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Perspectives on Electric Motor Market Transformation for a Net Zero Carbon Economy

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Abstract: Energy efficiency is one of the most powerful strategies to mitigate the impacts of climate change by reducing energy demand, which in turn reduces the emissions of Green House Gases (GHG), as well as reducing the burden on the supply side renewable generation expansion. Because electric motors systems represent such a large share of the overall electricity consumption (over 50%), large savings potential could be made available by the use of energy-efficient motor systems both in new installations and by accelerating the replacement of old inefficient motors. Since electric motors are very reliable, their lifetime is long (according to recent studies it may exceed 20 years) which translates into a very inefficient existing stock despite worldwide policy efforts. This paper analyzes the current efficiency of the installed stock and the causes for its low efficiency, possible policy options to increase its the efficiency, the role of new technologies and improvements possible by targeting the entire motor system at the time of motor replacement. The paper presents an innovative analysis of the estimated impact of increasing the uptake of high-efficiency motors and motor systems; effective policies could translate into 100 TWh/year in the European Union if additional measures, such as addressing oversizing, proper controls (VSDs) and digitisation, are also implemented. If similar measures were adopted globally, the savings triggered could be at least tenfold reaching over 1000 TWh/year.

Keywords: electric motors; electric motor systems; motor replacement; energy efficiency; net zero carbon; industry decarbonisation

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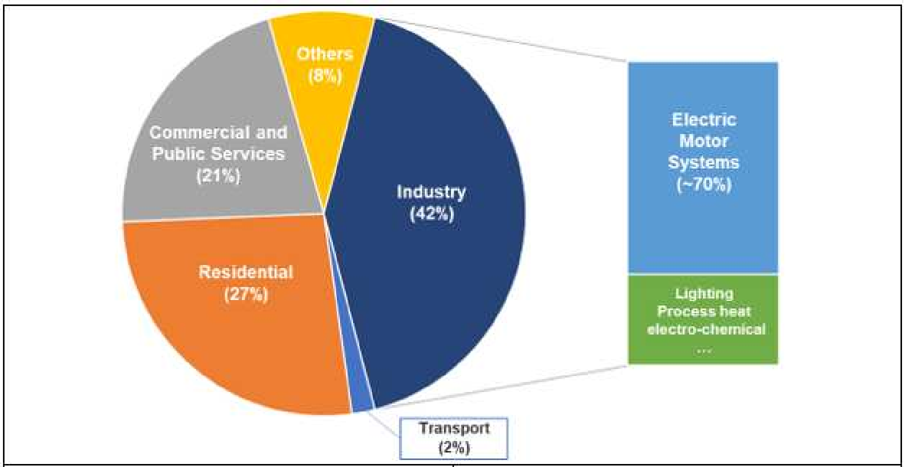
1. Introduction

In 2015, 195 countries signed the Paris Agreement [1], committing to 'to keep the increase in global mean surface temperature to well below 2 °C, and to limit the increase to 1.5 °C, since this would significantly reduce the risks and impacts of climate change'. To achieve this impressive goal, emissions need to be reduced by 45% by 2030 and reach net zero by 2050.

For that purpose, one of the most important contributions comes from the rapid deployment of energy-efficient technologies, which play a prominent role in the abatement of CO_2 emissions. Energy efficiency is essential in curbing energy demand and is most important in the early stages of the decarbonization process while other mitigation strategies are still in development. Improving the penetration of energy-efficient technologies will significantly reduce the burden on renewable generation, in particular because these technologies are readily available, are cost-effective and can be rapidly scaled-up [2]. In addition to global climate change mitigation, energy efficiency provides multiple benefits including a crucial contribution to energy supply security, to increase business competitiveness and citizens welfare, including major health benefits associated with a cleaner environment [3,4].

Some of the most relevant technologies, which have witnessed significant energy efficiency improvements in the last decades, are applied in electric motor systems. According to the IEA [5] 53% of the electricity worldwide is used in electric motor systems

(12,100 TWh) representing emissions of 6 Gton CO_2eq. In 2019, electric motors represented around 70% of the electricity consumption in industry (6700 TWh) (see Figure 1) and are a very relevant consumer in the tertiary sector (over 40%) [5,6]. In agriculture motor systems used for irrigation purposes, use most of the electricity in that sector. Their very large energy consumption means that even a small improvement in efficiency translates into very large absolute savings. Therefore, improving the uptake of energy-efficient motors and motor systems seems to be an important avenue to help reach the ambitious climate goals set out by European and international policy makers.



