral controller, as well as digital and analogue inputs and outputs for standard signals, support all the typical pump control modes. Motor protection functions are included as standard features.

Figure 24: Energy savings with speed control for a centrifugal pump without static pressure head



Source: Ferreira, 2009.

Figure 25: High-efficiency electronically commutated motor for pumps



Source: KSB/REEL, 2009.

An exemplary study of two optimal pump systems demonstrates that if all available state-of-the-art efficiency measures of a pump system are systematically applied, energy-efficiency savings of 80% to 90% can be achieved in heating-system circulator pumps and of 40% to 75% in industrial-size pumps. Key improvements come from larger pipe sizes, PM motors with a VFD (Figure 27) and correctly downsized pumps.

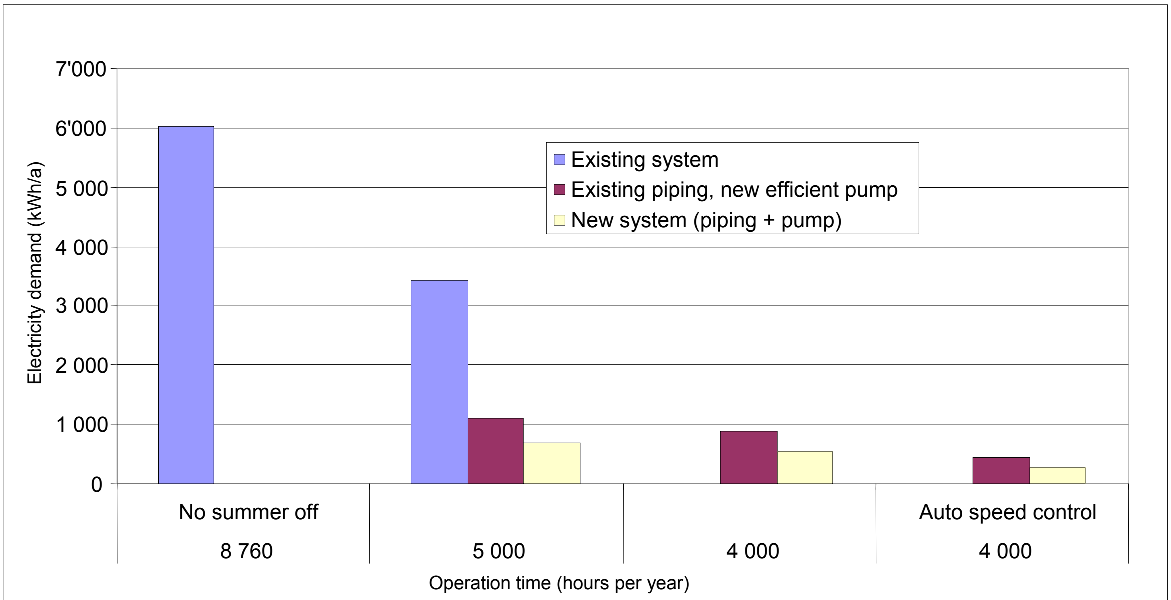
Figure 26: Glandless circulation pump with EC motor and automatic power adjustment

Source: Wilo.

Piping size (including fittings, valves, etc.) in existing equipment or plant cannot normally be changed. It is therefore extremely important to choose the optimal size when planning a new installation. In existing systems, parts of the piping may be downsized when these parts are replaced or added to existing equipment. New pumps, especially when smaller than the existing one, may have smaller connections (flanges), resulting in additional costs for adaptation. These have to be accounted for, but energy cost savings will not normally be strongly affected. In industry cooling or heat recovery circuits, heat exchangers may cause high pressure drops. The occasion of a system review or an extension should be used to study the replacement of heat exchangers by low-pressure types, or by the mounting of small extra pumps for high-pressure heat exchangers.

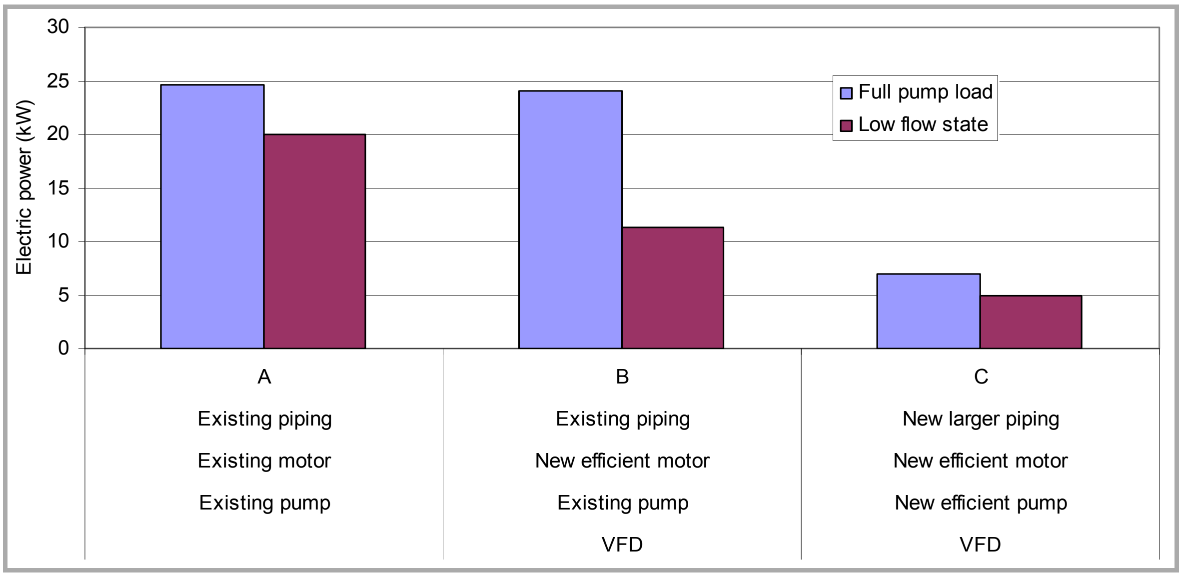
Optimal pump systems offer significant potential energy savings in both in domestic heating circulators and in industrial-size pump applications (Figure 27, Figure 28, Table 23 and Table 24).

Figure 27: Electricity savings of circulator pump in heating system



Source: Nipkow, 2009.

Figure 28: Reduced electric power use in industrial-size pump system



Abbreviation: VFD = variable-frequency drive.

Source: Nipkow, 2009.

Table 23: Comparison of annual electricity use in circulator pump systems

Circulator pump in heating system		Units	Existing system	Existing piping, new efficient pump	New system (piping + pump)	New pump /old	New system /old
Flow necessary for 150 kW heating load		m3/h	10	10			
Head (pressure drop)	Piping "standard" diameters	kPa	50	50			
	Piping, larger diameters (+1 nominal width step)	kPa			25		50%
Hydraulic power needed (full load)		W	139	139	69		50%
Pump selected/set in practice, hydraulic power		W	220	140	70		
	Oversizing (setting resp.)		158%	101%	101%		
			Old pump, low efficiency	A-class pump (permanent magnet motor, speed controlled)			
Glandless circulator overall efficiency, best operating point			38%	63%	63%		
	Real operating point		32%	63%	51%		
Electric power		W	688	222	137	32%	20%
Electricity consumption	(heating systems)						
	8 760 hours (no summer switching)	kWh	6 023				
	5 000 hours	kWh	3 438	1 111	686	32%	20%
	4 000 hours	kWh		889	546	26%	16%
	4 000 hours and auto speed control	kWh		444	275	13%	8%

Source: Nipkow, 2009.

Table 24: Comparison of annual electricity use in industrial-size pump systems

Pump in industry application	Units	Existing system	Piping as existing, new motor, VFD (if applicable)	New system (piping+heat exch.+pump +motor/VFD)	New motor (VFD)/old	New system /old
Flow necessary for plant	m^3/h	170		170		100.0%
Head (pressure drop) piping + heat-exchange "standard"	kPa	300				
Piping + heat-exchange "optimised"	kW			130		
Hydraulic power needed (full load)	kW	14.2		6.1		43.3%
Pump selected in practice		Grundfos NB/NK 100-315 4p 50Hz/imp.334	Grundfos NB/NK 100-200 4p 50Hz/impeller 219			
Resulting flow without VFD	m^3/h	185		173		
Resulting head	kPa	355		138		
Resulting hydraulic power	kW	18.2		6.6		
Over-sizing of pump power		29%		8%		
Motor P2 out of pump diagram	kW	22.4		7.7		
Selected	kW	30	22	7.5		
Oversizing		34%	-2%	-3%		
Efficiency, IE1		90.7%				
Efficiency, IE3			93.0%	90.4%		
P1, full pump load	kW	24.70	24.09	6.96	97.5%	28.2%
Flow variations, VFD "Low flow" state, 75%	m^3/h	128	128	128		
Resulting head	kPa	384	200	75		
P2	kW	18	9.5	3.8		
Motor efficiency (part load)		90%	88%	82%		
VFD efficiency			95%	93%		
P1, low flow state	kW	20.00	11.36	4.98	56.8%	24.9%

Abbreviation: VFD = variable frequency drive.

Source: Nipkow, 2009.

Fans

Fans are used for transport of gas (mostly air) in industrial, commercial and residential applications in open-loop and closed-loop systems. Fans are sold in integrated systems as fan sets (up to 2 kW) and separately in motor plus fan wheels that are assembled on site only. General applications for fans are:

- **Building technology:** ventilation fans for supply, exhaust and air recirculation, air supply and in combination with heating, cooling, humidifying and dehumidifying systems.
- **Industry:** blowers for heating, cooling and drying and clean room ventilation.
- **Traffic:** tunnel ventilation.

A state-of-the-art analysis of fan technology according to flow direction (cross, axial and centrifugal flow) and efficiency potential was made by Radgen (2008) in EuP Lot 11. The efficiency of fans varies with size (flow, diameter, power) and type of gas. A major impact is the operation point versus the optimal point. Constant flow systems can be sized close to the maximum efficiency point. In most applications with variable load, the fan has to work with changing flow and pressure and moves away from its optimal efficiency. Only large fans with adjustable blades (tunnel ventilation) can avoid this.

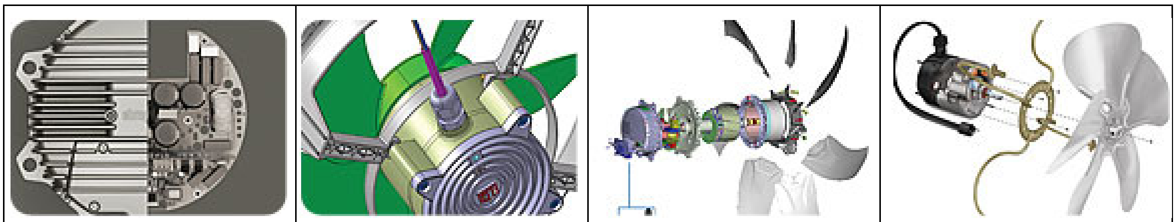
Table 25: Major fan product categories and characteristics

Product category	Direction of flow	Type	Typical sizes (mm)
1	Axial	≤300 Pa (static pressure)	200 - 1 400
2		>300 Pa (static pressure)	200 - 1 400
3	Centrifugal	Forward curved blades (with casing)	120 - 1 600
4		Backward curved blades (no casing)	120 - 1 600
5		Backward curved blades (with scroll housing)	120 - 1 600
6	Other	Box fans	100 - 1 000
7		Roof fans	250 - 1 000
8		Cross-flow fans	60 - 120

Source: Radgen, 2008.

In 2008, several manufacturers from Germany, Italy and the United States introduced fan products with high-efficiency EC motors (Figures 29 and 30). This development encompasses products with an output of 0.01 kW to 10 kW that can be produced in millions. The major energy-efficiency benefit from using EC technology comes from lower losses in partial-load operation.

Figure 29: EC motors for fans



EC fan motors feature completely integrated electronics (ebm-papst).	EC motors can drive 15 cm to 25 cm fans and feature efficiencies of up to 70% (Elco).	1.1 kW EC fan motor with integrated electronics and fan blade (ebm-papst).	EC motors work with pulse width modulation (GE EC motor by Regal Beloit).

Abbreviation: EC = electronically commutated.

Source: Adams, 2008. Reproduced with permission of Appliance Design/BNP Media.

The energy consumption of a fan is calculated as:

Equation 4:

$$E = \frac{h \cdot V \cdot \Delta p}{\eta_F \cdot \eta_M \cdot \eta_D \cdot \eta_C}$$

E	electric energy consumption
H	running hours
V	air flow
Δp	pressure difference
η_F	efficiency of fan
η_M	efficiency of motor
η_D	efficiency of drive
η_C	efficiency of control

In a given duct system, the following basic rules are true:

Pressure difference

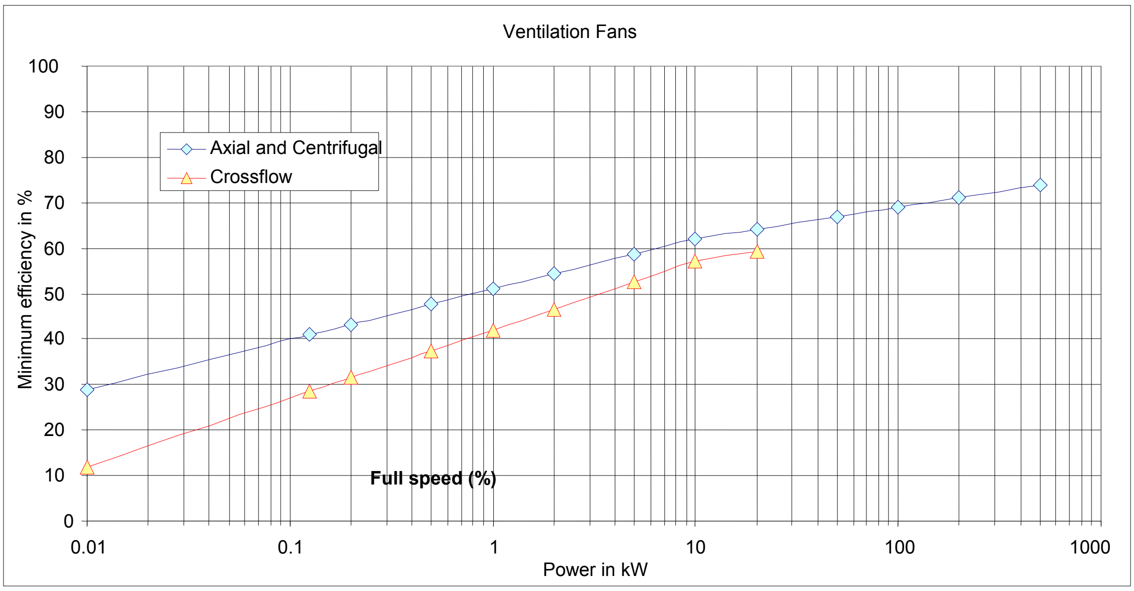
$$\frac{\Delta p_1}{\Delta p_2} = \left(\frac{V_1}{V_2}\right)^2$$

Power

$$\frac{N_1}{N_2} = \left(\frac{V_1}{V_2}\right)^3$$

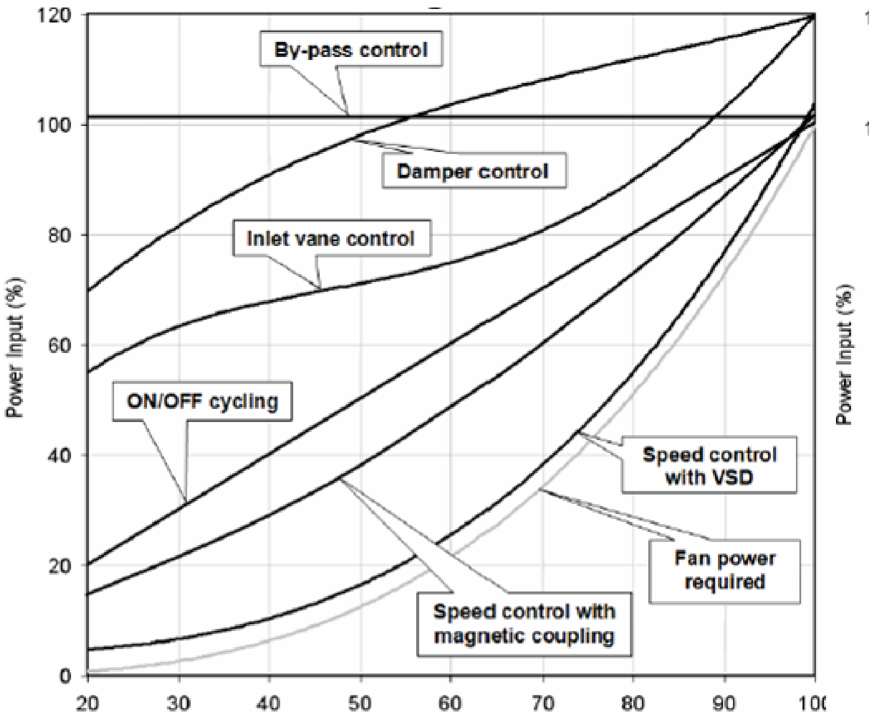
Reducing air flow to meet real needs achieves a large reduction in energy demand. With an air flow of 50% in a given system, the pressure difference decreases to 50% and the power needed is 12.5%. State-of-the-art efficiency measures available for a fan system can be systematically applied.

Figure 30: Future EU minimum energy performance standards (MEPS) for fans/ventilation



Source: Steinemann, 2008.

Figure 31: Centrifugal fans: energy savings with different methods of air-flow control



Source: Ferreira, 2008.

Over the course of the European Commission discussions on standards for fans, the criteria for axial, centrifugal and cross-flow fans were covered. Eventually, the best air-movement technology with the best blade type should prevail for each size. The types of fans that best demonstrate this potential are centrifugal fans with a backward curved blade and axial fans (Figure 31 and Figure 32).

Table 26: Measures and potentials for reducing the energy demand of fans

Running hours	A fan should only be run when it is required and the air flow should be adapted to real needs. The saving potential is up to 100%.
Air flow	The installation should be designed for real needs. Design and control of the system should consider cases with variable requirements. The saving potential is up to 80%.
Pressure difference	Low pressure differences can be achieved at low velocities (bigger duct cross areas), short duct systems and good aerodynamic layout. This goes together with lower sound levels, but higher investment costs and space are required for the installation. The savings potential is 50% and more.
Total efficiency	The best available technology could significantly increase total efficiencies for fans, motors, drives and controls. The savings potential is up to 50%. As a frequency control always causes an additional loss, this technique should be applied only when needed. Then the benefit is much higher than the additional loss.

The energy demand of fans is strongly dependent on the design of the entire installation and the components, as well as on the running conditions of the fan system (Table 27).

A study for an optimal-supply air fan system found that the use of optimal design and technology reduces energy consumption by a factor of 8, and that combining this with better time management reduces energy consumption by a factor of 62. Table 27, Figure 32 and Figure 33 show several optimisation steps, including reducing operation time, controlling motor efficiency and partial-load flow control with a VFD, and reducing speed and pressure with better ducting. In Table 27, electric power consumption of the best option (D) is compared with that of a continuous operation base case (option A).

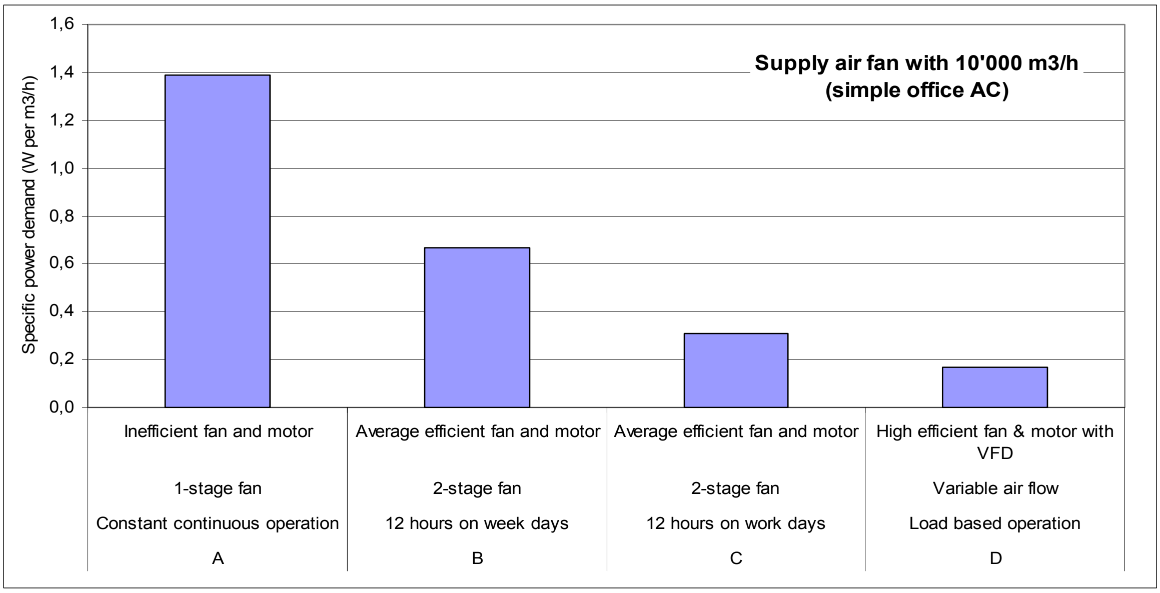
Table 27: Optimisation study of a fan

General characteristics		A	B	C	D
		Constant continuous operation 1-stage fan Inefficient fan and motor	12 hours on week days 2-stage fan Average-efficiency fan and motor	12 hours on work days 2-stage fan Average-efficiency fan and motor	Load based operation Variable air flow High-efficiency fan and motor with VFD
Variation of flow		Constant load	Constant with on/off time-switch with week programme	2-stage operation with factory control system with calendar	Variable load operation (*e.g.* CO_2 for people presence and activity)
Ventilation					
Level 4	%	100	100	100	100
Ventilation					
Level 3	%	0	0	50	80
Level 2	%	0	0	0	60
Level 1	%	0	0	0	40
Air volume					
Level 4	m^3/hour	10 000	10 000	10 000	10 000
Level 3	m^3/hour	0	0	5 000	8 000
Level 2	m^3/hour	0	0	0	6 000
Level 1	m^3/hour	0	0	0	4 000
Daily operation					
Level 4	hours/day	24	12	6	2
Level 3	hours/day	0	0	6	4
Level 2	hours/day	0	0	0	4
Level 1	hours/day	0	0	0	2
Daily operation	hours/day	24	12	12	12
Annual operation					
	days/year	365	260	220	220
Pressure difference (flow, speed and resistance)					
Level 4	Pa	2 000	1 200	700	460
Level 3	Pa	0	0	175	294
Level 2	Pa	0	0	0	166
Pressure difference (flow, speed and resistance)					
Level 1	Pa	0	0	0	74

Abbreviation: VFD = variable-frequency drive.

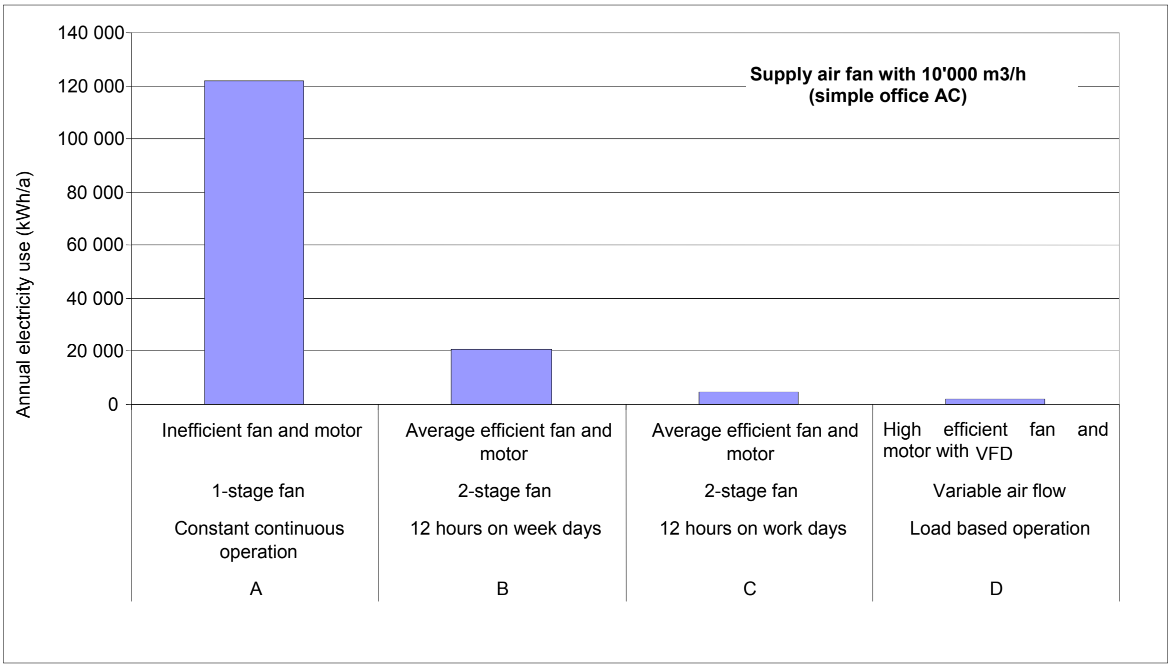
Source: Steinemann, 2009.

Figure 32: Fan efficiency potential — reduced specific power



Abbreviations: AC = alternating current; VFD = variable-frequency drive.
Source: Steinemann, 2009.

Figure 33: Fan efficiency potential — reduced annual electricity use



Abbreviations: AC= alternating current; VFD = variable-frequency drive.
Source: Steinemann, 2009.

Compressors

Compressors are used in the following three electric motor-system applications: air compressors for compressed air, liquid natural gas, gas transport, etc.; cooling compressors; and heat pumps. Their application is predominantly in the following sectors:

- **Appliances:** refrigerators and freezers for commercial and domestic use (beyond the scope of this study), generally fully enclosed cooling compressors with <0.2 kW.

- **Building technology:** cooling machines for central air conditioning (0.5 kW to 500 kW and more); room air conditioners (0.2 kW to 5 kW); pneumatic systems for motion control.
- **Industry:** process cooling systems with temperature ranges from ambient temperature down to -30 °C (food industry) and more; compressed-air systems for material handling.

Compressor technology uses reciprocating, rotary screw and centrifugal systems. Most compressors come in packaged systems in which the motor and the compressor are in a full- or semi-hermetic enclosure. Many compressor systems run in an efficiency range of only 5% to 10% (Table 28).

Table 28: Example of losses in a compressed-air system

Source of power loss	Transferred "useful" power (kW)	Power loss (kW)
Electrical power input	100	
Air from compressor	10	90 (heat)
Treatment	9	1 (*e.g.* filter pressure drop)
Leakage	6	3 (leakage)
Distribution system	5.5	0.5 (*e.g.* excess pressure drop)
Over-pressure	5.0	0.5 (heat)

Source: Falkner and Slade, 2009.

Many compressed-air and pneumatic control systems can be replaced by more efficient systems such as electric servo or linear motors. Very large international companies design, manufacture and sell large volumes of standard compressor packages, and this industry is moving very slowly to introduce new and advanced energy-efficient compressor systems. PM motors and VFDs are very powerful ways of making both cooling and compressed-air systems run more smoothly and efficiently.

Other applications

Industrial and commercial use of electric motors falls into several categories:

- **Transport of goods and people**[7]:
  - vertical (elevators), sloped (conveyors), horizontal (walkways etc.)
  - cranes and hoists
  - robotics for assembly
- **Material process*ing:***
  - mixers, crushers, cylinder rollers, injection moulding, extruding, etc.
  - temperature treatment (in combination with resistance heating, fossil heat and cooling system)

The motors used in the applications above are often part of larger production machines that are a combination of many motors and drives, and also have thermal treatment installed. The energy used by such motors is only significant when they run continuously or have frequent intermittent operation characteristics that amount to >1 000 hours per year of operation and more.

[7] Not covered in this study: electric motors in vehicles; electric vehicles, e.g. electric cars, vans and bikes; traction in transportation systems, e.g. tramways, trains, cable cars, etc.; auxiliary systems used in private cars and trucks, busses, trains, airplanes.

Related energy-savings opportunities

Engineering practice improvement

An electric motor converts grid electricity into mechanical power, usually in the form of a shaft delivering torque at a defined rotational speed to an application machine. The electric motor is correctly described in terms of physics as a converter of electrical into mechanical energy. The energy consumed by the motor represents the losses inherent in the motor and other mechanical and electrical components while delivering a 100% mechanical output. The main focus of engineering practice improvement is the reduction of losses in EDMS, but within this definition the 100% net mechanical energy used must also be scrutinised for sub-optimal applications and operation without any use and in idle conditions.

Table 29: Areas of energy efficiency in electric motor systems

		Involved equipment	Improvement possibilities
1	Electric input and conversion	Factory automation	Efficient low-voltage supply, low energy mode during standstill
		Transformation	Use efficient transformers
		Power factor compensation	Use motors with high power factor and use efficient power compensation
		Voltage 3 phases	Balanced voltage
		VFD	Properly sized, programmed and efficient VFD, use active end VFD
		Motor	Efficient, properly sized motor
2	Mechanical transformation	Throttle, damper	Avoid mechanical load management
		Clutch	Try direct drive, avoid worm gear
		Gear	Use efficient gearboxes
		Valves	Use fully open valves with wide gauge
		Transmission	Try direct drive, avoid V-belts and chains, use flat or synchronous belts
		Brake	Use efficient brake, try active braking
3	Application	Low volume	Avoid unnecessary high flow volume and mass
		Low speed	Avoid unnecessary high speed, increase pipe and duct size
		Low pressure	Avoid unnecessary pressure due to bends, use full size heat exchangers, valves, filters, etc.
4	Operation and maintenance	Shorter time	Avoid unnecessary operation time without use: factory automation with automatic load control/off
		No idle time	Avoid idle time: automatic load control/off
		Maintenance	Use regular maintenance for motor and mechanical components
		Rewinding	If not replacement: Try quality rewinding
		Replacement	Preventive maintenance and planned replacement
		Metering	Install and use system operation metering

Abbreviation: VFD = variable-frequency drive.

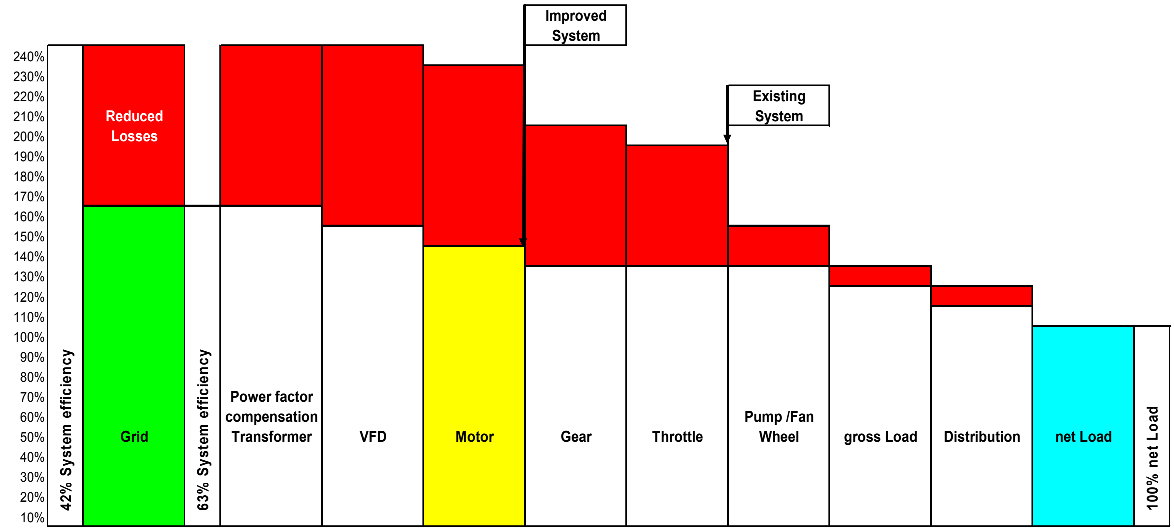
The major element for improving electric-motor system efficiency is better engineering practices in the following areas:

- Life-cycle cost: consider avoiding minimal first cost, decisions on repair versus replacement.

- Integrated machine design: OEMs tend to focus on production at low initial cost rather than efficiency.
- Packaged products: component integration to avoid the addition of maximised separate elements.
- Adequate sizing: calculated safety factors to avoid general oversizing practice.
- Efficient operation: factory automation systems with precise on/off and partial-load controls to avoid hours of operation without any use.

The largest benefit in energy-efficiency improvement comes from a systematic integration and optimisation of all mechanical and electrical components in a total motor system. Four major areas are involved (Table 29). As illustrated in Figure 34, motor-system efficiency can be improved from 42% to 63% or the total required grid peak load can be reduced from 240% to 160% of the net mechanical load. The improvement (red surface) results from several individual and consecutive improvement steps.

Figure 34: Systematic elimination of losses in an optimal drive system



Source: A+B International, 2009.

Designing the total motor system (the entire application from supply grid to output product) is a complex task. To achieve cost-effective installations and machines that operate safely and reliably, the engineering approach must set high targets for energy efficiency and apply an integrated design model. It is important to question production demands (capacity, speed, and environment) before selecting technical components.

Integrated machine design

Motors are often part of a highly complex industrial production system. OEMs design machines for cement, plastics, metals, nutrition, textiles etc., that include heating and cooling as well as linear forces and rotational torque. Many machines have an array of different motors, some working continuously and others having auxiliary functions (such as only on/off or short periods). Many OEMs tend to invest heavily in production performance; few invest in energy efficiency. To keep their machine price low they tend to use cheaper components, such as low-efficiency motors and drives. The total motor system concept has not yet become the optimisation routine of OEMs. One of the key cost-determining elements is the often vaguely known maximum performance criteria. This leads to an oversizing of many components, including motors and

VFDs. It obviously also leads to higher initial costs, but leaves the OEM in the (false) security of a reliable performance even outside the predetermined margins.

Packaged products as core motor systems

Motor manufacturers often integrates the motor, gearbox and VFD with sensors together with a fan or pump wheel into one packaged product, as a core motor system. This approach has several advantages:

- Total **product costs** are lower because designs are matched and no transmissions are needed.
- Total **volume of product** is less because no space is lost for couplings and other connectors.
- **Machines** are optimised because components are matched and perfectly aligned.
- **Performance** is better because packaged machines run more smoothly with less wear.
- **Torque and speed control** can be adapted to required performance with standard programmes and features.

Some manufacturers produce many or all of these components in-house. Others work in alliance with component manufacturers and eventually sell integrated packages. Overall, this is a market-development tendency, particularly in the range up to 30 kW.

Adequate sizing

Typical inappropriately sized machines have efficiency disadvantages. With regard to electric motors, peak efficiency of high-efficiency motors (depending on motor size) is at 75% to 100% load. Below 50%, the decrease in efficiency is severe. In older applications, the efficiency peak was closer to 100% and the decrease was already below 75% load. Past engineering practices were aware of critical temperature rises in full load and overload that could damage motor insulation.

Proper sizing is, of course, an issue not only with electric motors but with other system components, (*e.g.* in applications such as pump and fan systems, in which correct size pipe or duct work minimises flow velocities and friction losses). The proper sizing of a motor system requires knowledge on all typical use stages of an entire machine. This is relatively easy for a closed-loop water-pumping system, but it can be difficult for a complex material-handling process in which charges can vary within large boundaries.

In replacement cases, good engineering practice starts the sizing with the measurement of the typical load profiles of the machine, thus deriving a necessary peak load and starting torque condition. For new machines, the design will depend on calculations based on the knowledge of the engineering handbook. In any case, a new high- and premium-efficiency motor can be sized with less safety margin because it runs cooler and can stand 10% to 20% overload (in NEMA, this is called service factor) for a couple of hours repeatedly without hitting the allowed maximum temperature rise. Proper sizing offers several advantages: motors usually run more smoothly and for longer with less wear; they have fewer losses; and they cost less than oversized motors.

Efficient operation

A well-designed motor system also must be operated properly. Efficient operation means:

- no operation without use, no idle time (factory automation has to give on/off);
- no unnecessary fast start and brakes (well-defined production cycles and intervals)
- no unnecessary long overloads (defined starting conditions, soft start, VFD-starting programme, clutch);

- regular mechanical checks (oil quality for wear, vibration for bad alignment) and maintenance (bearings, fan, dust, oil);
- regular electrical checks (electronic spikes, thermal image of motor) and maintenance (overheated windings, unbalanced phases).

Efficient operation should also include monitoring the motor system to ensure early detection of wear and failures.

5. The Economics of Energy Savings in Electric Motor-Driven Systems

Following a description and analysis of the economics of energy savings in electric motor-driven systems (EMDS), the authors define current standard practice by end-use sector and application, and provide examples of the cost-effectiveness of systems optimisation. Drawing on the analysis of electricity demand and savings potentials in Chapters 3 and 4, they analyse the likely range of economic benefits from global optimisation of EMDS.

Factors that influence EMDS economics

Considered over a 20-year service life, the initial purchase price of the motor typically represents just 1% of the total cost of ownership. An EU study shows similar findings (Figure 35). In general, electric motor-driven systems cost far more to operate over their lifetime than the initial cost of purchase.

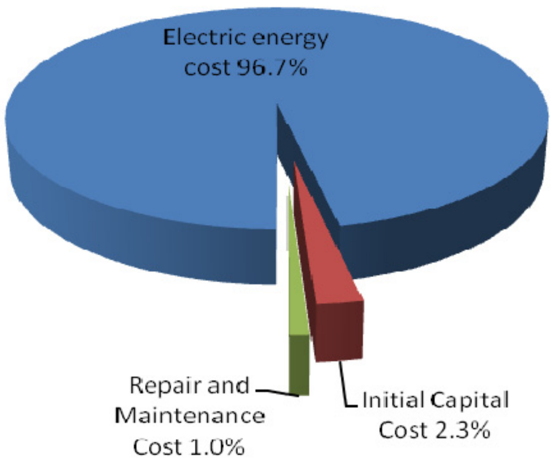
Power is the largest part of the cost of operating an electric motor. The US Department of Energy estimates power cost over the 20-year life of an electric motor to be 90% (with downtime costs estimated at 5%; rebuild costs at 4% and purchase price at 1%).

In the United States, a 200 hp pump motor running six days per week for 50 weeks per year will cost more than USD 70 000 in electricity in its first year of operation (*i.e.* seven times its initial cost). The breakdown of costs for a 200 hp, 1800 rpm, 460 V TEFC motor over a calendar year (7 200 hours of operation) is as follows:

- average cost of power assumed: USD 0.068 per kWh
- total power cost: USD 70 669
- initial purchase price: approximately USD 10 000

Thus, small gains in energy efficiency can be highly cost-effective over the lifetime of the EMDS.

Figure 35: Life-cycle cost of 11 kW IE3 motor with 4 000 operating hours per year



Source: De Almeida *et al.*, 2008b.

Engineering decision making

For any industrial system, it is essential to evaluate purchase price and operating cost to make informed decisions on continuous operation of existing systems and to plan tenders, purchase and applications of new systems. For some more efficient components, initial purchase prices are higher but running costs are lower. With proper engineering, however, it is possible to avoid some costly components. Precisely calculated components are often smaller and considerably less expensive. Cost-effectiveness is a function of the cost of the motor (market price for commodities such as copper, steel, aluminium and labour costs) and the price of electricity. In light of recent variations in copper and steel prices, the price differential may exceed the variation in price when moving to a higher-efficiency motor.

Operating costs include maintenance and energy. Maintenance costs are based on regular in-house greasing and cleaning, and regular out-house repair of worn bearings and eventual rewinding if an electrical failure has occurred in the copper wiring of the stator. By far the most important component of operating cost is electricity. In large industry transformation, equipment is generally either bought or leased and must be included in cost calculations. Consumption tariffs usually depend on annual, seasonal and daily load characteristics; they are either split into high and low tariffs or based on an average annual kWh price. The peak-power cost component can reach 30% or more, or even super-peak conditions when the supply grid is already overloaded (*e.g.* in warm summer conditions at 11 a.m.). Some power utilities then charge a peak-load premium which can be reduced with efficient motor systems or with load shedding (interruption of production). In efficiency calculations, this makes it very important to study when a motor is operating and how much it contributes to peak power reduction. Reactive power costs can be reduced with power compensation equipment.

Least life-cycle cost

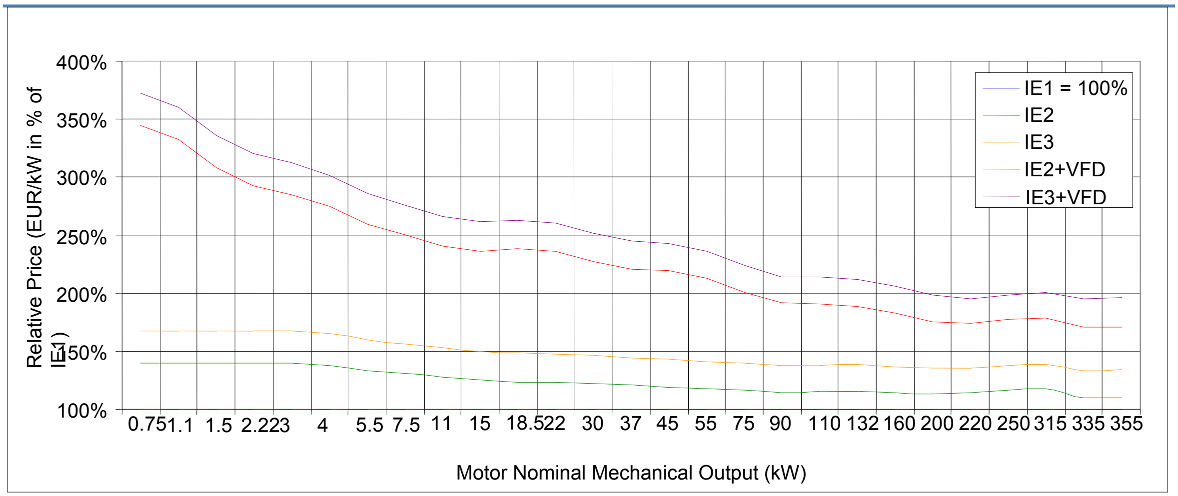
It is not yet standard engineering practice to make a life-cycle cost analysis and base investment decisions on the least cost. Doing so involves a careful estimate of operating conditions, energy and maintenance costs, taking into account the dynamics and magnitude of potential annual energy cost increases and inflation. It is much more common to make a simple payback-period analysis comparing the total cost of investment to commercial operating profits.

More efficient motors contain more active material than standard-efficiency motors and thus incur additional costs. Actual sales prices are not publicly available; they are heavily dependent on individual discount and rebate schemes based on customer volume. An annual survey in the Swiss motor market of the net purchase price in 2008 shows the following findings (Brunner and Heldstab, 2009):

- discounts seem not to vary with efficiency classes
- discounts of 30% to > 70% compared to published list prices are common
- prices tend to vary with potential purchase volume and copper price
- specific motor prices tend to be almost flat between 5 kW and 15 kW (Figure 36)
- relative motor prices for higher-efficiency classes are higher below 20 kW (Figure 36)
- additional prices for VFD are much higher than one or two additional efficiency classes (Figure 36).