Industry	**9566 TWh**
Transport	**420 TWh**
Residential	**6072 TWh**
Commercial and public services	**4849 TWh**
Others (agriculture and fishing)	**1940 TWh**
Total:	**22,847 TWh**

Figure 1. Worldwide electricity use / Industrial motor systems electricity use (Source: Authors, data from IEA, 2019).

To corroborate the importance of electric motors, in its 2021 World Energy Outlook [6], the IEA identified 40 milestones without which total final energy consumption would be around 30% higher by 2030 (Figure 2). One of these milestones is that all motor sales are best in class by 2035. This goal is unachievable if strong measures are not taken in the short term to steer the market in that direction.

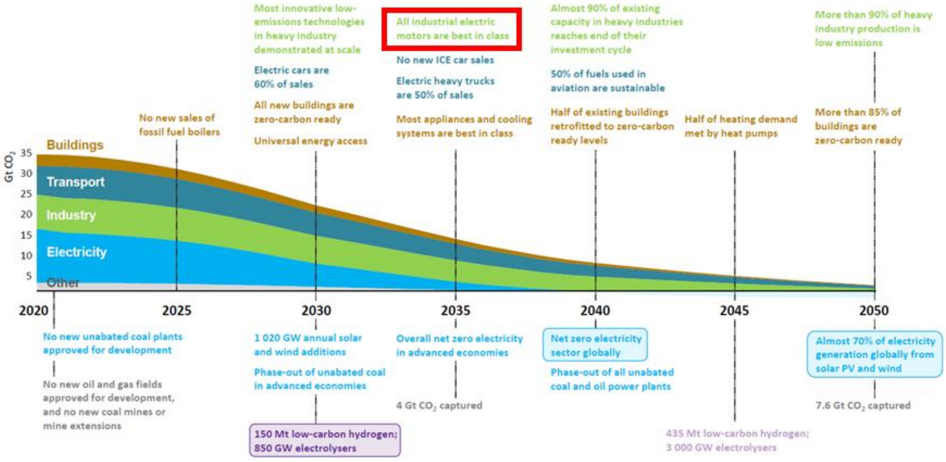


Figure 2. IEA Net Zero by 2050: A Roadmap for the Global Energy Sector [7].

This paper carries out an innovative analysis of the efficiency of the installed base of electric motors and, in particular, the effect of equipment lifetime in maintaining a low-efficiency stock, leading to the need of promoting its accelerated replacement. Recent studies indicate that the lifetime of motors is greater than previously considered which effects the estimation of the impact of the deployment of energy efficiency measures. Furthermore, the paper reviews the current barriers to the uptake of more efficient motors and common policy options used to overcome these barriers. It also reviews the potential savings that can be achieved by using the most recent high-efficiency motor technologies, as well as by putting in place additional associated measures directed not only at the motor but at the entire motor system at the same time of the replacement of old inefficient motors.

2. Efficiency of Installed Base

The importance of motor systems electricity consumption (and corresponding emissions) has long been recognised and minimum energy performance standards (MEPS) regulations and labelling programs for electric motors are now in place in all industrialised countries.

Although initially based on different national efficiency test and classification standards, making for a confusing global motor market, these MEPS are now based on internationally harmonised standards, namely the following:

- IEC 60034-2-1:2014—Rotating electrical machines—Part 2–1: Standard methods for determining losses and efficiency from tests (excluding machines for traction vehicles) [8]
- IEC 60034-30-1:2014—Rotating electrical machines—Part 30–1: Efficiency classes of line operated AC motors (IE code) [9]

IEC 60034-30-1 standard defines the motor efficiency classes from IE1 (Standard) to IE4 (Super-Premium). An additional class IE5 (Ultra-Premium) is proposed, but not defined in the standard. This classification is used to define the minimum efficiency levels for electric motors placed in the market in the respective countries. North America (United States and Canada) was the first economic area to implement MEPS, at the IE2 level, in 1997, which have meanwhile been raised in 2010 to the IE3 level [10]. Other countries have followed this model, using the IE2 level as a first step to allow manufacturers some time to adapt to the market, before raising MEPS to IE3. The European Union (EU), Switzerland and Turkey have recently introduced the most advanced MEPS at IE4 level for motors between 75 kW and 200 kW, active from July 2023. MEPS for Variable Speed Drives (VSDs) at IE2 level has also been adopted for the first time at world level in the same countries in 2021 (Figure 3).