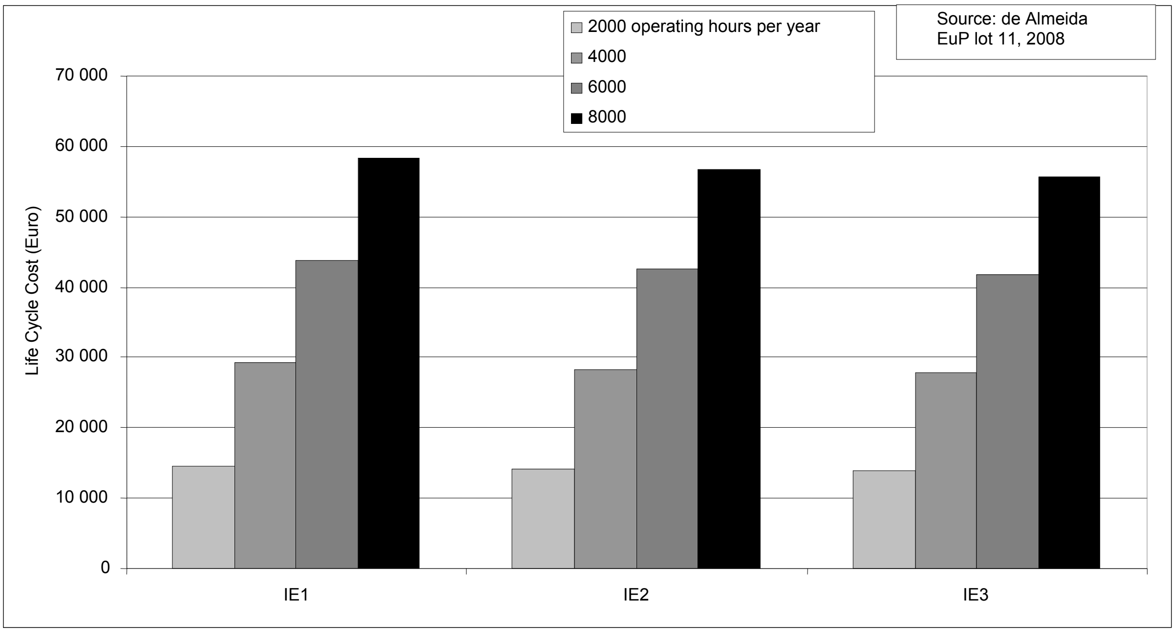
The results must be viewed with caution, because the transition between the old classification scheme (Eff1, Eff2, and Eff3) and the new IEC scheme (IE3, IE2, IE1) has not been fully digested. Many motor manufacturers still have incomplete series of Premium Efficiency products available. As long as market demand – stimulated by MEPS – does not require the IE3, no stable volume or stock is available and, as a result, no price competition exists. It is envisaged that the price premium between IE3 and IE2 and IE1 will fall and that the additional cost of VFD with standard and integrated (packaged) solutions will diminish.

Figure 36: Relative prices of electric motors with higher efficiency and variable-frequency drives, Switzerland, 2008



Abbreviation: VFD = variable-frequency drive.
Source: Brunner and Heldstab, 2009.

Figure 37: System life-cycle cost analysis of an 11 kW motor



Source: De Almeida *et al.*, 2008b.

Extensive calculations of life-cycle cost were made during the 2008 EuP technical studies (Figure 37). The cost calculation is based on purchase and installation, plus operating costs for maintenance and energy. Highlights of the analysis are as follows:

- Based on the current average European electricity price for industry (EUR 0.075/kWh), the key criterion for cost-effectiveness of Premium IE3 motors to replace IE1 or IE2 is annual hours of operation. Motors with over 2 000 hours per year are cost effective with current industry electricity prices.

- If a moderate increase of future electricity prices (EUR 0.011/kWh) is taken into account, minimal annual hours of operation to achieve cost-effectiveness with IE3 fall below 1 000 per year.
- Life-cycle cost savings are higher in smaller motors (5% to 10%) than in larger motors (1% to 2%) because the relative efficiency improvements in the smaller range are much greater.
- Typical operating hours in industry and infrastructure systems of between 4 000 hours per year and 8 000 hours per year produce bigger energy savings.
- The life-cycle cost of systems using VFDs is less than those without VFDs for those operating above 1 000 hours per year.

Repair versus replacement

Larger motors are repaired one, two or even three times during their lifetime. According to repair and winding assessments, the average motor comes out of a rewinding with a 1% to 5% lower efficiency, depending on the practice used (EASA, 2006). An old motor must first be analysed to pinpoint damage to mechanical (bearings and shaft) or electrical (stator windings), and it requires a cost-benefit assessment for every repair. After 40 000 or 100 000 operating hours (depending on motor size, speed, use and maintenance), more routine maintenance is the replacement of bearings. Replacing worn bearings, which account for the majority of motor failures, will not generally cause a loss in efficiency when the repaired motor is well installed and aligned.

If a motor has electrical damage (from overload, vibration, electric short circuits, overheating, damaged isolation, etc.), a serious rewind routine must be established. Crude practices to remove old windings from the stator and burn out old isolating material can damage the slots and the stack. Replacement wires of precise diameter are not always available and insufficient care is taken to fill the available slots with the maximum amount of copper material. In some cases, well-administered manual rewinding can improve badly wound machine motors. Software tools now exist for user-friendly optimal three-phase winding designs. Repair firms are often small- or medium-size enterprises with low-quality testing equipment that do not routinely test incoming and outgoing motors for energy efficiency. Knowledge on quality repair is scarcely available for the industrial sector and almost completely unavailable in developing countries. Typically, low labour and high material costs in developing countries make it more attractive to repair old motors than to purchase expensive, more efficient motors.

Nowadays, an old motor, with a 10-to-20-year running history, is typically an inefficient motor. This indicates that even with quality rewinding and repair, an inefficient motor often gets worse. Repair costs for smaller motors (<10 kW) are higher than replacement costs and hence prohibitive. Larger and special motors with custom-made features can be repaired and eventually rewound with great care. There is no standard practice for measuring efficiency before and after a rewinding – which would clearly show the loss of performance quality (in some cases broken motors no longer function upon delivery). Countries with MEPS for new motors (*e.g.* New Zealand) have considered banning rewinding of motors below 50 kW to avoid a secondary market disrupting mandatory introduction of new higher-efficiency motors.

Upgrading existing systems

Existing systems are sometimes upgraded to improve performance and/or efficiency by replacing components or adding new elements. Energy efficiency can be enhanced by replacing V-belts with flat belts, changing gear boxes and eliminating worm gears, or adding a VFD (if the motor allows).

Paying for a better motor by buying a smaller motor

With adequate sizing, an eventual replacement (*i.e.* new) motor installation typically has an output power that is 20% to 50% lower. For motors above 5 kW to 10 kW, the specific motor price is almost constant (Figure 36). This means a 30% smaller motor is 25% cheaper. The same is true for a VFD. With a typical initial price premium for an IE3 instead of an IE2, the additional cost can be offset by downsizing. When a 22 kW IE1 motor is replaced by a new 15 kW IE3 that costs 64% of the price of a new 22 kW motor, efficiency is increased by 3.6% (Figure 38).

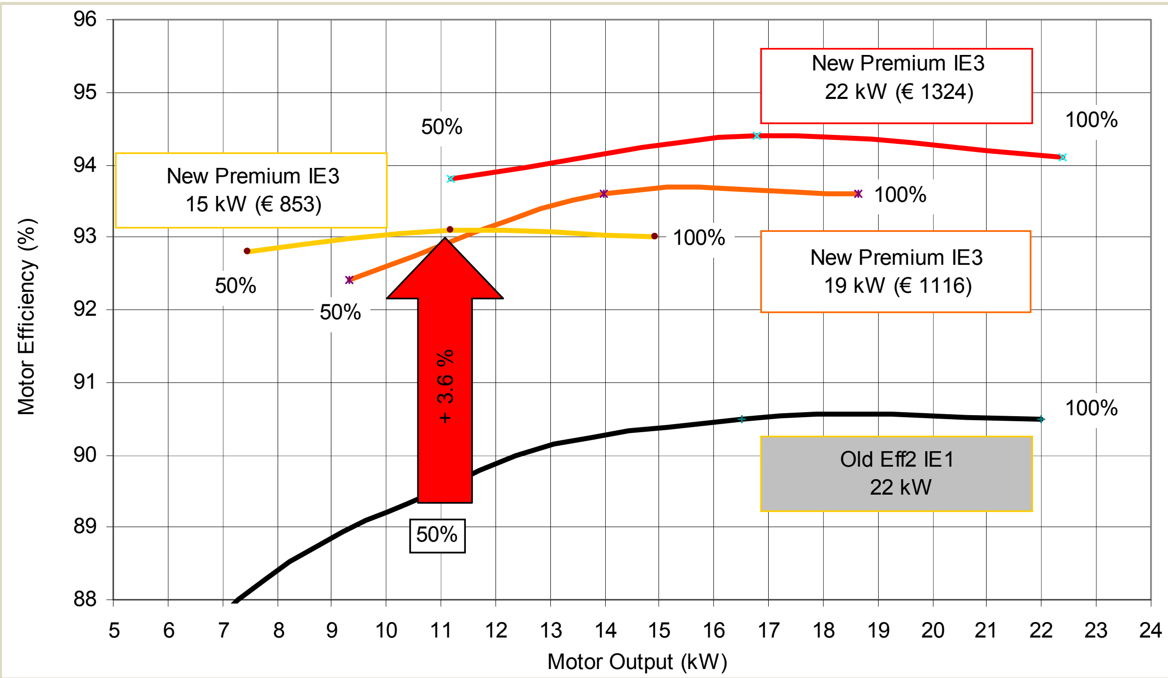
Tapping cost benefits from motor-system optimisation

Electric motor-driven systems have large untapped energy-efficiency potential. The following key findings can help tap that potential.

Life-cycle cost is the best method to identify optimally integrated EMDS, but it is still not industry practice. Purchasers do not often ask for this information and manufacturers do not generally offer it. OEM-designed machines need to be evaluated by life-cycle cost, not by their initial cost only. A precise performance description at the design stage facilitates the design and delivers an optimal machine.

Energy-efficiency decisions should always include the core motor system, given the larger and more cost-effective efficiency potential, and should also try to optimise the total motor system. Engineering development will allow for better sizing of machines and motors. Downsizing of planned motor systems will mean better performance and lower initial cost.

Figure 38: Example of how downsizing can pay for a more-efficient motor



Source: A+B International, 2007.

Efficiency gains will potentially come from matched components, including IE3 motors, VFDs and direct drive integration. The savings will come mainly from abandoning transmissions, low-efficiency gears and throttles, dampers, bypasses etc. All variable load processes have to be studied to allow better partial-load performance. It is important to carefully consider the use of VFD to avoid unnecessary investment and additional losses.

Pumps have traditionally been oversized. New engineering design tools allow for a much closer fit and better electronic controls in partial-load conditions.

Fans have usually been made with lower engineering precision than pumps, because air leaks do not have the same consequences as fluid leaks. Air ventilation and blower systems today can be much more efficient through precise engineering and providing for the lowest necessary fan power and operation time for the necessary service.

Compressors are manufactured by specialist firms with large global volumes in all types and sizes. They have tended to respond slowly to new ecological awareness and economic facts. This delay in responding to the challenges and potential for new technology has led to a negative image for the entire industry.

Overall, the average profitable energy-efficiency potential for EMDS is estimated at 20% to 30% (the average case for improvement projects in existing total motor systems). In existing improvements on the level of the core motor system, only 10% to 20% profitable energy-efficiency is feasible. In new designs, potential electricity savings with the optimal total motor system can be 30% to 80% on average, as demonstrated in the pump and fan studies in Chapter 4.

6. Barriers to Optimisation of Efficient Electric Motor-Driven Systems

Energy-efficiency potentials of electric motors and motors systems are not being realised, even when they are economically cost-effective. Numerous barriers impede adoption and rapid market diffusion of efficient electric motor-driven systems (EMDS) within major applications. Some non-economic factors could be addressed through energy policy. Such barriers encompass international trade issues and various economic aspects such as life-cycle cost perspectives, traditional investment decisions and high transaction costs for investors. A further barrier is that electricity prices do not reflect full social costs, given externalities from electricity generation and distribution.

Many barriers limit the market uptake of cost-effective EMDS solutions: lack of knowledge; short-term thinking over investments and operation; excessively risk averse production practices; higher initial costs; confusion in standards and labels; lack of performance visibility within main production performance benchmarks; difficulty in recouping the cost of more-efficient components; and international trade barriers. Some of these barriers are common to other energy-using products and hence are subject to similar policy analysis and solutions, but some barriers are unique to motors.

Concepts of barriers

According to traditional market theory, investors will choose efficient motors or motor systems when they become more profitable (*e.g.* the concept of least life-cycle cost or the lowest total cost of ownership). This theoretical concept is based on several assumptions, the most important being a well-educated investor, who is fully informed on the markets relating to the investment, the seller's behaviour and the quality of the various products. The investor has full access to capital or favours minimal cost of the system although the benefits may accrue to the system's user. Market theory usually ignores externalities such as environmental pollution, climate change or further indirect impacts such as corrosion, health and safety effects, or reduced productivity of economies.

In fact, several authors have written about market deficiencies, describing various aspects of actors: level of knowledge and information; limited access to capital; the investor/user dilemma; uncertainties about the risks involved (or at least perceived) in new technology; or the fact that organisational and social interaction may hinder decisions on minimal-cost energy-efficient solutions. Barriers to energy efficiency have been addressed since the 1980s, after the first two oil price shocks, when it became clear that only a limited number of investors in the final energy sectors had adopted energy-efficient solutions (UNDP/WEC/UNDESA, 2000; United Nations Foundation, 2007; Thollander, 2008).

Missed cost reductions for mass-produced products

The theoretical barriers listed (Table 30) reflect general barriers for choosing energy-efficient solutions, but do not include barriers that may be specific for mass-produced products, such as electric motors or motor systems, or those that specifically address the situation of globally traded or tradable products. These barriers play an important role in the case of EMDS, with respect to existing profitable energy-efficient products, as well as the additional economic efficiency potentials available through economies of scale and related reductions in the cost of higher-efficiency motors and motor systems.

The issue of missed cost reductions is important in the case of electric motors because, in many countries, electricity generation is responsible for high specific greenhouse gas emissions. A large and fast distribution of highly efficient electric motors and motor systems can contribute to reducing emissions from fossil-fuelled power plants. The concept of missed cost reductions is often related to internationally harmonised technical standards and testing procedures, as lack of harmonisation can result in major trade barriers and obstacles for larger production series.

Table 30: Classification of barriers to energy efficiency

Theoretical Barriers	Comment
Imperfect Information (Howarth and Andersson, 1993)	Lack of information may lead to cost-effective energy-efficiency measures opportunities being missed.
Adverse selection (Jaffe and Stavins, 1994)	If suppliers know more about the energy performance of goods than purchasers, the purchasers may select goods on the basis of visible aspects such as price.
Principal-agent relationships (Jaffe and Stavins, 1994)	Strict monitoring and control by the principal, since he or she cannot see what the agent is doing, may result in energy-efficiency measures being ignored.
Split incentives (Jaffe and Stavins, 1994)	If a person or department cannot gain benefits from energy-efficiency investment it is likely that implementation will be of less interest.
Hidden costs (Jaffe and Stavins, 1994)	Examples of hidden costs are overhead costs, cost of collecting and analysing information, production disruptions, inconvenience, etc.
Access to Capital (Jaffe and Stavins, 1994)	Limited access to capital may prevent energy-efficiency measures from being implemented.
Risk (Jaffe and Stavins, 1994)	Risk aversion may be the reason why energy-efficiency measures are constrained by short pay-back criteria.
Heterogeneity (Jaffe and Stavins, 1994)	A technology or measure may be cost-effective in general, but not in all cases.
Form of information (Stern and Aronsson, 1984)	Research has shown that the form of information is critical. Information should be specific, vivid, simple, and personal to increase its chances of being accepted.
Credibility and trust (Stern and Aronsson, 1984)	The information source should be credible and trustworthy in order to successfully deliver information regarding energy-efficiency measures. If these factors are lacking, this will result in inefficient choices.
Values (Stern, 1992)	Efficiency improvements are most likely to be successful if there are individuals with real ambition, preferably represented by a key individual within top management.
Inertia (Stern and Aronsson, 1984)	Individuals who are opponents to change within an organisation may result in overlooking energy-efficiency measures that are cost-effective.
Bounded rationality (DeCanio, 1993)	Instead of being based on perfect information, decisions are made by rule of thumb.
Power (Sorrell *et al.*, 2000)	Low status of energy management may lead to lower priority of energy issues within organisations.
Culture (Sorrell *et al.*, 2000)	Organisations may encourage energy-efficiency investments by developing a culture characterised by environmental values.

Source: Thollander, 2008 (based on Sorrell *et al.*, 2000).

So far, energy-policy analysis has focused on the barriers to energy-efficient solutions in final energy sectors but has not expanded the concept to non-economic aspects of social behaviour and decisions (Stern, 1992; Jochem *et al.*, 2000). In future, policy makers should take social and behavioural aspects into account. Social prestige within a given group is well known for car ownership or office buildings and lobbies. Such mechanisms of social acceptance may also play an important role in non-visible efficiency investments such as electric motors or motor systems. High responsiveness to environmental and climate change concerns may also be a starting point for changes in social values and a motivation for investors to distinguish themselves from their competitors. Governments, agencies or trade associations may recognise these "early movers" in changing social values, offering recognition and awards or designating special groups.

Barriers to international trade

Electric motors and motor systems are mass-produced. For producers of electric motors and motor systems, well-functioning international trade is important to realise economies of scale and reduce their production costs. Barriers to international trade include regional differences in voltages and frequencies, different measuring systems, and differences in standardisation and related testing standards. Because they need to respect varying market requirements and specific technical conditions and traditions of those markets, manufacturers cannot produce goods in larger series.

Technical barriers in electricity supply

Grid voltage and frequency

The majority of countries operate their regular electric grid at 50 Hz frequency (62% of global electricity demand), while the minority are at 60 Hz (38% of global electricity demand, mainly in Brazil, Canada, part of Japan, Mexico, and the United States). Special grids for electric railway trains and tramways are run with DC (600 V to 3 000 V) or AC (15 000 V to 25 000 V) and also in different frequencies (50 Hz, 16.66 Hz, etc.). Electric motor shafts with a supply frequency of 60 Hz rotate 20% faster (*e.g.* 1 800 rpm instead of 1 500 rpm), thus they potentially have a 20% higher torque. The sum of all mechanical and electrical loss components in a 60 Hz motor with the same torque is lower than in a 50 Hz motor.

Nominal supply voltage for low-voltage three-phase motors varies between 380 V and 480 V depending on national voltage standards. Also, the supplied voltage can vary in a given location more than the standard ±10% of the rated voltage. Motors are typically designed and optimised for a given frequency and a nominal voltage, and cannot normally be exchanged without loss of optimum performance and efficiency. There are also dual-frequency and multi-voltage designs available for special markets (Brazil, Japan, etc.) that generally have lower efficiency than single-frequency and fixed-voltage systems.

Different measuring systems

A second technical barrier is that two types of units are used for EMDS:

- In the United States and Canada (and some South American countries), motor outputs are sized in horsepower (1 hp = 0.7457 kW) and motor frame sizes (overall dimension, shaft diameter and height, fixation screws) are measured in imperial units (1 inch = 2.54 cm).
- Europe, Asia and other parts of the world use international system (SI) units. Motor output is measured in kilowatts (kW); motor frame and gear sizes, etc., are measured in metric units (millimetres).

This situation typically makes it difficult for a motor or a motor system to be exchanged or shipped to the “other world”. Manufactures must produce motors and motor systems in smaller series in order to serve the different regional markets.

All parts of the world use the same electrical units: volts (V), amperes (A) and watts (W).

Barriers in non-harmonised standards

Standards for motors and motor systems are a very efficient political instrument to overcome obstacles in markets of mass-produced equipment. However, given national or regional markets in the early stages of electrification and motor system diffusion, efficiency standards and related testing standards are often developed independently. As a result, the world market of electric motors and motor systems is further fragmented by different energy-efficiency standards (Chapter 7) and related testing procedures and regulations.

Minimum Energy Performance Standard (MEPS)

Unco-ordinated and unharmonised development and enactment of MEPS in different countries prevent producers of electric motors and motor systems from exploiting the full potential of decreasing costs through large mass production and global trade of energy-efficient products. Some large and small countries have already implemented performance standards, while others plan to implement standards in the next five years.

In 2008, the IEC 60034-30 Efficiency Classes harmonised previously divergent classes in Europe (Eff1/Eff2/Eff3), the United States (Epact/NEMA Premium), China (Class 1/2/3) and Australia (MEPS 2002 and 2006). Once harmonisation is fully implemented, this trade obstacle will be alleviated. It is also interesting to note that Canada, Mexico, New Zealand, South Korea and the United States took the lead in implementing high-efficiency standards (IE2), while the European Union is only planning to adopt the standards between 2011 and 2017.

Testing standards for motor efficiencies

Two existing motor testing standards split the global market: IEEE 112 B covers Brazil, Canada, Mexico, and the United States; IEC 60034-2 (edn 2, 1996) covers Asia, Australia, Europe and the rest of South America. The two standards set different values for motor efficiencies; the older IEC standard does not include full stray load losses and thus overestimates motor efficiency by 1% for larger motors and up to 3% for smaller motors. The IEC 60034-2-1 Testing Standard, published in 2007, contains internationally harmonised testing standards and a classification by level of uncertainty.

Two important trade associations (National Electrical Manufacturers Association [NEMA] in the United States and European Committee of Manufacturers of Electrical Machines and Power Electronics [CEMEP] in Europe) represent the Institute of Electrical and Electronics Engineers (IEEE) and the International Electrotechnical Commission (IEC) around the world. Once harmonisation of these standards is fully implemented, the same testing rules will apply worldwide and this trade obstacle will also be alleviated.

Testing standards of motor-system efficiencies

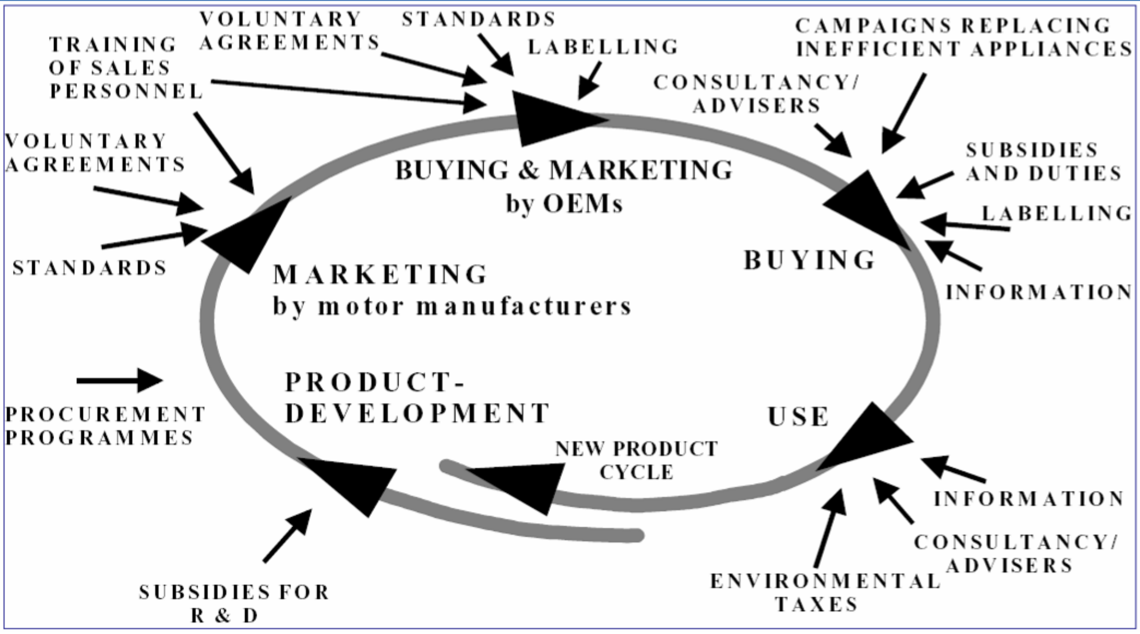
No international testing standards exist for entire motor systems, although there are some regional standards and some testing standards for partial core motor systems (pumps, fans). The concept of the core system – with its included mechanical (gears, transmissions, pump and fan wheel) and electrical components (motor, VFD) – should be made available for testing. Otherwise national and international trade is hampered by non-existent or non-comparable performance data. In small integrated core systems, such as circulator pumps and fans, new testing procedures are provided in the context of MEPS (*e.g.* EU EuP 2009 regulations for motors [European Commission, 2009a] and circulator pumps [European Commission, 2009b]). The proposed energy management standards for industry contain top-down benchmarking rules for energy use per product. This can, of course, also be used for energy-efficiency improvements by electricity users in industry and respective cross-cutting technologies.

Barriers at sector and business levels

In addition to obstacles at the international level, there are major obstacles at both sector and business levels. Most are not specific to electric motors or motor systems but very typical for target groups of the product cycle (Figure 39).

A number of obstacles must be alleviated in order to realise the full potential of high-efficiency electric motors or motor systems. Therefore, only a portfolio of policy measures is needed to serve this goal, as the obstacles must be removed simultaneously in a sector or country. Those policies must take into account the different alternatives for product cycles or use of electric motors (*e.g.* use by OEMs, use by wholesale, or use by direct purchase of the final investor). The enumeration of barriers presented below has been structured to follow the product cycle.

Figure 39: Policy instruments to reduce obstacles to diffusion of high-efficiency electric motors and motor systems along the product cycle



Source: Jochem, 2008.

Barriers at the level of manufacturers and OEMs

Customer demand for low investment cost: Many manufacturers of plants and machinery or OEMs rarely use premium-efficiency motors or motor systems because purchasing customers ask for *low investment cost,* not *low life-cycle cost.* Manufacturers know that to remain competitive, they must avoid the extra cost of high-efficiency solutions for motors or motor systems. As long as customers do not ask explicitly for high-efficiency or least life-cycle cost solutions, manufacturers and OEMs will tend to install and sell the least expensive versions of electric motors and motor systems, *i.e.* the less efficient solutions.

To remove these barriers: The concept of life-cycle cost must be introduced at all levels of basic engineering training. Factory owners must establish clear rules for calculation of cost-effectiveness for new and replacement production equipment.

Manufacturer tendency to discourage energy-efficient EDMS: In recent years, it has been observed (Jochem, 2008) that even when customers ask for high-efficiency motors for production machinery or plants, manufacturers are hesitant. They ask for unrealistically high additional investment costs, try to significantly postpone delivery dates, or refuse to give the operating guarantees available for "normally" equipped machinery or plants. The authors of this report don't fully understand the reasons for this attitude, but they assume that manufacturers and OEMs may want to sustain economies of scale in production or maintain price reductions from producers of motors or components of motor systems (*e.g.* ventilators, pumps or compressors).

To remove these barriers: Manufacturer and OEM trade associations could launch an information campaign and make recommendations to member companies about what each offer should include beyond investment cost and life-cycle cost. Of course, life-cycle cost must be calculated in the standard manner, taking into account the operating period and interest rate applied to capital costs. These data may depend on sectors or country traditions. Customers could also specify in their tenders the input data necessary to calculate life-cycle cost of the investment and the different efficiency solutions. Quick information on life-cycle cost for a particular investment could be easily calculated using an electronic tool specifically developed for this purpose and publicly available to manufacturers, consulting engineers, energy managers and investors or purchasers.

A second simple option for OEMs is to introduce an efficiency label for certain types of mass-produced machinery or plants, something similar to the "Intel inside" label (*e.g.* "only Premium Efficiency motors inside"). This label could be initiated by trade associations at a national, regional or multinational level, starting with product classes that involve mass production and international trade. If the trade associations involved cannot implement rules for those labels, national governments or regional bodies (such as the European Commission) could initiate this through a directive or an ordinance. In order to highlight this issue to investors, for a limited period, national governments could provide subsidies to final investors to cover the difference in cost between standard and premium efficiency.

Inability to effectively explain the economy of energy-efficient EDMS and customer loyalty: Many motor manufacturers and their sales engineers are not able to explain the economy of an energy-efficient motor and the benefits of a cost-effective premium-efficiency motor system. Product documentation, catalogues, electronic tools, web platforms or presentations to clients do not focus on energy efficiency and economy, or give clear explanatory information to decision makers. In a recent test tender with seven motor manufacturers in Switzerland (Brunner, 2007), even the actual offers were confusing to the client: motor-efficiency classes were not included; efficiency values were not clearly stated; and prices relating to taxes, special copper price premiums and discounts were unclear. For many motor manufacturers and wholesale distributors, it is unusual for clients to seek offers from different companies. Manufacturers continuously relate to their clients and do not like to compete with standard products under market conditions. Clients also generally prefer steady and reliable relationships with manufacturers for new investment and service companies. This precludes competition.

To remove these barriers: Manufacturers need to better train personnel responsible for customer contact. Their company and product documentation should be up to date, responding to actual testing standards, efficiency classifications, available rebate schemes and national MEPS, etc. They should offer on-site counselling with testing equipment to check oversized motors and advise on VFD use, etc. The pricing mechanism in tenders should be in a transparent standard format for each company, showing net price and product efficiency. Testing results for motor efficiency should be in a standard reporting format and relate to actual IEC standards.

Inadequate assessment of actual use for EDMS: As key market players, OEMs tend to provide machines for safe and continuous operation even if they do not know the conditions under which the equipment will eventually be operated by their clients. This can lead to grossly oversized motors and other driven equipment with lower efficiency and higher investment costs at time of purchase. Because uninterruptible operation and low maintenance costs are key criteria for purchasers, OEMs are unlikely to change their attitude.

To remove these barriers: Factory owners and motor users should describe their intended application more completely. In cases of replacement and enlargement, it is usually possible to monitor existing processes and measure equipment to define critical dimensioning parameters.

Fear of EDMS failure that will disrupt production: An old fear is that overheating, burning and eventual stalling of electric motors will interrupt industrial processes and cause high production losses and damages. The old fears persist, although general-purpose electric motors in industry today are more efficient and do not heat up as they once did (they never reach their allowed maximum temperature). Moreover, motors are protected with an elaborate scheme of cooling with defined over-temperatures and electric isolator performance, etc. In the United States, service factors of 1.1 to 1.2 are standard (*i.e.* a motor can be run safely at 110% to 120% of its rated output power).

To remove these barriers: Motor performance documentation should clearly state what ambient and over-temperatures are allowed, and to what extent motors and systems can be safely operated in overload conditions.

Lack of incentive to innovate: Manufacturers of various standardised motor applications, such as ventilators, pumps and compressors, have so far little incentive to innovate, produce and market premium energy-efficiency products. Neither OEMs nor the wholesale sector have requested these products. Wholesalers generally want to reduce capital costs for products stored on their shelves.

To remove these barriers: Labelling differences in efficiencies of packaged motor components would help the investor make decisions quickly on the basis of efficiency information. Again, manufacturer trade associations at national, regional or multinational levels should develop efficiency standards for mass-produced components (*e.g.* pumps, ventilators, compressors, pistons for compressed air). National governments or international organisations could co-ordinate to set time limits for either a voluntary manufacturer standardisation process or multinational standards for major components for pumps and ventilators.

Barriers in wholesale, planning and engineering

Limiting types of motors and components to minimise capital costs: The wholesale sector for electric motors and motor systems tends to minimise capital costs by reducing types and number of electric motors and motor system components to a minimum of frequently sold items. In most cases, they offer not premium-efficiency solutions, but standard-efficiency options for the various types and power sizes. Less frequently demanded components or motors must be ordered from the manufacturer, which can take several days or even weeks. When an electric motor or motor system stops operating, the energy manger or product engineer is often forced to find a replacement component within hours, because production must continue in order to minimise total production cost. If the wholesale sector cannot immediately deliver the premium-efficiency version, or a premium-efficiency alternative, customers will find it unacceptable to wait for several days (or even weeks).Because it is rare for anybody to ask for premium-efficiency products, wholesale companies feel their current storage strategies are quite efficient.

To remove these barriers: Most important is an information campaign targeting both users of electric motor systems and wholesalers. This should eventually be reinforced by a procurement programme organised by national energy agencies or an association of learning efficiency networks, which have interest and insight into high energy-efficiency solutions.

Outdated engineering skills: The skills of consulting engineers and engineers of OEMs who design, plan new plants or retrofit existing factories may be outdated and not reflect the most current energy-efficiency solutions (*e.g.* over-dimensioning rules learned in the past or during previous education, no use of electronic discounted cash-flow investment planning or decision tools, no up-to-date knowledge of new technical solutions). There is also some contractual or emotional attachment to certain technical solutions and preferences (*e.g.* waste heat recovery from motor systems) instead of using more efficient technology (*e.g.* hydraulic control instead of pneumatic control) or turning to high-efficiency solutions in the production process itself (*e.g.* substantial reduction of cooling demand by substituting a different production process).

To remove these barriers: Professional training of consulting engineers is quite important. They should make use of easily available investment calculation tools of high technical quality or seek professional calculations to determining profitability of the various investment options (*e.g.* by net present value or internal rate of return and not just by payback times).

Barriers at the level of investors and energy managers

Complexity of EDMS: Motor systems are complex: mechanical and electric components must be matched carefully to the required task and the motor's torque and speed. Replacing a single component with a premium component does not generally lead to satisfying energy-efficiency gains or short payback times. To study the entire system and optimise operation requires more time, qualified staff and advanced engineering know-how.

To remove this barrier: Training programmes and tools for factory technical staff must be readily available. Staff with adequate qualifications must be selected and trained regularly.

Sales generally not to end-users: Eighty percent of equipment sales from manufacturers go directly to wholesalers, distributors and OEMs, not to end-users. This means that the line of purchase is broken. End-users may have little knowledge about motors, and the buyers of motors are not necessarily interested in using premium-efficiency motors in machine design. Complete machinery may cost 10 to 100 times as much as the motor, with purchasing decisions based on product performance, not energy cost.

To remove this barrier: OEMs must be trained to include life-cycle costing in equipment performance specification. When evaluating different products, end-users should be educated to ask for life-cycle cost calculations for entire production machines.

Large stocks of replacement motors: Industry tends to have replacement motors in store to avoid lengthy interruption of production when a motor fails. Usually for five new motors, a sixth is bought and stored. This practice has been common for decades, since times when motor failure due to overheating and mechanical bearing failure was more frequent. Most industries have a large inventory of old, never-used motors. When a motor efficiency upgrading campaign starts industry faces sunk costs of unused and unusable old motors.

To remove this barrier: Energy-efficiency campaigns for industry should include an incentive system for lowering the purchase price of premium motors and an additional incentive for the return and destruction of old motors.

Purchasing decisions typically based on lowest investment cost: Energy managers and purchasing departments of companies often make decisions on the basis of lowest investment without calculating life-cycle cost of the investment. Those who make the purchase also often get a bonus if they negotiate additional reductions from manufacturers of the machinery or plants. This exerts pressure on manufacturers to reduce prices, and often leads to selection of inefficient motors and motor systems if the customer does not clearly specify required efficiencies. In many cases, manufacturers of the machinery or plants already contracted and installed could not report on expected electricity demand (or pretended not to know). This decision-making process from customers, along with the search for inexpensive equipment from both customers and manufacturers, leads to sub-optimal energy-efficient solutions in most investments by medium-size industries.

To remove these barriers: Investment decisions on long-lasting, energy-using equipment should always be based on a profitability calculation, not just on the payback period (whether static or dynamic), which is only a risk indicator. The authors suggest a major information campaign by trade associations at national and multinational levels, possibly supported by energy agencies and other government agencies. It is of major importance that investors' profitability calculations accompany offers made by producers or wholesalers, along with information in the tenders on life-cycle cost (particularly on electricity demand of machinery and plants).

Energy managers and purchasers of investments should have professional training on these issues; these programmes can be organised by chambers of industry and commerce, energy agencies or other institutions offering high-level professional training. National or regional governments could support these courses by providing funds to develop training material or grants for small and medium-size companies to attend the courses.

Limited knowledge of energy-efficiency options: Investors in machinery and production plants equipped with EDMS often lack the necessary knowledge about energy-efficiency options. Therefore, they either stick to traditional technical solutions (standard electric motor systems) or look for new solutions, undertake market research and technical studies, and convince the board and their company's purchasing department of the advantages of new energy-efficient solutions. It takes time to search for new technical solutions and to convince others in the decision-making and purchasing process, and there are transaction costs. For more modest investments, such as electric motors and motor systems, these costs are relatively high; for smaller electric motors or motor systems, these transaction costs can exceed the entire investment (when installation costs are included).

To remove these barriers: To eliminate these high transaction costs, labelling and technical standards are important options (including banning inefficient systems from the market). Another option is to introduce internal company rules and standards for energy managers and purchasing departments responsible for investments in electric motors and motor systems. Consulting engineers and energy managers should have electronic calculation tools to quickly and reliably identify the least costly solution for the investment. Energy-efficiency learning networks of medium-size companies at local or regional levels (called "energy models" in Switzerland) allow participants to exchange knowledge and experience on all issues of energy efficiency and energy substitution, not just in electric motor solutions (Jochem and Gruber, 2007).

Inadequate understanding of how to avoid energy losses: The users of machinery and production plants equipped with electric motors often lack knowledge on energy-efficient operations through related controls or limitations of energy losses (*e.g.* controls of factory, plant or machine automation, or of pressure or leakage of compressed-air systems). They either underestimate the positive effect of careful maintenance on efficient energy use (*e.g.* maintenance of cooling units, heat exchangers, filters), or are simply unaware of it.

To remove these barriers: General management or energy managers could change daily routines and initiate thorough and regular maintenance operations. Professional training for machine and plant engineers and operators may be important and should be offered within and outside the companies. Factory automation can be used to monitor and benchmark efficiency in production processes. Governments could support these activities by funding training material and attendance of participants from small and medium-size companies. Consulting engineers could play a positive role as lecturers in these training programmes.

Payback period and internal rate of return: risk and profitability analysis

Decisions based on short payback periods: As business firms are concerned with the number of years required to recover initial outlay on an investment, the payback period is very often used to evaluate the feasibility of projects. Many engineers view the result as an incomplete profitability indicator, which can lead to the wrong decisions (Table 31). The payback period is calculated in two ways: either conventionally with even (not discounted) cash flow or by discounting the cash flow:

- Conventional (or static) payback time: The payback period is calculated simply by counting the number of years it takes to accumulate the amount of cash equal to the initial investment.
- *Discounted payback period:* The payback period is calculated to reflect the time value of money and energy expended. This method is more realistic, while the conventional method underestimates the payback period.

As electric motors or motor systems have lifetimes of 10 years to 20 years, the use of payback periods very often leads to a decision in favour of the normal efficient motor and system because the payback required is limited to two or three years. This means that many very profitable investments in high-efficiency motor solutions with internal rates of return of more than 20% are not realised (payback time of four years and useful lifetime of more than 10 years (Table 31)).

Table 31: Internal rate of return and payback period difference between risk and profitability analysis

Payback time requirement (years)	Internal rate of return (% per year)[1]							
	Useful life of plant (years)							
	3	4	5	6	7	10	12	15
2	24%	35%	41%	45%	47%	49%	49.5%	50%
3	0%	13%	20%	25%	27%	31%	32%	33%
4		0%	8%	13%	17%	22%	23%	24%
5			0%	6%	10%	16%	17%	18.5%
6	Unprofitable			0%	4%	10.5%	12.5%	14.5%
8						4.5%	7%	9%

Notes:
1. Continuous energy saving is assumed over the whole useful life of the plant.
2. Figures in red are profitable investment possibilities eliminated by a four-year payback period requirement.
Sources: Radgen, 2002; Radgen and Blaustein, 2001.

This important barrier is described by estimating the life-cycle cost for an IE1 (Standard Efficiency) and an IE2 (High Efficiency) motor from one manufacturer using the same operating conditions for three different motor sizes (between 5.5 kW and 200 kW) operating for 3 500 hours to 6 000 hours per year. The capital costs cover the investment (80% of the price lists of a large manufacturer, no competitive price was researched) and transaction costs for the small and large motors. The cost-benefit calculations were done on a specific software tool provided by a manufacturer for the motor selection in their catalogue. The conventional (static) payback period shows the following results (Figure 41):

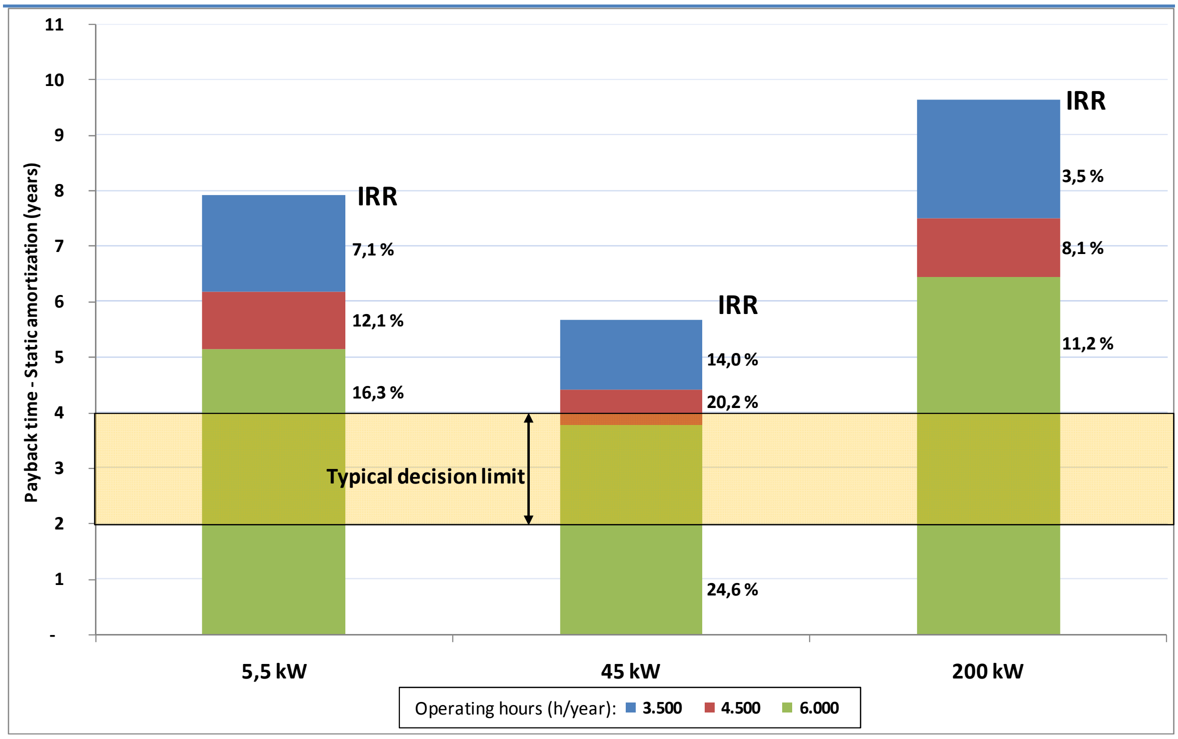
- With this limited scope of comparison (no motor systems improvement considerations, only one step improvement in efficiency class, and using a same size motor), none of the IE2 efficiency electric motors would be selected, if the payback period was limited to three years.
- Only the 45 kW motor has a chance to be considered as a valuable investment, if it runs at full load for 6 000 hours per year. The internal rate of return (IRR) would be 25%.

- The only questionable investment from the perspective of profitability is a 200 kW high-efficiency motor operating for only 3 500 hours per year; this case achieves an IRR of only 3.5%. Even this exception may occur rarely, as larger motors usually operate for more than 4 000 hours per year.

To conclude, if investors base their decisions on payback periods limited to only three or four years, they are more likely to exclude important and profitable investments in efficient motors and motor systems. Investment decisions on long-lasting motors and motor systems should always be made on the basis of profitability calculations, not just on the payback period (a risk indicator).

To remove these barriers: There are several ways to follow technical standards for certain applications that are likely to be profitable and could prescribe (or highly recommend) Premium Efficiency motors or motor systems. Trade associations could implement wide-reaching information campaigns at national and multinational levels, with support from energy and government agencies. Associations of motor and motor-system producers could also be required (or voluntarily agree) to include in their products offers transparent information on life-cycle cost and internal rates of return, comparing the best motor (or motor system) with their normal product or with a standardised variant.