Unfortunately, the penetration rate of these highly efficient technologies is slowed down due to the long lifetime of electric motors which is retarding the realisation of the energy savings potential of the MEPS regulations.

Average motor lifetimes have usually been considered to be 12 to 20 years depending on nominal power [11–13]—the lower value corresponding to small motors (from 1 kW to 7.5 kW) and the larger value to larger motors (from 75 kW up to 375 kW). Recent major field assessments in USA and Europe have shown that these average figures seriously underestimate the actual lifetimes, with substantially older motors still in operation.

In 2013 the Swiss Energy Agency S.A.F.E. assessed 4124 separate motor systems in 18 factories [14]. The results are shown in Figure 4.

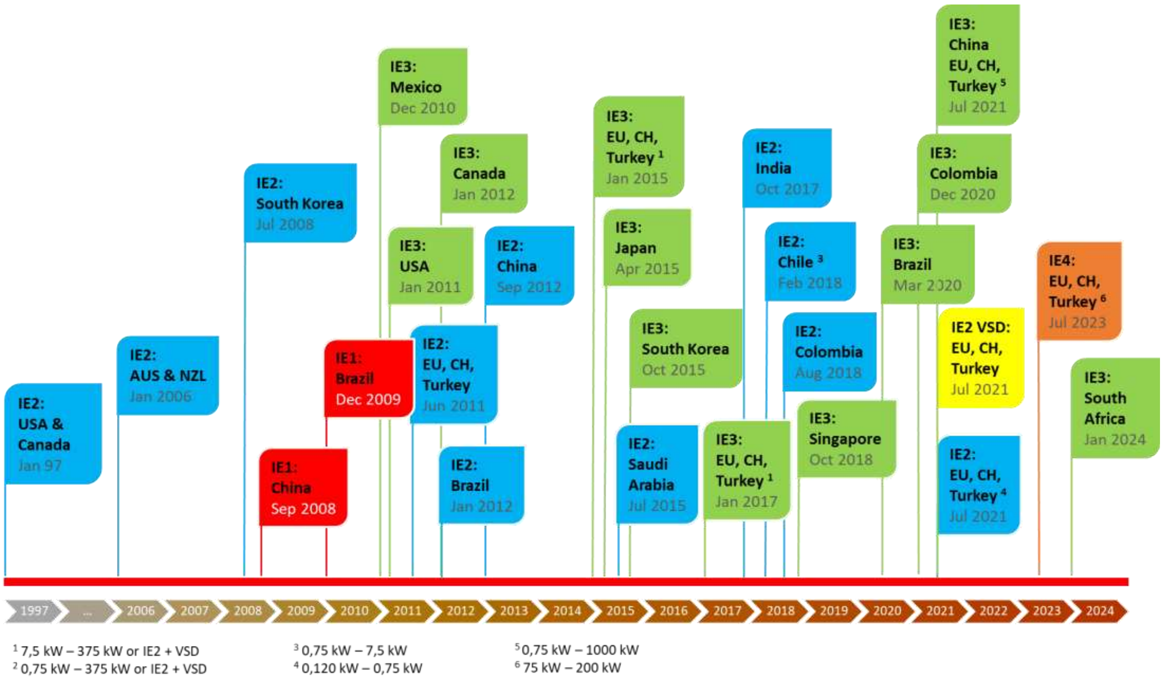


Figure 3. Timeline of introduction of MEPS in different countries/economies (Source: Authors).