Figure 40: Conventional (static) payback period and IRR of high-efficiency motors compared to normal motors at different yearly operating hours



Abbreviation: IRR = internal rate of return.

Source: BSR-Sustainability, 2009.

Externalities of electricity use by electric motors and motor systems

The problem of external costs to society associated with emissions from power generation is well known. Investors do not consider any externalities when they are not included in the energy prices. Even at a political level, external costs to society are often not considered because the macro-economic models used as the information basis do not monetise external cost. Avoided external costs resulting from energy or climate policies are discussed as ancillary benefits, often limited in analyses to conventional pollutants such as particulate matter, sulphur dioxide or nitrogen oxides, and related health and mortality effects (IPCC, 2001).

The Intergovernmental Panel on Climate Change (IPCC) report says that "the order of magnitude of positive ancillary impacts of greenhouse mitigation policies can be high enough to offset a substantial portion of the estimated GDP losses". The ancillary benefits for Norway and the United Kingdom, for example, are reported to lie within the range of USD 70/t to USD 110/t of avoided CO_2, and for the United States between USD 125/t and USD 205/t, depending upon the number of pollutants incorporated into various models.

Given the fact that ancillary benefits stemming from more energy-efficient solutions are mostly not included in today's calculations of macroeconomic models, policy makers have to make the final trade-off between the results of the models and the ancillary benefits, which are more difficult to monetise. But it is essential to note that the ancillary benefits from lower electricity use are those that occur in the near term as avoided external costs of conventional damage from electricity generation. The avoided external costs of climate change, however, are still neglected, even in cost-benefit analyses that take into account ancillary benefits.

Expressing external cost of climate change in "dollars and cents" leads to divergent results. The reasons for the wide range of results are numerous, but they also raise questions of ethics and foreign policy. Thus, uncertainties in natural science research lead to very strong variations when assessing damage in the relevant categories, such as future probabilities and intensities of major storms or floods, heat waves, the standstill of the Gulf Stream or future droughts in semi-arid zones. The question of how future damage should be evaluated – particularly the ethically controversial monetary evaluation of fatalities ("casualties") in the future and in developing countries – has an extremely high influence on the results.

Conclusions on removing barriers

Reducing all barriers and alleviating all obstacles and market imperfections to implementing Premium Efficiency motors and motors systems is a complex issue requiring multiple approaches.

If the markets for electric motors and motor systems are no longer segmented by technical standards but harmonised by global standards, the potential for further cost decreases from the highly efficient solutions can be realised. This would make investments in premium efficiency solutions profitable where they currently are not (*e.g.* also in lower annual operating hours).

Overcoming the barriers identified along the product cycle requires simultaneous introduction of a portfolio of measures: if all barriers are not removed or alleviated at the same time, there is high risk that the impact of a single measure, such as efficiency standards or labelling, will not bring about the expected efficiency potential.

Trade associations of manufacturers, wholesalers and investors, as well as local chambers of industry and commerce must play an active role in removing these barriers, improving knowledge and changing daily routines. They will need support from energy agencies and governments to overcome inertia and the lack of knowledge among member companies about barriers and the potential for saving energy costs in their sectors.

Political decisions must be based not only on profitability considerations of private investors, but also on the total cost to society in a way that reflects the ancillary benefits of reduced electricity demand by more efficient motors and motor systems. This also provides a rational basis for subsidising information campaigns, professional training or other policies to promote diffusion of highly efficient electric motors and motor systems.

7. Energy-Efficiency Policy Experience for Electric Motor-Driven Systems

Economies around the world have been relatively late in introducing regulations for electric motor-driven systems (EDMS) and very significant gaps in coverage remain in all economies. However in recent years, a number of major economies have adopted measures or have new measures in the pipeline.[8]

This review of global policy experience in encouraging enhanced efficiency in EDMS provides a detailed examination of major economies on the following topics:

- Regulations and labelling for integrated equipment and components.
- Systems performance specifications.
- Tools to encourage adoption of enhanced motor-driven systems.
- Awareness-raising efforts.
- Economic incentives.
- Industrial-sector energy service companies.
- Industrial energy-efficiency programmes and capacity building.
- Links with macro-policy initiatives.
- Evaluation and impacts.

Regulations and labelling for integrated equipment and components

Electric motors

European Union

The European Union adopted minimum efficiency regulations for electric motors in European Commission Regulation No. 640/2009 of 22 July 2009, which implemented Directive 2005/32/EC with regard to Eco-design requirements for electric motors.

The European regulation defines "electric motor" as a device that converts electrical energy into mechanical energy. The Terms of Reference describe the product group as electric motors in the output power range of 1 kW to 150 kW. However, the study considered a lower bound of 0.75 kW and an upper bound of 200 kW to take into account standard power sizes and the new proposed IEC 60034-30 efficiency classification standard on motor efficiency. Almost all motors in this power range are of low voltage. Medium-voltage motors are typically used in very high power applications of >500 kW; as they are of non-standard design, they are sold in very small numbers and are not yet included in any targeted energy-efficiency policies.

The European regulation provides some flexibility for regulated entities with respect to use of a variable-speed drive (VSD). For this reason it defines this term as follows:

> "Variable-speed drive" means an electronic power converter that continuously adapts the electrical power supplied to the electric motor in order to control the mechanical power

[8] See Annex A for a detailed review of technical standards for AC and DC motors, VSDs in common integrated applications (pumps, fans, compressors), and assemblies operating within site-assembled motor-driven systems.

output of the motor according to the torque-speed characteristic of the load (being driven by the motor), by adjusting the 3-phase 50 Hz power supply to a variable frequency and voltage supplied to the motor.

Eco-design requirements for electric motors (Table 32) will be phased in according to the following timetable:

- **16 June 2011:** motors shall not be less efficient than the IE2 efficiency level.
- **1 January 2015:** motors with a rated output of 7.5 kW to 375 kW shall not be less efficient than the IE3 efficiency level, or meet the IE2 efficiency level and be equipped with a VSD.
- **1 January 2017:** all motors with a rated output of 0.75 kW to 375 kW shall not be less efficient than the IE3 efficiency level or shall meet the IE2 efficiency level and be equipped with a VSD.

Table 32: Nominal minimum efficiencies (η) for electric motors in Europe (50 Hz)

Rated output power (kW)	Number of poles					
	IE2 efficiency level[1]			IE3 efficiency level[2]		
	2 poles	4 poles	6 poles	2 poles	4 poles	6 poles
0.75	77.4	79.6	75.9	80.7	82.5	78.9
1.1	79.6	81.4	78.1	82.7	84.1	81.0
1.5	81.3	82.8	79.8	84.2	85.3	82.5
2.2	83.2	84.3	81.8	85.9	86.7	84.3
3.0	84.6	85.5	83.3	87.1	87.7	85.6
4.0	85.8	86.6	84.6	88.1	88.6	86.8
5.5	87.0	87.7	86.0	89.2	89.6	88.0
7.5	88.1	88.7	87.2	90.1	90.4	89.1
11.0	89.4	89.8	88.7	91.2	91.4	90.3
15.0	90.3	90.6	89.7	91.9	92.1	91.2
18.5	90.9	91.2	90.4	92.4	92.6	91.7
22.0	91.3	91.6	90.9	92.7	93.0	92.2
30.0	92.0	92.3	91.7	93.3	93.6	92.9
37.0	92.5	92.7	92.2	93.7	93.9	93.3
45.0	92.9	93.1	92.7	94.0	94.2	93.7
55.0	93.2	93.5	93.1	94.3	94.6	94.1
75.0	93.8	94.0	93.7	94.7	95.0	94.6
90.0	94.1	94.2	94.0	95.0	95.2	94.9
110.0	94.3	94.5	94.3	95.2	95.4	95.1
132.0	94.6	94.7	94.6	95.4	95.6	95.4
160.0	94.8	94.9	94.8	95.6	95.8	95.6
200 - 375	95.0	95.1	95.0	95.8	96.0	95.8

Notes:

1. Efficiency ratings under the heading IE2 are equivalent to EFF1 from the CEMEP/EU voluntary programme and to the United States Energy Policy and Conservation Act of 1992.

2. The efficiency ratings under the heading IE3 are equivalent to the United States Energy Independence and Security Act of 2007 / NEMA Premium efficiency classification.

Source: Commission Regulation (EC) No 640/2009 of 22 July 2009 implementing Directive 2005/32/EC of the European Parliament and of the Council with regard to ecodesign requirements for electric motors.

The EU regulation contains detailed requirements on labelling and documentation. Generally, the following information must be prominently displayed:

1. nominal efficiency (η) at the full, 75% and 50% rated load and voltage (U_N)
2. efficiency level (IE2 or IE3)
3. year of manufacture
4. manufacturer's name or trade mark, commercial registration number and place of manufacture
5. product model number
6. number of poles of the motor
7. rated power output(s) or range of rated power output (kW)
8. rated input frequency(ies) of the motor (Hz)
9. rated voltage(s) or range of rated voltage (V)
10. rated speed(s) or range of rated speed (rpm)
11. information relevant for disassembly, recycling or disposal at end of life
12. information on the range of operating conditions for which the motor is specifically designed:

(i) altitude above sea level
(ii) ambient air temperature, including for motors with air cooling
(iii) water coolant temperature at the inlet to the product
(iv) maximum operating temperature
(v) potentially explosive atmospheres

The regulation specifies which information must be reported on the motor, on the included documentation and on the manufacturer's website (*e.g.* the information referred to in points 1, 2 and 3 must be durably marked on or near the rating plate of the motor).

United States

Electric motors were first regulated in the United States through the Energy Policy Act of 1992 (EPAct 92). This was the first major energy law to require minimum, nominal, full-load motor efficiency ratings applying to the following motors: "general purpose, T-frame, single speed, squirrel cage, induction type; 230/460-V, NEMA Designs A or B, continuous rated, 60 Hz, from 1 to 200 hp, 2-, 4- and 6-pole (3 600-, 1 800- and 1 200-rpm), open and enclosed". That definition represented the majority of electric motors commonly specified for industrial equipment, and they became known as "EPAct motors." The nominal efficiencies of these motors are 1% to 4% higher than the standard motors they replaced.

In 2005, Congress passed the Energy Policy Act of 2005 (EPAct 2005), which required all federal motor purchases to attain NEMA Premium efficiency ratings (*i.e.* higher than EPAct 92). The NEMA Premium motor efficiency ratings are up to several percentage points higher than those of their EPAct predecessors.

In 2007, Congress passed the Energy Independence and Security Act (EISA), which updated efficiency regulations for motors covered under EPAct 92, extended coverage to several new categories of motors and established efficiency regulations for them.

Specifically, EISA expanded the scope of covered motors to include:

- **Subtype I motors:** These include so-called traditional general-purpose motors that were already covered and regulated by EPAct 92.
- **Subtype II motors:** This new classification encompasses motors that were previously exempted from minimum efficiency performance standards (MEPS). These motors incorporate design elements of Subtype I general-purpose motors but can be configured as U-frame motors,

NEMA Design C motors, close-coupled pump motors, footless motors, vertical solid-shaft normal-thrust motors (as tested in a horizontal position), 8-pole (900 rpm) motors and polyphase motors with a voltage of not more than 600 V (other than 230 V or 460 V).

EISA established minimum nominal full-load efficiency requirements for Subtype I and II motors:

- Subtype I motors from 1 hp to 200 hp and manufactured alone or as a component of another piece of equipment must meet the NEMA Premium efficiency ratings.
- Subtype II motors are required to meet the less stringent EPAct 92 minimum nominal efficiencies.

EISA 2007 grants two exceptions: Subtype I, NEMA Design B motors between 201 hp and 500 hp and fire-pump motors need to meet only the less stringent EPAct 92 efficiency ratings.

These efficiency ratings are the same as those included in NEMA MG-1-2006, Table 12.12. This regulation applies to all Subtype I general-purpose electric motors manufactured (alone or as a component of another piece of equipment) on or after 19 December 2010.

Table 33: Motor types subject to MEPS in the United States[1]

Motor type and size	Table of efficiency levels from NEMA MG 1-2006
Subtype I, 1 hp - 200 hp	Table 12.12, (NEMA Premium)
Subtype I, NEMA Design B, 201hp - 500 hp	Table 12.11, (EPAct 92)
Fire-pump motors, 1 - 500 hp	Table 12.11, (EPAct 92)
Subtype II, 1 hp - 200 hp	Table 12.11, (EPAct 92)

Abbreviation: MEPS = minimum energy performance standards.

Note: 1. These MEPS came into effect on 19 December 2010.

Source: US Code of Federal Regulations: 10 CFR Part 431.25 - Subpart B - Electric Motors

Table 34: Nominal minimum full-load efficiencies for Subtype I electric motors in the United States (60 Hz)[1]

Motor hp	Motor kW[2]	Nominal full-load efficiency (%)					
		Open motors			Enclosed motors		
		2 poles	4 poles	6 poles	2 poles	4 poles	6 poles
1.0	0.75	77.0	85.5	82.5	77.0	85.5	82.5
1.5	1.1	84.0	86.5	86.5	84.0	86.5	87.5
2.0	1.5	85.5	86.5	87.5	85.5	86.5	88.5
3.0	2.2	85.5	89.5	88.5	86.5	89.5	89.5
5.0	3.7	86.5	89.5	89.5	88.5	89.5	89.5
7.5	5.5	88.5	91.0	90.2	89.5	91.7	91.0
10.0	7.5	89.5	91.7	91.7	90.2	91.7	91.0
15.0	11.0	90.2	93.0	91.7	91.0	92.4	91.7
20.0	15.0	91.0	93.0	92.4	91.0	93.0	91.7
25.0	18.5	91.7	93.6	93.0	91.7	93.6	93.0
30.0	22.0	91.7	94.1	93.6	91.7	93.6	93.0
40	30.0	92.4	94.1	94.1	92.4	94.1	94.1

Motor hp	Motor kW[2]	Nominal full-load efficiency (%)					
		Open motors			Enclosed motors		
		2 poles	4 poles	6 poles	2 poles	4 poles	6 poles
50	37.0	93.0	94.5	94.1	93.0	94.5	94.1
60	45.0	93.6	95.0	94.5	93.6	95.0	94.5
75	55.0	93.6	95.0	94.5	93.6	95.4	94.5
100	75.0	93.6	95.4	95.0	94.1	95.4	95.0
125	90.0	94.1	95.4	95.0	95.0	95.4	95.0
150	110.0	94.1	95.8	95.4	95.0	95.8	95.8
200	150.0	95.0	95.8	95.4	95.4	96.2	95.8

Notes:

1. Subtype I general-purpose electric motors rated at of 1 hp or more but not greater than 200 hp.

2. As of the time of print, the US Regulation does not provide the equivalent kilowatt ratings for the horsepower ratings shown in this table; they have been added for clarity of interpretation.

Source: US Code of Federal Regulations: 10 CFR Part 431.25

Australia

Since October 2001, Australia has required three-phase electric motors from 0.73 kW to <185 kW manufactured in or imported into Australia to comply with mandatory MEPS. From 1 April 2006 in Australia and 16 June 2006 in New Zealand, MEPS levels for three-phase electric motors were revised to become more stringent. The new Australian Energy Performance Program, MEPS (AS 1359.5:2004), has efficiency levels equivalent to those of Eff1/EPAct.

Air compressors are not currently regulated for energy efficiency, and there are no proposals to regulate the efficiency of compressed-air systems. However, a number of reports and brochures have been prepared to encourage best practice. MEPS are applied to motors used in the compressor but not to the compressor itself.

Brazil

In December 2002, the Specific Motors Regulation was passed by Presidential Order 4508. The regulation introduced new minimum efficiency levels for standard and high-efficiency motors (High Efficiency [IE2 induction motors]). The regulation applies to the following motor types, whether sold separately or integrated into commercial equipment: 1 hp to 250 hp, 3-phase, 2, 4, 6 and 8 poles, and 600 V maximum. The regulation applies to imported equipment and equipment manufactured in Brazil, and covers approximately 70% of the Brazilian motors market. Brazil is currently working toward a premium efficiency minimum standard.

China

Article 17 of the Methods of Administration of Electricity Conservation (promulgated on 19 December 2000 by the State Economic and Trade Commission) encourages energy conservation measures that accelerate renewal and upgrade of inefficient fans, pumps, motors and transformers to improve efficiency of motor systems and promote AC motor-speed regulation energy-saving technologies.

China adopted MEPS for small- and medium-size three-phase asynchronous motors in 2006. The National Development and Reform Commission initiated ten major energy conservation projects within the China Medium- and Long-Term Energy Conservation Plan of 2006; one of those had a focus on energy-efficient motor systems. The plan requires: accelerated elimination of outdated and inefficient motors, promotion of variable-frequency and adjustable-speed energy-saving technologies (that can be applied in general machines such as fans, pumps and air compressors); adoption of AC motor variable-frequency adjustable-speed technologies in industrial machinery; formulation of preferential policies and technological policies; and improvement of motor efficiency standards. During the 11th Five-Year Plan period, it is intended that operating efficiency of motor systems will increase by 2%, saving 20 TWh per year.

Specifically, China has now adopted the following energy-efficiency regulations:

- GB18613-2006: Minimum Allowable Values of Energy Efficiency and Energy-Efficiency Grades for Small and Medium-Size 3-Phase Asynchronous Motors
- GB19153-2009: Limited Values of Energy Efficiency and Evaluating Values of Energy Conservation for Displacement Air Compressors
- GB19577-2004: Minimum Allowable Values of the Energy Efficiency and Energy-Efficiency Grades of Water Chillers
- GB19761-2009: Minimum Allowable Values of Energy Efficiency and Evaluating Values of Energy Conservation for Fans
- GB19762-2007: Minimum Allowable Values of Energy Efficiency and Evaluating Values of Energy Conservation of Centrifugal Pumps for Fresh Water Applications
- GB21518-2008: Minimum Allowable Values of Energy Efficiency and Energy-Efficiency Grade for AC Contactors.

On 18 January 2008, the National Development and Reform Commission and General Administration of Quality Supervision, Inspection and Quarantine made public an inventory of the third group of products (split into five categories) that will bear efficiency labels, which includes small and medium-size three-phase asynchronous motors. Within the 11th Five-Year Plan period, China will work to complete 20 efficiency labelling goals for energy-consuming products, including air compressors, fans and similar products. This will facilitate reshuffling of the market for related products and accelerate elimination of outdated products.

Table 35: Regulations for electric motors in some other countries

Country	Regulations
Chile	Mandatory Label – Labelling Program for 1-phase Induction Motors. Test Standard: NCh 2096: 2002, NCh 2548: 2001. Reference Test Standard: IEC 60034-2 and NOM-014-ENER-1997.
	Mandatory MEPS – Motors (1-phase Induction). Test Standard: NCh 2096: 2002 and NCh 2548: 2001. Reference Test Standard: IEC 60034-2 and NOM-014-ENER-1997.
	Mandatory Label – Labelling Program for 3-Phase Induction Motors. Test Standard: NCh 3086: 2008. Reference Test Standard: IEC 60034-2-1.
	Mandatory MEPS – on MEPS for 3-Phase Induction Motors. Test Standard: NCh 3086: 2008. Reference Test Standard: IEC 60034-2-1.
	Mandatory Label -- Test Standard: NCh 2700: 2002. Reference Test Standard: NOM-010-ENER-2004, last updated 2005 – Pumps (Submersible).
	Mandatory Label -- Test Standard: NCh 2699: 2002. Reference Test Standard: NOM-006-ENER-1995, last updated 2005 (under revision) – Pumps (Deep Well).
India	Voluntary MEPS – MEPS for Induction Motors – 3-Phase Squirrel Cage Induction Motor. Test Standard: IS 12615, IS 4029 and IS 325. Reference Test Standard: IEC 60034-2.

Country	Regulations
	Voluntary Label – Endorsement Label for Induction Motor – 3-Phase Squirrel Cage Induction. Test Standard: IS 12615, IS 4029 and IS 325. Reference Test Standard: IEC 60034-2.
Korea	Three-phase induction motors over 37 kW have been required to comply with MEPS since 2008, and those under 37 kW must comply from 2010. The following are energy-efficiency regulations for motors.
	Mandatory MEPS – MEPS for 3-Phase Electric Motors. Product: Motors (3-phase Induction). Test Standard: KS C 4202-97, KSC 4203, KSC 4201 and KSC IEC 61972. Reference Test Standard: IEC 60034-1, IEC 60034-1 and IEC 60034-9.
	Voluntary Label – High-efficiency Appliance Certification Program for 3-phase Induction Motors. Test Standard: KS C 4202-97, KSC 4203, KSC 4201 and KSC IEC 61972. Reference Test Standard: IEC 60034-1, IEC 60034-1 and IEC 60034-9.
	Voluntary Label – Certification of High Energy-Efficiency Appliance Program for Single Phase Motors. Test Standard: KSC 4204.
	Mandatory Label – Energy-Efficiency Rating Labelling Program – Electric Fan. Test Standard: KS C 9301.
	Mandatory MEPS – MEPS for Electric Fans – Korea. Test Standard: KS C 9301.
	Voluntary Label – High-efficiency Appliance Certification Program for Ventilation Fans. Test Standard: KS C 9301.
Mexico	Mandatory MEPS – NOM-014-ENER-2004: Energy Efficiency of Air-Cooled Single-Phase Squirrel-Cage Electric AC Induction Motors with a Rated Output of 0.180 kW to 1 500 kW. Test Standard: NOM-014-ENER 2004. Reference Test Standard: CAN/CSA C747, IEC 60034-1, IEC 60034-2, IEEE 114-2001, JIS C 4203, NEMA MG 1 and NEMA MG 11.
	Voluntary Label – Sello FIDE – 1-Phase Induction Motors. Test Standard: NOM-014-ENER-2004. Reference Test Standard: CAN/CSA C747, IEC 60034-1, IEC 60034-2, IEEE 114-2001, JIS C 4203, NEMA MG 1 and NEMA MG 11.
	NOM-016-ENER-2002: Energy Efficiency of Three-Phase Squirrel-Cage AC Induction Motors with a Rated Output of 0.746 kW to 373 kW. Test Methods and Marking.
	Mandatory MEPS – Motors (3-phase Induction). Test Standard: NOM-016-ENER-2002. Reference Test Standard: CAN/CSA C390, IEC 60034-1, IEC 60034-2, IEEE 112 Method B and NEMA MG 1.
	Voluntary Label – Sello FIDE – 3-Phase Induction Motors. Test Standard: NOM-016-ENER-2002. Reference Test Standard: CAN/CSA C390, IEC 60034-1, IEC 60034-2, IEEE 112 Method B and NEMA MG 1.
New Zealand	Mandatory MEPS – AS/NZS 1359.5 – Rotating Electrical Machines – General Requirements Part 5: Three-Phase Cage Induction Motors – High Efficiency and Minimum Energy. Test Standard: AS/NZS 1359.5, AS 1359.101, AS 1359.102.1 and AS/NZS 1359.102.3. Reference Test Standard: ANSI/IEEE 112-1984 (Method B), IEC 60034-1, IEC 60034-2, IEC 61972 and NEMA MG 1.
	Voluntary Label – Labelling Programme for Three-phase Electric (Induction) Motors. Test Standard: AS/NZS 1359.5, AS 1359.101, AS 1359.102.1 and AS/NZS 1359.102.3. Reference Test Standard: ANSI/IEEE 112-1984 (Method B), IEC 60034-1, IEC 60034-2, IEC 61972 and NEMA MG 1.

Source: IEA

Pumps

In the European Union, pump systems are divided into two subgroups for regulatory purposes: building circulator pumps and pump motor systems. Building circulator pumps are used to circulate heating and cooling fluids in a closed system, typically within a building. There are two types: stand-alone circulator pumps that are separate from a boiler or chiller system; and integrated pumps that are designed to operate with specific boiler systems and integrated with a product at the time of manufacture.

Circulator pumps

European Union

Circulators consume a significant share of the energy used in heating systems in buildings. Furthermore, most standard circulators operate continuously, regardless of heating needs. Circulators were therefore selected as a priority for the establishment of Eco-design requirements. Circulators were subsequently regulated on 22 July 2009 under the Implementing Directive 2005/32/EC concerning Eco-design requirements. The European Commission is still working on the test standard for circulator pumps, which requires refinements to the calculation method and a means of measuring permanent magnet (PM) motors.

The Commission's preparatory study found that most circulators are used to pump water in central heating systems. Less than 4% are used for other applications, such as solar water heating or chilling systems. According to the "Energy+ Pumps" programme, over 100 million circulators are installed in the European Union, most of which have a rated power <250 W. The programme estimates that they can account for as much as 5% to 10% of a household electricity bill.

The Commission estimates that 14 million circulators are sold in Europe annually and that, of all the life-cycle phases, their most significant environmental impact arises from the energy consumed in use, which amounted to 50 TWh in 2005, resulting in 23 million tonnes (Mt) of CO_2 emissions. Without market intervention, electricity consumption is projected to increase to 55 TWh by 2020. The EuP study found that the amount of electricity consumed by circulator pumps could be significantly reduced through a minimum energy performance standard.

Scope of coverage

Article 2 of the 22 July 2009 regulation provides the following definitions, which help to clarify the scope of coverage:

- A **circulator** is an impeller pump with a rated hydraulic output power of 1W to 2 500 W and is designed for use in heating systems or in secondary circuits of cooling distribution systems.
- A **glandless** circulator has its motor shaft directly coupled to the impeller and the motor is immersed in the pumped medium.
- A **stand-alone circulator** is designed to operate independently from the product.
- A **product** is an appliance that generates and/or transfers heat.
- A **drinking water circulator** is specifically designed to re-circulate drinking water as defined in Council Directive 98/83/EC (2).

Article 1 of the 22 July 2009 regulation establishes Eco-design requirements for glandless stand-alone circulators and glandless circulators integrated in products. For a limited time period, it does not apply to certain drinking water circulators or certain replacement regulators.

Energy-efficiency regulations

The 22 July 2009 regulation establishes two Eco-design requirements regarding energy efficiency and product information. Energy-efficiency requirements will be phased in over time, starting at a lower efficiency level in 2013 and becoming more stringent in 2015. The regulation reads as follows:

- From 1 January 2013, glandless stand-alone circulators, with the exception of those specifically designed for primary circuits of thermal solar systems and of heat pumps, shall have an energy-efficiency index (EEI) of not more than 0.27.

- From 1 August 2015, glandless stand-alone circulators and glandless circulators integrated in products shall have an energy-efficiency index (EEI) of not more than 0.23.

Product information requirements will not change over time. As of 1 January 2013:

- The EEI for circulators, calculated in accordance with Annex II of the regulation, shall be indicated on the name plate and packaging of the product and in the technical documentation in the form "EEI ≤ 0.[xx]".
- The following information shall be provided: "The benchmark for most efficient circulators is EEI ≤ 0.20".
- Information concerning disassembly, recycling, or disposal of components and materials at end of life shall be made available for treatment facilities.
- The packaging and the technical documentation of drinking water circulators must state: "This circulator is suitable for drinking water only."

Manufacturers must also provide information on how to install, use and maintain the circulator in order to minimise its impact on the environment. Finally, the regulation requires that all the information listed be visibly displayed on freely accessible websites of the circulator manufacturers.

Energy-efficiency labelling

The leading European circulator manufacturers, represented by Europump, developed a voluntary labelling scheme that applies to circulators up to 2 500 W in heating applications (Table 36). Circulators included in the scheme are only those used in residential and commercial heating systems within the European Union. In addition, in order to be included, the circulators must meet the following technical criteria:

- stand-alone circulators with integrated pumps and motors
- wet running (*i.e.* the rotor operates in the pumped fluid)
- centrifugal pumping
- a power rating <2 500 W (for each pump head on twin pumps).

Table 36: Energy labelling efficiency thresholds for circulator pumps in the European Union

EU Label Class	Energy-Efficiency Index (EEI)
A	< 0.40
B	0.40 ≤ - < 0.60
C	0.60 ≤ - < 0.80
D	0.80 ≤ - < 1.00
E	1.00 ≤ - < 1.20
F	1.20 ≤ - < 1.40
G	≥ 1.40

Source: Europump

Given the recent regulation (July 2009) of circulator pumps, adopting Energy-Efficiency Index (EEI) ratings of 0.27 in 2013 and 0.23 for 2015, it will be necessary to review continuation of this labelling scheme.

Pump motor systems

European Union

The European Commission is also considering regulatory options for a range of pumps used in commercial buildings, drinking water, agriculture and the food industry. The types of pump considered include:

- single-stage close-coupled (end-suction close-coupled) (ESCC)
- in-line ESCC pumps (ESCCi)
- single-stage water (end-suction own-bearing) (ESOB)
- submersible multi-stage well pumps (4” and 6”)
- vertical multi-stage water pumps

The EuP study on water pumps was completed in April 2008, and the Commission is preparing a draft regulation for stakeholder review in early 2010. A European Commission proposal is currently being scrutinised by the Ecodesign Regulatory Committee. Further information on the EuP study can be found at: http://www.ecomotors.org/.

United States

The pump industry is the largest consumer of electric motors in the United States, but there is no regulatory standard on pump systems. Instead, there is a twofold effort to encourage installation of energy-efficient pump systems:

(1) An aggressive efficiency regulation on electric motors, from 1 hp to 500 hp. This was originally started by EPACT 1992 and was amended by EISA 2007. It entered into review by the US DOE through a rule-making process for energy-conservation standards that began in 2010.

(2) The provision of software tools, marketing efforts and training on the specification and installation of energy-efficient pump systems, particularly Pump Systems Matter (www.pumpsystemsmatter.org) and the DOE’s Pumping System Assessment Tool (http://www1.eere.energy.gov/industry/bestpractices/software_psat.html).

China

In 1991, Chinese pump manufacturers developed recommended efficiency levels that were in a national standard (GBT13007-1991), which is currently available only in Chinese but includes a graph of efficiency against specific flow for each of the pump types covered by the scheme:

- single-stage centrifugal pumps for freshwater pumping (5 m^3/hour to 10 000 m^3/hour)
- multistage pumps for clean water (5 m^3/hour to 3 000 m^3/hour)
- petrochemical pumps (5 m^3/hour to 3 000 m^3/hour).

A correction factor (or efficiency allowance) is added to the actual pump efficiency, taking account of the actual head and flow (*i.e.* it considers the limitations of specific speed on pump efficiency). The test method allows for both peak and off-peak efficiency. A mandatory National Standard of the People’s Republic of China came into effect in December 2005. Although it uses a very similar methodology to that of GBT13007-1991, the levels are much lower. The pumps covered are for clear water and are of the following types: single-stage (single and double suction); multistage; multistage well.

India

India has a voluntary labelling scheme using the Star rating method for promoting more energy-efficient submersible pumps. This programme is based on Indian test standards IS 9079, IS 8034, IS 14220 and IS 11346, and was most recently updated in 2009.

Korea

The Korean programme, devised by the Korea Energy Management Corporation (KEMCO), aims at the voluntary certification of pump efficiency, with the objective of encouraging development of new, efficient pumps. The focus is on single-stage and multistage water supply pumps with 25 mm to 200 mm bore discharge branches, running at 2-pole and 4-pole speeds.

Table 37: Regulations for pump motor systems in some other countries

Country	Regulations
Iran	Mandatory EE Label of Energy Consuming Products, 2006 – Pumps (Centrifugal).
Israel	Mandatory MEPS, 2004 – Axial Pumps.
	Mandatory MEPS, 2004 – Pumps (Centrifugal).
Mexico	Mandatory MEPS – Test Standard: NOM-010-ENER-2004. Reference Test Standard: ISO 3555 Class B, last updated 2004 (Pumps – Submersible).
	Voluntary Label – Sello FIDE Test Standard: NOM-010-ENER-2004. Reference Test Standard: ISO 3555 Class B, last updated 2008 (Pumps – Submersible).
	Mandatory MEPS – Test Standard: NOM-001-ENER-2000. Reference Test Standard: ISO 3555 Class B, last updated 2004 – Pumps (Vertical).
	Voluntary Label – Sello FIDE Test Standard: NOM-001-ENER-2000. Reference Test Standard: ISO 3555 Class B, last updated 2008 – Pumps (Vertical).
	Mandatory MEPS – NOM-006-ENER-1995 – 2004 – Deep Well Pumps.
	Voluntary label – NOM-006-ENER-1995 – 2008 – Deep Well Pumps.
	Mandatory Label – Test Standard: NOM-004-ENER-2008. Reference Test Standard: ISO 3555 Class B Centrifugal Pumps.

Source: IEA

The scheme requires the following:

- The flow at best efficiency must be within a specified range for each discharge branch bore (different flow ranges for single-stage and multistage pumps).
- The best efficiency value must exceed a figure shown on a plot of efficiency against flow, designated the "A" efficiency.
- The efficiency at all flows within the specified range for a pump's discharge bore must exceed a figure shown on another plot of efficiency against flow, designated the "B" efficiency (about 12 points of efficiency below the best efficiency value). This is intended to encourage "broad" high-efficiency curves.

Fans

Fan motor systems

European Union

Fan motor systems consume approximately 20% of all electricity in the European Union, making them a high priority for the European Commission and the EuP (ebm-papst). The Commission issued a draft regulation on fan systems in December 2009 which was endorsed by the Ecodesign Regulatory Committee in June 2010. The resulting draft directive is awaiting approval by the European Parliament. The draft proposes phased-in regulation, starting in 2012 and increasing in 2015. Definitions, calculation methods, test standards and efficiency levels are all presented in the draft document.

Scope of coverage

The draft Eco-design regulation for fan motor systems covers "Fans within a 125 W to 500 kW power range, including those integrated in other products."

The draft Eco-design measure shall not apply to:

(a) fans within a 125 W to 500 kW power range designed to operate in potentially explosive atmospheres as defined in Directive 94/9/EC 1;

(b) fans within a 125 W to 500 kW power range designed for emergency use only, at short-time duty, with regards to fire safety requirements set out in Directive 89/106/EC 2;

(c) fans within a 125 W to 500 kW power range specifically designed to operate:

- where operating ambient temperatures exceed 100 °C
- where operating ambient temperatures are lower than - 40 °C
- with a supply voltage >1000 V AC or >1500 V DC
- in toxic, highly corrosive or flammable environments or in environments with abrasive substances.

Energy-efficiency regulations

The draft Eco-design requirements presented in the December 2009 document establish a two-tier regulation for fan motor systems. As previously defined, it covers small fans from 125 W through to large fans operating at 500 000 W. The effective dates are set to be two years and five years from 2010, with an average improvement in efficiency grade of 10% from 2012 to 2015 (actual values range from 5% to 17% for specific types of fan systems).

The draft Eco-design regulation establishes the following timetable:

(1) From 1 January 2012, all fans within a 125 W to 500 kW power range shall not have a lower efficiency grade than as defined in Annex I, point 1, Table 1 (*i.e.* the Tier 1 efficiency requirement).

(2) From 1 January 2015, all fans within a 125 W to 500 kW power range shall not have a lower efficiency grade than as defined in Annex I, point 1, Table 2 (*i.e.* the Tier 2 efficiency requirement).

The draft Eco-design document establishes a set of definitions that are used within the regulation itself. For example, the regulation defines measurement categories A, B, C and D, which refer to the condition of the air inlet and outlet of the fan motor system. These conditions are necessary for measuring the performance of the system and for determining compliance with the regulation.

European country-level programmes

National legislation for fan motor systems is usually based on total system efficiency:

- **Sweden** has adopted an approach to specify ventilation system energy consumption by measuring specific fan power (SFP), which specifies the fan's energy consumption per volume of air delivered. System pressure losses and motor/control system losses are accounted for in the specific value. This is a good energy-performance indicator for the whole system, but it does not necessarily indicate the efficiency of the fan.
- An SFP approach has been adopted in the **United Kingdom's** new building regulations (Department for Communities and Local Government, 2006).
- **Germany** is considering following Sweden and United Kingdom. The German EnEV, 2006 will also use the SFP related to a single fan or the weighted average for all fans of a building. Minimum efficiency required will be selected from the efficiency classes as given in prEN 13779:2005(D).
- **Denmark** has a voluntary labelling scheme for fans called Spareventilator®. Data must be described in the report measuring the individual fan and must be verifiable; the documentation of the fan's efficiency concerning pressure and air volume must be in accordance with ISO 5801. The stated efficiency rate must be as a minimum in accordance with the Tolerance Class 2 as per ISO 24166.

United States

The United States has no regulatory standards for fans. Instead, there is a twofold effort to try to encourage the installation of energy-efficient fans:

(1) An aggressive efficiency regulation on electric motors from 1 hp to 500 hp. As noted previously, this was originally started by EPAct 1992, was amended by EISA 2007, and is now being reviewed by the US DOE in an energy-conservation standards rule-making that began in 2010.

(2) The provision of software tools, marketing efforts and training on the specification and installation of energy-efficient fan systems (*e.g.* the Fan System Assessment Tool).

Compressors

Compressed-air systems are defined as a group of sub-systems comprising integrated sets of components including air compressors, treatment equipment, controls, piping, pneumatic tools, pneumatically powered machinery and process applications utilising compressed air. These systems provide consistent, reliable and efficient delivery of compressed air to manufacturing equipment and processes.

United States

The United States has no regulatory standard on air compressors. Instead, there is a twofold effort to try to encourage the installation of energy-efficient compressor systems:

(1) An aggressive efficiency regulation on electric motors from 1 hp to 500 hp, originally started by EPAct 1992 and amended by EISA 2007. As noted above, it is now being reviewed by the US Department of Energy in an energy-conservation standards rule-making.

(2) The provision of software tools, marketing efforts and training on the specification and installation of energy-efficient compressors systems (in particular, see AirMaster+ and Compressed Air Challenge [www.compressedairchallenge.org/]).

China

China applies MEPS to displacement air compressors including: direct-drive portable reciprocating-piston air compressors, oil-jet screw air compressors for general use and oil-jet sliding vane air compressors for general use.

Systems performance specifications

Electric motors

North America

The relevant performance testing standards for electric motors are:

- **IEEE 112 (2004):** Covers conduct and reporting of more generally applicable and acceptable tests to determine not only efficiency but also other performance parameters and characteristics of polyphase induction motors and generators.
- **IEEE 114 (2001):** Deals with the performance testing of single-phase induction motors. NEMA MG1 - Motors and Generators: Assists users in the proper selection and application of motors and generators. Revised periodically, the standard provides for changes in user needs, advances in technology, changing economic trends and practical information concerning performance, safety, test, construction and manufacture of AC and DC motors and generators.
- **C390-98 (2005):** This Canadian standard, very similar to IEEE 112-B, specifies the test methods for measuring the energy efficiency of three-phase induction motors. It applies to 3-phase induction motors rated 0.746 kW at 1 800 rpm (or equivalent) and greater. An equivalent motor is one with the same torque output but with different kilowatt output and speed.

Pumps

European Union

The European Commission is still reviewing the test method for measuring pump performance; however, it will likely be based on ISO 9906:1999. It provides for performance testing of two grades of pumps: Grade 1, considered to be the most accurate, and Grade 2, a less accurate measure. The tolerance on efficiency for Grade 2, representing the typical mass-produced pumps that were analysed in the EuP study, is approximately 5%. For larger pumps, a user may request a test of the actual pump at Grade 1, but this more accurate test is more expensive. Smaller pumps are mass-produced and are often sold without being tested. For these pumps, manufacturers use a statistical approach for all except a small proportion. This type of acceptance testing is conducted by the manufacturers in their own testing facilities.

North America

In January 2010, the American Society of Mechanical Engineers (ASME) and the American National Standards Institute (ANSI) issued a new testing standard for pumping systems: the Energy Assessment for Pumping Systems (ASME EA-2-2009). This standard covers pumping systems, defined as one or more pumps and those interacting or interrelating elements that together accomplish the desired work of moving a fluid. The system comprises pump(s), driver, drives, distribution piping, valves, sealing systems, controls, instrumentation and end-use equipment (such as heat exchangers).

This ASME standard addresses open- and closed-loop pumping systems, typically used in industry, as well as other applications. It establishes requirements for measuring and reporting the results of a pumping-system assessment, taking into account the entire pumping system, from energy input to work output. An assessment compliant with this standard need not address with equal weight each individual system component or sub-system within an industrial facility; however, it must be sufficiently comprehensive to identify the major opportunities for improving overall system performance. This standard is designed to be applied primarily at industrial facilities, but many of the concepts can be used in other facilities such as institutional, commercial, and water and wastewater facilities.

Fans

European Union

The European Commission intends to use ISO/DIS 12759 (Fans – Efficiency classification for fans) to measure the performance of air systems. On 22 December 2009, the standard achieved Draft International Standards (DIS) approval for registration as Final Draft International Standard (FDIS). Thus the standard is close to being finalised, but it is still in review. ISO 12759 will address the overall efficiency of both impellers and motor-impeller combinations through a series of efficiency grade classifications, with the lowest expected to be phased out over time. Finally, specifiers and end-users will be able to compare the efficiency of different products from different manufacturers, and legislators will have agreed standards by which to set future efficiency targets. The draft European regulatory document presents a detailed process for calculating the efficiency grade for each of the motor types.

Air compressors

International testing standards

The ISO is developing a standard for compressed air system assessments, ISO 11011 (Air compressors and compressed air systems – Energy-efficiency audit reporting). This is still under development (as of November 2010). ISO Technical Committee 118 addresses "compressors and pneumatic tools, machines and equipment" and is developing ISO 11011. Within this technical committee, Sub-committee 6 is tasked with this project.

Development of ISO 11011 began several years ago in order to establish what a competent examiner should do to complete a proper assessment of a compressed-air system. This lack of a certification metric or other means of qualification was also the motivation behind a US initiative under development with the ASME.

In the United Kingdom, the British Compressed Air Society (BCAS) expressed concern that the lack of a standard made it possible for people with varying degrees of expertise to promote just about any level of system examination as a compressed air system assessment. BCAS addressed this market gap by developing a training and certification programme. BCAS has also been extensively involved in the development of ISO 11011.

North America

In 2010, ASME and ANSI published a testing standard for assessing the energy performance of a compressed-air system (ASME/ANSI EA-4-2010, Energy Assessment of Industrial Compressed Air Systems). This testing standard is consistent with the draft international standard, ISO 11011.

This standard considers the entire system, from energy inputs to the work performed as the result of these inputs. It sets requirements for: (1) organising and conducting an assessment; (2) analysing the data from an assessment; and (3) assessment reporting and documentation. As for pumps, an assessment complying with this standard need not address with equal weight each individual system component or sub-system within an industrial facility. However, it must be sufficiently comprehensive to identify the major energy-efficiency opportunities for improving the overall energy performance of the system. This standard is designed to be applied primarily at industrial facilities, but many of the concepts can be used in other facilities such as those in the institutional and commercial sectors.

Tools to encourage adoption of enhanced motor-driven systems

United States: pump motor systems

Pump Systems Matter

Conceived by the Hydraulic Institute, Pump Systems Matter (PSM) is an educational initiative created to assist North American pump-system users to gain a competitive business advantage through strategic, broad-based energy management and pump system performance optimisation. A primary objective of the initiative is to change the decision-making process for purchase of pumping systems.

Pump Systems Matter promotes educated decision-making based on life-cycle costs and systems-optimisation concepts, thereby accounting for energy, maintenance and other significant cost factors of operating a pumping system. PSM seeks to transform the market by changing decision-making on pumping systems by owners and operators from a focus on first cost to a focus on life-cycle costs, while helping pump users capture significant energy savings and performance improvements. The key elements of PSM are:

- To build awareness of the common definition and benefits of systems optimisation and pump system life-cycle cost at the management, production and technical levels of companies throughout the supply chain.
- To assist the pump industry in building their capacity to deliver system-optimisation solutions.
- To partner with key groups such as the energy-efficiency community, utilities, engineering consulting firms, pump-system users, the Hydraulic Institute and other associations, and government agencies to strategically support educating, encouraging and creating incentives for end-users and trade partners to adopt systems-optimisation products, services and practices.