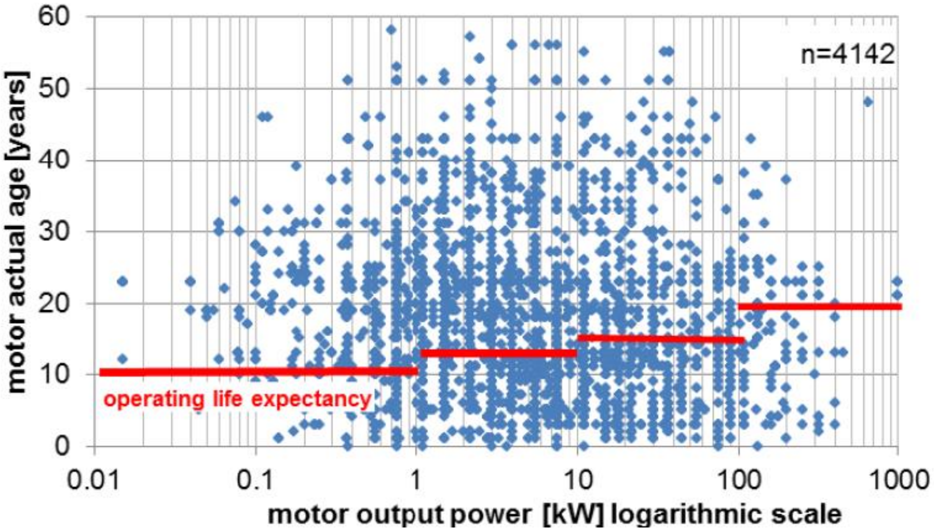


Figure 4. Electric motor age, Switzerland (S.A.F.E. 2013).

The analysis shows that 56% of all motors and their respective systems were older than their expected operating lifetime (some were twice the expected age). Although the analysis was restricted to Switzerland it can be expected that the situation is similar in the EU.

In 2021, an updated DoE US Motor System Market Assessment [15] led by Lawrence Berkeley National Laboratory (LBNL) was published, which provides an updated, more comprehensive assessment of the installed stock of motor systems in both the industrial and commercial sectors. The analysis concerning the age of the installed stock also points in the same direction, as shown in Figure 5.

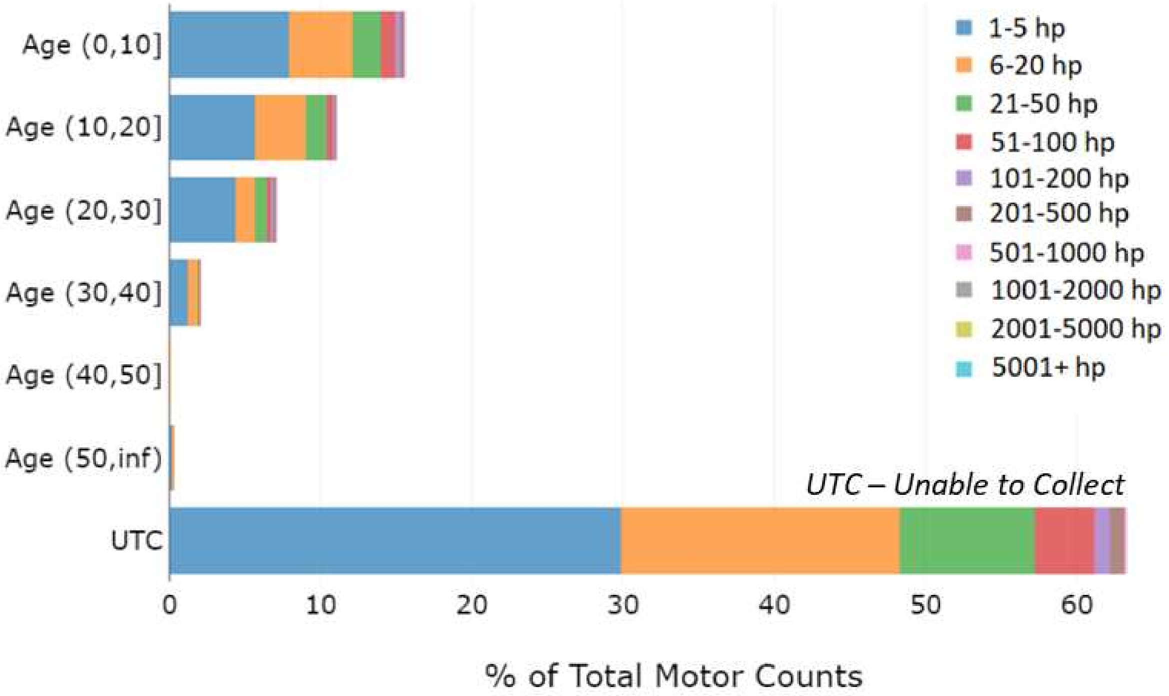


Figure 5. Age of industrial motor systems broken down by size (Source: DoE, 2021).