PSM (www.pumpsystemsmatter.org) offers information, training, software tools, databases and other technical information to enable users to educate themselves about efficient pumping systems.

Pumping System Assessment Tool

The Pumping System Assessment Tool (PSAT) is a free, online software tool to help industrial users assess the efficiency of pumping-system operations. PSAT uses achievable pump performance data from Hydraulic Institute standards and motor performance data from the MotorMaster+ database to calculate potential energy and associated cost savings (visit: (www.pumpsystemsmatter.org/content_detail.aspx?id=112). The tool also enables users to save and retrieve log files, default values and system curves for sharing analyses with other users. It is designed for industrial plant managers and personnel who are interested in improving pumping-system efficiency and measuring potential monetary and energy savings opportunities.

United States: fan motor systems

Fan System Assessment Tool

For fan motor systems, the United States works to encourage installation of energy-efficient fans through the provision of software tools, marketing efforts and training. The US DOE published and maintains the Fan System Assessment Tool as a free software tool to assist industrial users to calculate energy consumption and savings opportunities in industrial fan systems. As indicated on the website (www1.eere.energy.gov/industry/bestpractices/software_fsat.html), the software assesses performance of fan systems to determine which options for system modification are most economically viable, quantifying potential energy and cost savings opportunities.

United States: air compressor systems

Compressed Air Challenge

The Compressed Air Challenge® (CAC) is a voluntary collaboration of industrial users, manufacturers, distributors and their associations, consultants, government representatives, utilities and efficiency advocates focusing on improving performance and efficiency of compressed-air systems. On their website (www.compressedairchallenge.org), the group states: “By focusing on your entire compressed air system, rather than taking a piecemeal approach, you can reduce leaks, better match supply to demand, and ensure appropriate use of air. The result is increased productivity, less waste and lower operating costs.” (CAC) The group works to provide resources to educate stakeholders about optimising compressed-air systems, offering training sessions, a best-practices manual, along with case studies and fact sheets.

AIRMaster+

The US Department of Energy and CAC established the AIRMaster+ initiative, which includes both a software tool and a training/certification scheme to provide qualified specialists to industrial end-users. AIRMaster+ (www1.eere.energy.gov/industry/bestpractices/software_airmaster.html) is a powerful tool for modelling "what if" scenarios for possible improvements to compressed-air systems. A qualified specialist can use AIRMaster+ to identify system improvement opportunities. The US DOE and CAC offer a 3½-day training programme for compressed air system specialists that includes classroom instruction, a practical exam testing hands-on measurement, and a written exam.

AIRMaster+ software is a free online tool to analyse energy use and savings opportunities in industrial compressed air systems. As explained on the AIRMaster+ website, the software can be used to model existing and future system operations improvements, and to evaluate energy and cost savings from a range of energy-efficiency measures. AIRMaster+ provides a systematic approach to assessing compressed air systems, analysing collected data and reporting results. The AIRMaster+ LogTool, used to gather critical performance data, helps determine operating dynamics of a compressed system. This software package is designed for people working to improve compressed air system performance (*e.g.* plant engineers, distributors of compressed-air equipment, energy consultants and utility energy auditors).

Awareness-raising efforts

European Union: pumps

In the European Union, the main voluntary scheme is the Europump/SAVE circulatory voluntary labelling scheme. However, it is not practical to extend this labelling scheme to include water pumps as they have duty cycles that range from low to high use and from no-head circulation systems to high-head boost systems.

The Europump/SAVE pump efficiency selection guide (www.europump.org) provides procurement advice on the expected efficiency for own-bearing and ESCC pumps, which represent 50% of the total energy use of pumps in Europe. The guide uses the relationship between specific speed and efficiency of pumps operating at optimum specific speed, which is thought to fairly represent the limited pump types considered. Pump users can enter the curves for the chosen pump type and desired head, flow and speed, and establish pump efficiency levels (this methodology has a small approximation that renders it inappropriate for legislation). The guide also provides recommendations on how to reduce the loss of pump efficiency with time.

Europe also has a regional voluntary scheme aimed at the promotion of energy-efficient circulator pumps, called Energy Plus Pumps (www.energypluspumps.eu). This programme promotes market adoption of higher-efficiency circulators (supported by the European Commission Intelligent Energy programme). The programme identifies and endorses top-performing products through an award competition, and provides information to influence purchasing decisions toward higher-efficiency models. The long-term objective of the Energy Plus Pumps programme is to transform the market such that premium-efficiency technology becomes the standard selected, at affordable prices.

In addition to pan-European initiatives, certain countries in Europe have programmes that affect circulators and promote energy-savings opportunities:

- **Denmark** requires that heating systems be designed with the lowest possible pressure loss, while ensuring system functionality is unaffected and the measures are cost-effective. The selection and control of circulator pumps must ensure the lowest possible electricity consumption, and there must be automatic controls for flow and pressure. However, the pump control must not limit the ability to achieve the desired comfort level or minimum flow rate requirements.
- **Germany's** regulations require variable-speed drives to be installed with heating systems larger than 25 kW (heating capacity). The Blue Angel (*Blauer Engel*) eco-labelling scheme applies to circulators and identifies domestic central heating circulators as self-controlled circulators with a maximum size of 250 W.

Economic incentives

North America

The introduction of more energy-efficient motor systems can reduce industrial motor-system electricity demand by 11% to 18% (62 billion kWh/year to 104 billion kWh/year). Valued at USD 3 billion to USD 5 billion per year, these savings are obtainable through cost-effective measures using efficiency technologies and practices. In addition, industrial customers would benefit from improved control of production processes, reduction in waste materials and improved environmental compliance. There are over 50 different electricity utility incentive programmes in North America that promote the use of more energy efficient motors and motor systems. A database of programmes is maintained by the Consortium for Energy Efficiency (www.cee1.org/ind/mot-sys/mtr-ms-main.php3).

China

China has formulated and revised several national economic operation standards since 1992, including:

- GB/T12497-2006: Three-phase Induction Motors, Economic Operation
- GB/T13466-2006: The General Principles of Economic Operation for AC-driven Fan (Pump, Air Compressor) System
- GB/T13469-2008: Economic Operation for Industrial Centrifugal, Mixed Flow and Vortex Pump Systems
- GB/T13470-2008: Economic Operation of Ventilator System
- GB/T17981-2007: Economic Operation of Air-conditioning System

Industrial-sector energy service companies

An energy service company (ESCO) is a business that analyses, develops, installs and organises financing for projects that improve energy efficiency and maintenance costs. ESCOs generally act as project developers and assume the technical and performance risk associated with a project. Typically, ESCOs:

- audit and analyse energy use on a particular project site;
- develop more energy efficient technologies and systems improvements as well as better maintenance practices and control regimes;
- install and maintain the energy-efficient equipment involved;
- arrange financing for energy-efficiency projects;
- measure, monitor and verify the project's energy savings.

All of these ESCO services are bundled into the project's cost and are repaid through the energy savings generated. ESCO projects tend to be comprehensive, which means that experts working on an assignment will employ a wide array of cost-effective measures to achieve energy savings. In the industrial sector, these will include building-related systems (such as lighting, heating, air conditioning and controls), process-related systems (such as energy-efficient motors) and motor systems (such as pumps, compressors, fans and other systems).

Malaysia's Industrial ESCO programme, for example, has the overall objective of supporting the development of ESCOs, and conducts projects to help the Malaysian business sector be more energy efficient and competitive in the global market.

Industrial energy-efficiency programmes and capacity building

European Union

The European Union has a voluntary programme in place to encourage adoption of more energy-efficient electric motors while it waits for its regulatory standard on electric motors to take effect in 2011.

In 1998, the European Committee of Manufacturers of Electrical Machines and Power Electronics (CEMEP) and the European Commission signed an agreement to promote more-efficient AC three-phase induction motors.

Motors covered in the CEMEP/EU agreement include 3-phase AC squirrel-cage induction motors; rated power: 1.1–90 kW; totally enclosed fan ventilated; line voltage: 400 V; 50 Hz; S1 duty class (continuous mode); efficiency tested in accordance with IEC 60034-2 using the "summation of losses" test procedure with PLL from assigned allowance. For these motors, the agreement established three levels of efficiency:

- EFF1 – high-efficiency motors
- EFF2 – medium-efficiency motors
- EFF3 – low-efficiency motors

Efficiency level EFF2 is considered a "standard-efficiency motor" by the European minimum-efficiency regulation adopted in 2009. EFF1, the most-efficient motor supported by the CEMEP/EU agreement, is equivalent to IE2, the "high-efficiency motors" that will be required from 2011. After that time, this programme will no longer be active, as it will be superseded by the European regulatory standard.

When this scheme was first introduced, there was a voluntary undertaking by motor manufacturers to reduce the sale of motors with the lowest efficiency (EFF3). The CEMEP/EU agreement was a critical first step to advancing motor-efficiency classification and labelling, together with an effective market-transformation programme. Low-efficiency motors (EFF3) were essentially removed from the EU market as a result of this voluntary agreement.

China

Since 1992, China has formulated and revised several national economic operation standards, including:

- GB/T12497-2006: Three-phase Induction Motors, Economic Operation
- GB/T13466-2006: The General Principles of Economic Operation for AC-driven Fan (Pump, Air Compressor) System
- GB/T13469-2008: Economic Operation for Industrial Centrifugal, Mixed Flow and Vortex Pump Systems
- GB/T13470-2008: Economic Operation of Ventilator Systems and GB/T17981-2007 Economic Operation of Air-conditioning Systems

Links with macro-policy initiatives

The activities underway to promote energy-efficient motors and motor systems are all connected with overarching macro-policy objectives of improving global competitiveness of the industrial sector, facilitating development of a green technology industry with export value, and reducing greenhouse gas emissions. Programmes that regulate, promote, educate and encourage the use of more energy-efficient motors and motor systems are aligned with these three broad policy objectives in most major economies.

Evaluation and impacts

Each of the regulators implementing a programme that affects motors or motor systems has a means of evaluating and enforcing regulatory standards. These programmes work to monitor markets, review data and certified test reports, and compare them with regulatory standards. If a product is found to be non-compliant, the procedure followed typically involves consultation, supplementary testing and ultimately potential redesign and penalties.

Voluntary programmes typically also include a monitoring component to assess success of their marketing efforts and market-transformation incentives. This monitoring and evaluation is critical to continuation of the programme and/or strategic redesign and realignment with the target audience.

8. Options and Recommendations for New Policies on Electric Motor-Driven Systems

Policy context

More rigorous policies are required to encourage adoption of energy-efficient electric motor-driven systems (EDMS) and realise the substantial cost-effective savings potentials identified in this report. Despite progress in recent years, international experience demonstrates that without such stimuli, current market barriers significantly impede large-scale adoption of efficient solutions. In economies that have implemented proactive policy measures, there is a marked increase in the diffusion of more efficient electric motors and systems.

To achieve the scale of savings identified, it will be necessary to adopt of a broad range of policy measures in line with best international practice, and to extend the scope of best practice to cover more types of electric motor systems and more of the components within them.

In general, policies need to encourage:

- adoption of more-efficient components within EMDS
- better sizing to task of EMDS
- optimisation of the ensemble of components within EMDS
- use of VFDs for variable-load applications
- better in-field management of EMDS

Minimum energy performance requirements have proved to be the policy approach with most certain impact and the greatest chance of achieving substantial energy savings at low cost. In the form of minimum energy performance standards (MEPS), such policies have been applied successfully to electric motors, pumps, fans and compressors. In the form of MEPS or minimum fleet-average[9] efficiency requirements, they have also worked well for whole classes of packaged integrated systems with electric motors, such as:

- **Domestic appliances:** water circulation pumps including central heating system and pool pumps, refrigerators, freezers, air conditioners, circulation fans, clothes washers, dryers, extractor fans, ovens, etc.
- **Commercial equipment:** circulation pumps, chillers, commercial refrigeration equipment, air conditioners, ventilation fans and air-handling units.

Overall, such system-level minimum energy performance requirements could be applied to almost all electric motor energy use in the residential and commercial sectors, and about 20 % to 40% of industrial-sector EMDS energy use.

In the industrial sector, minimum energy performance requirements for electric motors alone could be set for 75% to 80% of motor electricity use. Furthermore, some common components used in a significant proportion of EMDS are not yet subject to energy-efficiency requirements (*e.g.* transmission belts, gears and VFDs). Regulations for these components could also produce substantial energy savings.

Such minimum energy performance requirements for systems and components can generate significant energy savings in a cost-effective manner. But to achieve maximum energy savings, policies must also take account of load-usage conditions in the duty cycle (full- and partial-load

[9] The fleet average is the weighted-average energy efficiency of each manufacturer's and importer's shipments in predefined product categories.

hours). To encourage adoption of such measures to minimise energy use and/or abate greenhouse gas emissions, policy requirements must be at levels which are cost-effective when compared to other abatement solutions.

In some economies, very significant gaps remain in any type of regulatory policy for motor systems and components; in other economies, coverage is more complete but policies do not yet adequately target major part-load savings. Because it offers the most significant opportunity for savings, regulatory policy for motor systems and components needs the greatest policy attention.

It is also possible and appropriate to set system-level performance requirements at the application level, for example water-pumping energy performance standards set for some water utilities. In principle, similar standards could be developed for a range of applications including:

- conveyors, escalators and moving walkways;
- lifts (elevators);
- water pumping in specified applications;
- compressors in specified applications for compressed air and cooling;
- fans in specified applications.

More work is required to define the scope, structure and potential of such system-level requirements, with options ranging from best practice guidelines to regulatory requirements.

One major barrier requiring policy action is the lack of market transparency regarding energy-efficient solutions for EMDS. In many cases, there is no agreed test procedure or methodology for determining efficiency of EMDS. Equipment suppliers and OEMs may claim certain energy-performance characteristics and benefits, but without standardised tests or methodology, there is an understandable lack of confidence in these claims. This can lead purchasers to reject solutions that are more costly, but potentially justifiable on the basis of life-cycle cost or internal rate of return. Thus, there is a need to conduct a thorough review of all major electric motor-system applications to determine when it will be possible to develop and endorse standard performance assessment procedures on which to base market diffusion and policy support options for energy-efficient EMDS.

Policy recommendations

Although stronger regulation is a powerful tool, there are limitations to what can be achieved through regulation. It is, therefore, important to develop complementary policies to encourage adoption of more energy-efficient EMDS and raise awareness of savings potentials among key stakeholders. The context and opportunities outlined above give rise to recommendations for both regulatory and non-regulatory policy action. An IEA information paper, [Walking the Torque – Energy-Efficiency Policy Opportunities for Electric Motor-Driven Systems September, 2010 sets out a detailed global work plan to implement the recommendations for regulatory policy measures.

Regulatory policy measures

Components: MEPS, energy labelling and test procedures

For components, energy-performance requirements (as either MEPS or minimum fleet-average energy-performance requirements) and energy performance labelling should be applied to:

- AC synchronous motors from 0.75 kW to 375 kW (eventually 100 W to 1 000 kW) sold as individual motors or as motors incorporated into packaged EMDS;
- other types of electric motors (as many as reasonable/feasible);

- types of gears used in EMDS (as many as reasonable/feasible);
- types of transmission systems (as many as reasonable/feasible);
- types of VFDs (as many as reasonable/feasible).

For AC synchronous electric motors, it is recommended that requirements be set at a level that designates IE3 motors or better as the standard motor. Where an economy currently applies such regulations but the requirements do not cover the full power range of 0.75 kW to 375 kW (as set out in IEC efficiency classification IEC 60034-30 [2008]), it is recommended that regulations be revised to cover motors across the full power range as soon as is practicable. Where an economy has set energy-efficiency requirements but is using a test procedure that is not fully aligned with the new IEC test procedures (IEC 60034-2-1 [2007] and IEC 60034-30 [2008]), it is recommended that policy makers consider alignment with IEC test procedures and any modification of the associated efficiency settings that this may entail.

For the other classes of motors that are not covered by IEC, it is proposed that work on defining energy-efficiency test procedures begin as soon as possible to facilitate market transparency and enable the setting of energy performance regulations (such as MEPS and energy labelling). These test procedures should be developed at the international level through the IEC, to serve as complementary standards to the IEC 60034-2-1 standard, which only addresses asynchronous AC induction motors. This will support international transparency in energy-performance settings, and facilitate trade and diffusion of energy-efficient technologies.

For gears, transmission systems and VFDs, it is recommended that work be undertaken to establish and classify categories of products by service function, and to develop repeatable and reproducible energy-performance test procedures. This should improve transparency of energy-performance characteristics of these technologies and facilitate adoption of supportive policy measures such as labelling, minimum energy performance requirements and incentives. It is recommended that policy makers explore options to eliminate inefficient and redundant technologies such as worm gears and V-belts from the market as soon as possible. It will be necessary to develop energy-performance test procedures and efficiency metrics, as it is preferable to avoid technology-prescriptive policy settings by defining such requirements in terms of technology-neutral energy-performance specifications.

Core motor systems: MEPS, energy labelling and test procedures

For core motor systems, energy-performance requirements (as either MEPS or minimum fleet-average energy-performance requirements) and energy-performance labelling should be developed for and applied to standardised large-series varieties of:

- fans
- pumps (explicitly centrifugal pumps and circulation pumps)
- compressors (compressed air and cooling)

For fans, it is recommended that regulations be set to cover all major fan types (axial, centrifugal, mixed-flow, crossed-flow, boxed and roof fans) over as wide an input power range as possible (*e.g.* 0.1 kW to 500 kW). These regulations should apply to fans sold with or without an integrated VSD, and to those which may or may not be equipped with an electric motor when put on the market. The revised international test procedure ISO 5801:2007 deals with determination of the performance of industrial fans of all types except those designed solely for air circulation (*e.g.* ceiling fans and table fans), and is a suitable basis for most required performance measurements. These measures are of high priority because fans account for approximately 18.9% of electric motor-system energy consumption, and potential systems improvements for fans in OECD economies are probably of the order of 40%.

For pumps, the European Union's EuP Lot-11 study allows comparison of the efficiency of a very wide variety of pumps[10] on a three-dimensional surface plot expressing efficiency as a function of pump speed and flow rate. A related metric compares pump efficiency at the pump's best energy performance point (BEP) load, at 0.75 times the BEP load and 1.10 times the BEP load to create a part-load weighted-average performance. It is proposed that other economies consider using this work as a starting basis for defining their energy-efficiency metrics for pumps. If complementary test standards are developed to compare pumps with integrated VFDs with other classes of pumps, it would be possible to define core system-performance requirements that would allow adoption of minimum energy performance regulations favouring solutions which minimise part-load losses and encourage efficient pump control solutions. For some other types of pumps (such as impellers used for water circulation in secondary heating or cooling systems), it may be appropriate to set requirements using an energy-efficiency index. These measures are of high priority because pumps also account for approximately 18.7% of electric motor system energy consumption, and potential systems improvements for pumps in OECD economies are probably of the order of 40%.

Compressors account for approximately 32% of electric motor-system energy consumption, and systems improvements of at least 25% are viable. Adopting policy measures to increase compressor efficiency should therefore also be a high priority. In principle, it is possible to adopt MEPS for compressors, although currently only China has done so. For further policy development targeting compressors, pressing issues to be addressed include how to treat the different classes of air and cooling compressors and how to take account of part-load performance. High priority should be accorded to developing international energy-performance measurement standards for compressors, with the ultimate goal of developing energy-efficiency metrics and minimum energy performance regulations.

Full motor systems: Minimum energy performance guidelines and regulations

In some cases, it is possible to define overall electric motor-system performance specifications that can then be applied as guidelines and or even regulatory energy-performance obligations. The full EMDS combines the core system and the electromechanical application; for performance specifications to be set at this level, the application and service must be sufficiently commonplace and standardised. Applications where this is, or is likely to be, achievable include:

- water pumping for mains water and sewage works;
- conveyors, escalators and moving walkways;
- lifts (elevators).

It is recommended that end-use industrial electric motor applications be better characterised to determine which systems are viable candidates for systems-level performance specifications and guidelines. For those so identified, energy-performance guidelines, and potentially regulations, should be produced in due course.

Non-regulatory policy measures

Some important aspects of electric motor-system energy performance cannot be easily regulated and thus additional policy measures are needed to bring about substantive progress. In general, there is a need to increase awareness of opportunities and issues; encourage more rational system procurement; encourage better system management; and encourage the supply of energy-efficient EMDS solutions.

[10] These include: ESOB (end-suction own-bearings pumps), ESCC (end-suction close-coupled pumps), ESCCI (inline end-suction close-coupled pumps), MS (multistage pumps) and MSS (submersible multistage pumps).

Awareness

To move forward on these issues, it is essential to enhance awareness of the scope for cost-effective energy savings among all stakeholders: energy managers, plant operators, equipment procurers and senior management within companies. This requires specific and sustained activities, tools, exercises and literature targeted to each of the key actors within the decision-making chain. The objective is to boost end-users' demand for energy-efficient EMDS solutions and their willingness to invest in cost-effective solutions to help them achieve energy services at least cost (including at least CO_2-abatement cost if carbon cap and trade obligations apply).

In addition, substantive efforts are needed to encourage optimal decision-making and improved electric motor-system management practices. These should target energy, plant and procurement managers' needs with respect to EMDS to encourage:

- **Optimal selection of EMDS for task:** including best practice in sizing and control options, calculating the internal rate of return on given energy-efficient investments, assessing system reliability and investment risks.
- **Optimal motor management practice:** including integrating new energy-efficient solutions into existing plant with minimum risk of service or production disruption, monitoring electric motor stocks and managing replacement options.

Incentives

In the absence of stronger end-user demand for more-efficient EMDS, it is likely that OEMs will continue to supply products using low-cost solutions and will underinvest in energy-efficient solutions such as variable-frequency drives (VFD). To help overcome this, governments may wish to encourage the provision of fiscal or financial incentives to help cover the first cost of energy-efficient EMDS. These incentives may not be needed where MEPS or other energy-performance regulations are set at a level that would promote least life-cycle cost or least-cost carbon-abatement solutions. However, where this is not (or not yet) the case, such incentives would be a helpful means of overcoming the disincentive for OEMs to supply energy-efficient systems. In addition, it must be recognised that regulations that stimulate increased efficiency of new EMDS may increase the first cost of new systems and thereby inadvertently stimulate retrofit and repair of old, inefficient electric motors and EMDS. Fiscal or financial incentives could play a positive role in stimulating the sale of new, efficient equipment and accelerating the phase-out of inefficient solutions.

Thus, it is recommended that:

- For EMDS where regulations do not push markets towards least life-cycle cost or least-cost carbon-abatement solutions, governments should consider introducing fiscal or financial incentives to buy down the first-cost increment of energy-efficient electric motor systems compared with standard-efficiency solutions.
- Where there is a risk that energy-efficiency regulations may prolong the life of inefficient EMDS, governments may wish to introduce fiscal or financial incentives to buy-down the first-cost increment of energy-efficient electric motor systems compared with standard-efficiency solutions.
- When public-policy environments acknowledge the need to enhance energy security and reduce greenhouse gas emissions at a faster rate than the natural replacement cycle, governments may wish to introduce incentives to encourage the replacement of existing inefficient EMDS at an accelerated rate to effect the most rapid transformation of the market to high-efficiency electric-motor systems.
- For economies that apply direct financial support to sustainable energy solutions (such as feed-in tariffs or utility portfolio requirements for renewable energy), it is proposed that energy-efficient EMDS be prioritised for economic assistance to prevent inefficient use of

public resources. As the majority of energy-efficient EMDS are significantly less costly per kilowatt installed (avoided watts of installed power demand) than are sustainable electricity-supply options per kilowatt installed, it makes sense to prioritise advancement of energy-efficient EMDS through public subsidy.

In all the above cases, policy makers have a choice of economic instruments that can be applied to encourage the uptake of energy-efficient EMDS. These include:

- Provision of soft loans (pay as you go) to buy down the cost of interest on borrowing to invest in more energy-efficient EMDS where energy cost savings pay for the interest.
- Direct financial incentives on product purchase price.
- Tax credits such as allowing incremental or full costs of energy-efficient systems to be written off against taxable corporate profits, reducing tax on profits from the sale of energy-efficient EMDS by OEMs, or reducing the VAT (or GST) on the sale of efficient systems.
- Utility energy-efficiency schemes to buy down the cost of energy-efficient EMDS.

Capacity building

Considering the huge importance of EMDS for the energy sector as a whole, and the need to increase capacity at multiple levels and to improve the performance of EMDS in a range of applications, governments should:

- Consider providing extensive and co-ordinated research support for energy-efficient electric motor-driven systems.
- Build capacity, knowledge and awareness, possibly by creating national or international institutions dedicated to supporting the development and adoption of energy-efficient EMDS.
- Support efforts to build capacity and boost awareness targeting key economic actors and sectors.
- Support international capacity-building through enhanced international co-operative efforts and inclusion of measures in development support programmes.

Monitoring

To assist the application of incentives, work is needed to clearly define classifications of energy-efficient EMDS to ensure that incentives put in place address real market barriers and do not encourage sub-optimal solutions. For example, incentives should encourage use of VFDs, but not to the degree that they are used in constant-load applications, where they would simply incur additional costs and increase energy use. Similarly, incentives should be developed to encourage and support the correct sizing of equipment, the systematic monitoring of system energy performance and use, and the use of energy-efficient mechanical solutions.

Potential policy impacts

To enable modelling of rough policy-scenario impacts based on full implementation of the recommendations above, a simple bottom-up model was developed based on the findings in Chapter 3.

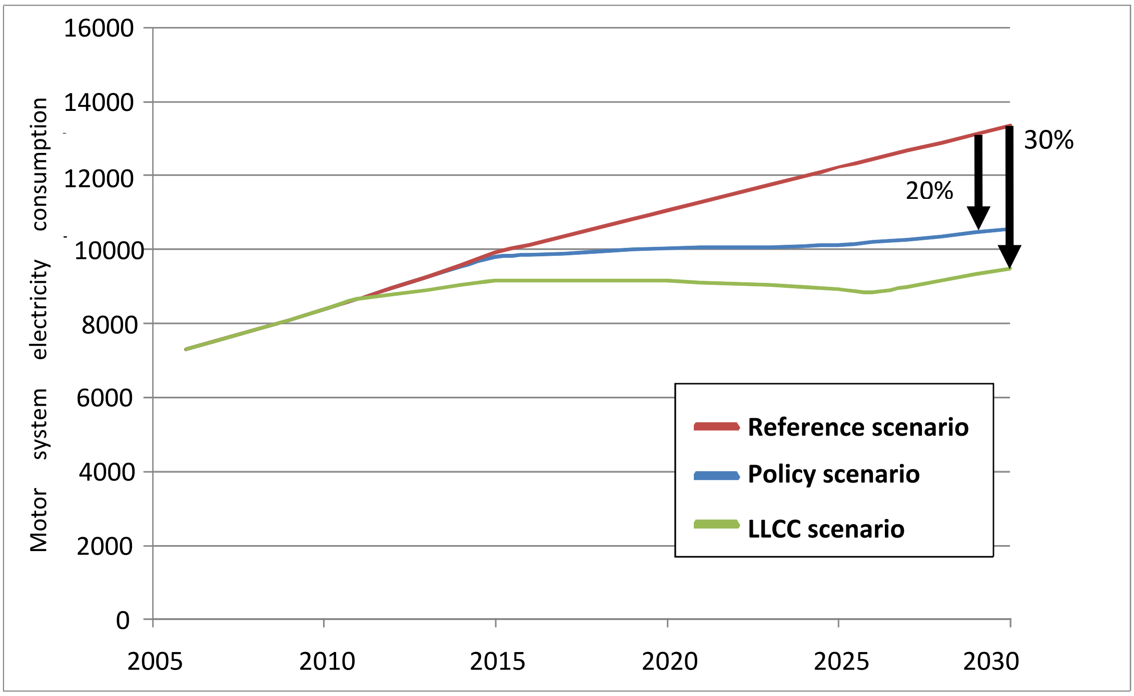
Using this model, it is projected that, without additional policy measures, global energy consumption from EMDS will rise from 8 360 TWh per year in 2010 to 13 360 TWh in 2030 – an increase of 60%. Associated CO_2 emissions will increase from 6 041 Mt in 2010 to 8 570 Mt in 2030. End-users currently pay about USD 565 billion per year for electricity consumed by EMDS; without enhanced energy-efficiency measures, this is projected to rise to almost USD 900 billion by 2030.

If all countries were to adopt only one measure, best practice MEPS for industrial electric motors, it is estimated that approximately 322 TWh of annual electricity demand would be saved by 2030, giving rise to corresponding savings of 206 Mt of CO_2 emissions. Important as these savings are, much larger savings would accrue if all motor-driven systems were properly optimised across the system as a whole.

If a broad-based and rigorous policy package were put in place, it is estimated that globally, by 2030, it would save some 24 000 TWh in electricity demand, avoid some 16 Gt of CO_2 emissions and generate cost savings of about USD 1.7 trillion(Figure 41). These savings would come at less cost than supplying this energy. Annual savings in 2030 would be of the order of 2 800 TWh in electricity demand, 1 790 Mt of CO_2 emissions and USD 190 billion in electricity costs.

If it were possible to move all EMDS towards the least life-cycle cost level as rapidly as technically possible, it is estimated that some 42 000 TWh of electricity demand, 29 Gt of CO_2 emissions and USD 2.8 trillion in electricity costs would be saved globally by 2030. Annual savings in 2030 would be of the order of 3 890 TWh in electricity demand, 2 490 Mt of CO_2 emissions and USD 264 billion in electricity costs.

Figure 41: Projected global electric motor-system electricity consumption



Abbreviation: LLCC = least life-cycle cost.

Notes:
Reference scenario: when the current situation is maintained without additional policy measures.
Policy scenario: when all countries adopt a broad-based and rigorous policy package on EMDS.
LLCC scenario: when all EMDS are moved toward the least life-cycle cost level.
Source: IEA estimate.

Comprehensive integrated policy package

To help achieve the tremendous potential for cost-effective energy savings in electric motor-driven systems, governments should consider, as a first measure, adopting mandatory MEPS for electric motors in line with international best practice, subject to due process and cost-effectiveness analysis.

These standards should apply to as many types and sizes of electric motor as it is feasible to address and should not just be confined to mid-size asynchronous AC motors that are sold as separate components. The level of these standards should be set at no lower than the least life-cycle cost, which is generally at IE3 or higher for mid-size asynchronous AC induction motors. Even larger energy savings can be achieved by using VFDs, which dynamically match the output power of motor systems to the power demanded by the drive train. Further savings can be achieved by using efficient transmission and gear systems, and through better sizing and management of electric motor-driven systems.

Overall it is estimated that it is cost-effective to save about 20% to 30% of total global electric motor demand (*i.e.* roughly 10% of all global electricity consumption) through the use of more-efficient electric motors and drives. Achieving such savings will require individual and concerted action on the part of all players, including regulators, policy makers and standards development agencies.

It is proposed that IEA member countries and non-member economies apply a market-transformation package based on the proposed portfolio of energy performance policies including regulations, incentives, awareness-raising, capacity-building and monitoring efforts set out in the following package of policy recommendations:

Regulatory

1. **MEPS** should be introduced in IEA member countries in line with international best practice for all major classes of electric motors. They should not be set at levels less than IE3 (as defined within IEC 60034-30 and IEC 60034-31) for asynchronous motors. These requirements should apply to motors sold individually or integrated into pre-packaged electric motor-driven systems, and should apply to motors with as wide a range of output power as is practicable (100 W to 1000 kW).
2. Regulatory measures, such as **MEPS and energy labelling**, should be introduced for packaged integrated motor-driven energy end-uses between 100 W and 1000 kW, including fans, pumps, circulation pumps and compressors that are produced in sufficiently large volumes to have significant energy consumption.
3. Regulators, policy makers and standards development agencies should ensure that **energy performance test procedures are developed for all motor types** that use significant amounts of electricity and are not covered by existing internationally agreed test procedures.
4. Regulators, policy makers and standards development agencies should commission the development and application of **energy-performance test procedures to cover other essential components** of electric motor-driven systems, including transmissions, gears and system control devices (*e.g.* VFDs). In addition, efforts should be made to develop energy-performance test procedures and guidelines that apply to whole electric motor system applications, such as utility water-pumping, lifts (elevators), escalators, conveyors, etc.
5. Regulators should explore the feasibility of developing **minimum energy performance standards for certain classes of gears and transmissions** to discourage (and later prohibit) the use of inefficient solutions such as worm gears and V-belts.

Non-regulatory

6. Large-scale **awareness programmes** should be developed and put in place to inform industrial and commercial electricity users of the significant savings potentials possible through the use of efficient electric motor-driven systems. These programmes should target those responsible for procurement of electric motors and motor-driven systems, including

operations and maintenance managers, production and plant managers, and company executives and decision makers responsible for overall company policy on energy, carbon and cost reduction.

7. **Incentive schemes** should be developed and applied to encourage adoption and use of best practice motor sizing, management and integration, including the appropriate use of VFDs. These should be targeted at the systems producing the highest benefit, namely for pumps, fans and other applications with variable mechanical loads (where torque increases nearly as the square of the rotational speed of the motor). In most cases, cost-effective savings can also be achieved when VFDs are used for conveyors, hoists, escalators and similar applications (where torque is more or less independent of the motor speed). Incentive schemes are also likely to be beneficial for these applications.
8. **International capacity-building** efforts should be substantially expanded to create permanent structures, at a scale sufficient to support ongoing needs in the domain of energy-efficient electric motor-driven systems.
9. **Global market monitoring** should be established at defined intervals, to support national regulation and incentive programmes with market-transformation data.

Putting ideas into practice

Realising these savings opportunities by 2030 will require a clear a plan of action and rapid implementation of an effective set of structural and consensus-building endeavours. It is proposed that IEA member countries establish a timetable for implementation of the nine policy recommendations. To aid that process, the authors have identified timelines for completion of the steps necessary to progress EMDS toward the identified energy-savings goals by 2030. (Table 38).

Table 38: Proposed timetable for implementation of recommendations

Recommendations	Phase 1 In 2011	Phase 2 2012-15	Phase 3 2016-20	Phase 4 2021-25	Phase 5 2026-30
Regulatory policy measures					
Implementation of motor MEPS.	COMMENCE	COMPLETED			
Regulatory measures for packaged integrated motor-driven energy end-uses.	COMMENCE	COMPLETED			
Development of international test procedures for other electric motor types.	COMMENCE	CONTINUE	COMPLETED		
Development of international test procedures for other electric motor system components.		COMMENCE	COMPLETED		
Regulatory measures for gears and transmissions.		COMMENCE	COMPLETED		
Non-regulatory policy measures					

Recommendations	Phase 1 In 2011	Phase 2 2012-15	Phase 3 2016-20	Phase 4 2021-25	
Development of large-scale awareness programmes.		DEVELOP	ROLL-OUT	ROLL-OUT	ROLL-OUT
Development of incentive schemes.		DEVELOP	IMPLEMENT		
International capacity-building efforts and creation of a permanent support structure.	COMMENCE	COMPLETE	ROLL-OUT	ROLL-OUT	ROLL-OUT
Global market monitoring (to support national regulation and incentive programmes with market-transformational data).	COMMENCE	REPORT 2015	REPORT 2020	REPORT 2025	REPORT 2030

To support the underpinning recommendation regarding the adoption of mandatory minimum energy performance standards for electric motors, it is proposed that IEA member countries adopt a policy position as quickly as possible, with an IEA report on it before 2015. IEA member countries can then be positioned as lead actors in a push for globally co-ordinated action on motors, with supporting project work to engage with major motor-manufacturing countries (such as China, Brazil, India and others).

In addition, it is proposed that the IEA immediately commission a comprehensive study, for delivery in 2011, to assist member countries in their efforts to implement these measures within the proposed timeframes. As binding policy decisions are taken by IEA member countries, this study should evolve into a regular update on implementation plans.

The IEA Secretariat should also work with the non-member economies that produce and export significant volumes of electric motors and electric motor-driven components to ensure that this co-ordinated plan will gain their support.

Annex A. Technical Standards for EMDS

Internationally harmonised performance standards are crucial for market development of high-efficiency products and systems. If testing standards, performance definitions and efficiency classifications are inconsistent and confusing for product users, eventual market transformation lags.

In this annex, the authors review technical standards for motors (AC and DC), VSDs in common integrated applications (pumps, fans, compressors), and assemblies operating within site-assembled motor-driven systems.

Recently updated standards for electric motors have reached the first level of international harmonisation:

- IEC 60034-2-1 (2007) Testing Standard
- IEC 60034-30 (2008) Efficiency Classification

Testing standards for converter-fed motors are underway and will be available as IEC 60034-2-3 in 2011. Efficiency classifications for VFD will follow. For pumps and fans, ISO testing standards exist and are currently being updated. Performance and efficiency classifications are only now being studied.

Establishing minimum energy performance standards (MEPS) in national legislation and regulation requires a solid base with internationally agreed testing and performance standards and a global efficiency classification. It is obviously much more complex to establish MEPS at the total-system level. However, MEPS can be developed for core systems with packaged products such as pumps and fans, as demonstrated by the most recent EuP decision on circulator pumps.

The top-down approach with formal Energy Management Standards in ISO and European Standards (EN), including benchmarks and regular assessment of potential energy savings, will help industry to identify the best cost benefit solutions.

In addition to the standards mentioned above, the IEC's Technical Committee 2 (IEC/TC 2) addressing rotating machinery has developed a draft standard to support selection and application of energy-efficient motors, including variable-speed applications. This document (*IEC 60034-31: Rotating electrical machines - Part 31: Guide for the selection and application of energy-efficient motors including variable-speed applications*) contains technical guidelines for the application of energy-efficient motors in constant-speed and variable-speed applications.

For approximately 15 years, regional agreements were negotiated in many areas of the world regarding efficiency classes of three-phase, cage-induction motors with outputs up to about 200 kW, as motors of this size are installed in high quantities and are for the most part produced in series. Energy efficiency was not a top priority because the design of these motors is often driven by market demand for low investment cost.

Standards developed by IEC/TC 2 do not deal with methods of how to obtain a high efficiency, but rather with tests to verify the guaranteed value. IEC 60034-2-1 is the most important standard for this purpose. IEC 60034-30 IE defines efficiency classes for single-speed cage-induction motors and specifies test procedures as follows:

- IE1 Standard-Efficiency
- IE2 High-Efficiency
- IE3 Premium-Efficiency
- IE4 Super-Premium-Efficiency

The pending IEC standard 60034-2-3 will include determination of efficiency for motors powered by a frequency converter. However, for motors rated 1 MW and above, which are usually custom-made, high efficiency has always been one of the most important design goals. The full-load efficiency of these machines typically ranges between 95% and 98%. Efficiency is usually part of the purchase contract, with provision for penalties if guaranteed values are not met.

Table 39: Key international standards

Standard	Content
IEC 60034-1	Rotating electrical machines – Part 1: Rating and performance
IEC 60034-2-1 4th edition	Rotating electrical machines – Part 2: Methods for determining losses and efficiency of rotating electrical machinery from tests (excluding machines for traction vehicles)
IEC 60034-12	Rotating electrical machines – Part 12: Starting performance of single-speed three-phase cage induction motors
IEC TS 60034-17	Rotating electrical machines – Part 17: Cage induction motors when fed from converters - Application guide
IEC TS 60034-25	Rotating electrical machines – Part 25: Guidance for the design and performance of A.C. motors specifically designed for converter supply
IEC 60034-26	Rotating electrical machines – Part 26: Effects of unbalanced voltages on the performance of three-phase cage-induction motors
IEC 60072-1	Dimensions and output series for rotating electrical machines – Part 1: Frame numbers 56 to 400 and flange numbers 55 to 1 080
IEC 60079-0	Explosive atmospheres – Part 0: Equipment – General requirements
IEC 60300-3-3	Dependability management - Application guide – Life cycle costing
IEC 61800-8	Adjustable speed electrical power drive systems – Part 8: Specification of voltage on the power interface

Source: International Electrotechnical Commission.

Table 40: Other regional standards

Standard	Content
EN 50347	General purpose three-phase induction motors with standard dimensions and outputs – Frame numbers 56 to 315 and flange numbers 65 to 740
NEMA ICS7.1	Safety Standards for Construction and Guide for Selection, Installation, and Operation of Adjustable-Speed Drive Systems
NEMA MG1	Motors and Generators
NEMA MG10	Energy Management Guide for Selection and Use of Fixed Frequency Medium AC Squirrel-Cage Polyphase Induction Motors
NEMA MG11	Energy Management Guide for Selection and Use of Single-Phase Motors

Source: European Committee for Electrochemical Standardization (CENELEC) and National Electrical Manufacturers Association (NEMA).

Abbreviations

ASD	Adjustable-speed drive (general term for adapting to partial load)
ANSI	American National Standards Institute
ASME	American Society of Mechanical Engineers
BEP	Best energy performance point
CEMEP	European Committee of Manufacturers of Electrical Machines and Power Electronics
CAC	Compressed Air Challenge®
CSA	Canadian Standards Association
DIS	Draft International Standards
DOE	US Department of Energy
EC	Electronically commutated (motor)
Eco-design	EC Directive for Energy-using Products 2005/32/EC
EEI	Energy-Efficiency Index
Eff	CEMEP motor classification (Eff1, Eff2, Eff3)
EISA	Energy Independence and Security Act (United States)
EMDS	Electric motor-driven system
EN	European Standards
EPA	US Environmental Protection Agency
EPAct	Energy Policy Act, 1992 minimum energy performance standards for electric motors
ESCC	End-suction close-coupled
EU	European Union (numbers refer to the number of countries included, *e.g.* "EU-27")
EuP	Eco-design Directive for Energy-Using Products 2005/32/EC
FDIS	Final Draft International Standard
FEMP	Federal Energy Management Program
GDP	Gross domestic product
GW	Gigawatt (10^9 W)
HEM	Higher-efficiency motor (*e.g.* IE3 or NEMA Premium efficiency class)
hp	Horsepower
HVAC	Heating, ventilating and air conditioning
Hz	Hertz
ICT	Information and communication technology
IE1	New IEC 60034-30 Energy-Efficiency Classes for electric motors (roughly equivalent to Eff2)
IE2	New IEC 60034-30 Energy-Efficiency Classes for electric motors (roughly equivalent to Eff1 and EPAct)
IE3	New IEC 60034-30 Energy-Efficiency Classes for electric motors (roughly equivalent to NEMA Premium)
IE4	Super premium efficiency level as defined within IEC 60034-30 and IEC 60034-31
IEA	International Energy Agency, Paris, France
IEC	International Electrotechnical Commission, Geneva, Switzerland
IEEE	Institute of Electrical and Electronics Engineers

IPCC	Intergovernmental Panel on Climate Change
IRR	Internal rate of return
kW	Kilowatt (10^3 W)
LCC	Life-cycle cost
LLCC	Least life-cycle cost
MEPS	Minimum energy performance standard
MW	Megawatt (10^6 W)
Nm	Newton metre
NEMA	US National Electrical Manufacturers Association
OEM	Original equipment manufacturer
PLL	Phase-locked loop
PM	Permanent magnet (motor)
rpm	Revolutions per minute
SEEEM	Standards for Energy Efficiency of Electric Motor systems (www.seeem.org)
SFP	Specific fan power
TEP	Technology Economics Policy, Research and Advice, Zurich, Switzerland
Topmotors	Swiss efficient-motors implementation programme (www.topmotors.ch)
TWh	Terawatt-hour (10^{12} Wh)
VFD	Variable-frequency drive (specific technology to adapt to variable load)
VSD	Variable-speed drive (see ASD)

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