The extended lifetime of motors is due to persisting barriers to the uptake of more efficient motors, identified in [10–12], such as the following:

- **Efficiency impact**. Major energy savings (typically in the range 20–30%) are possible when the replacement of the old inefficient motor is made with the optimisation of the whole motor system.
- **Efficiency ranking**. When considering options for efficiency improvements in a company, motors are considered as low priority compared to other measures, notably due to the fact that the percentage points gain is limited (though absolute electricity saving figures are relevant).
- **Higher initial investment**. Companies often decide based on initial upfront investment rather than on life cycle costs.
- **Lack of awareness** about the additional benefits of energy-efficient motors and motor systems. The use of higher-efficiency motors and motor systems bring along benefits, such as lower maintenance due to lower operating temperatures or process improvements, that are often not taken into account in the decision-making process.
- **Quick availability**. When vital plant equipment fails there is a need for it to be brought on-line again as soon as possible. This means that when a motor fails maintenance staff will take the quickest action in order to keep downtime at a minimum. This often means repairing the motor or replacing it with an old motor in stock. Additionally, repairing a motor is often viewed as being the technically lowest risk option.
- **Stocks of old motors**. Many sites have stocks of older “salvaged” motors and “new old stock” motors of low efficiency, which are ready to replace a damaged motor and there is a natural tendency to use these “free” motors rather than purchasing new motors.
- **Split goals**. Different company departments (production, energy, maintenance, commercial, financial, etc.) often have different immediate goals. Sometimes, lack of coordination between different departments, together with the low budgets for energy efficiency projects, may lead to electric motor systems efficiency improvements being disregarded.

- **Energy audits**. Energy audits are, sometimes, not anchored in the reality of installations, and sometimes do not identify energy savings opportunities in motor systems, leading to recommendations that are not practical or cost-effective to implement.

This results in a very aged and inefficient installed stock of electric motors, probably below IE1 Class at global level (some motors may have been repaired more than once leading to an efficiency drop), underlining the need to introduce effective policies to renovate the electric motors installed base, raising its efficiency to meet today's technological potential and to contribute to addressing climate change mitigation goals.

3. Policy Options

To overcome these barriers, and reap the significant savings possible, implementation of different policies aimed at increasing the uptake of energy-efficient electric motors is needed. These policies include the following [11,12,16,17]:

- Raising MEPS levels
- Financial Incentives
- Energy Audit Programs
- Raising Awareness and Information Provision

Although minimum energy efficiency regulations for electric motors are in place in all industrialised countries, raising the level of minimum requirements to meet the most recent cost-effective technology developments is paramount, particularly in countries where standards are still at IE2 level. Recent technological development has led to the market introduction of motors exceeding IE4 and IE5 efficiency levels, using standard induction motor technology (IE4) and other technologies such as permanent magnet synchronous motors (PMSM), synchronous reluctance motors (SynRM) and copper rotor induction motors (IE4 and IE5).

These are all technologically mature solutions that can be scaled up quickly. There is no reason why MEPS should not accompany these technology developments all the more so since their application is cost-effective even for a low number of operating hours per year [18–21].

Financial incentives are a common way of promoting the use of energy-efficient equipment. Usually, they take the form of rebates, tax incentives or financing programs and work by lowering the initial investment and improving payback time. This can be a good option since companies often base their purchasing decisions on upfront cost. One common option is having the financial incentive equal the price difference between the lower-efficiency and the higher-efficiency option.

Energy audit programmes can be voluntary or mandatory, respectively encouraging or requiring companies to carry out energy audits within their facilities. Since motor systems are such a large energy consumer, energy audits should be specific to these systems providing a systematic analysis of their key operating characteristics and identifying opportunities for improved energy performance. In principle, audited companies should commit to the implementation of cost-effective energy saving measures identified.

All these policy actions should be accompanied by information and awareness raising campaigns, informing stakeholders such as policy makers, plant operations, production, maintenance and energy managers, on the significant savings potential made available by improving the energy performance of electric motor systems. The campaigns should highlight not only the energy savings possible but also additional benefits that arise from using high-efficiency motors.

4. The Role of Advanced Motor Technologies

Induction motors are used in the vast majority of industrial applications, due to their low cost, fairly high efficiency and high reliability, but this dominance is being challenged by new technologies [22]. Electric motors have been the subject of significant performance improvements in the last two decades, driven by minimum efficiency regulations, increased awareness of the importance of energy efficiency and its benefits, as well as by new technology developments accelerated by competition among motor manufacturers. Induction motors are available with efficiencies over IE4 whereas Permanent Magnet Motors and SynRM motors are available with efficiencies above IE5 level. These motors operate at synchronous speed, eliminating almost entirely the electrical and magnetic losses in the rotor, being more efficient and presenting a significantly larger power to weight ratio.

These efficiency gains can provide significant power savings, as can be seen in Figure 6.

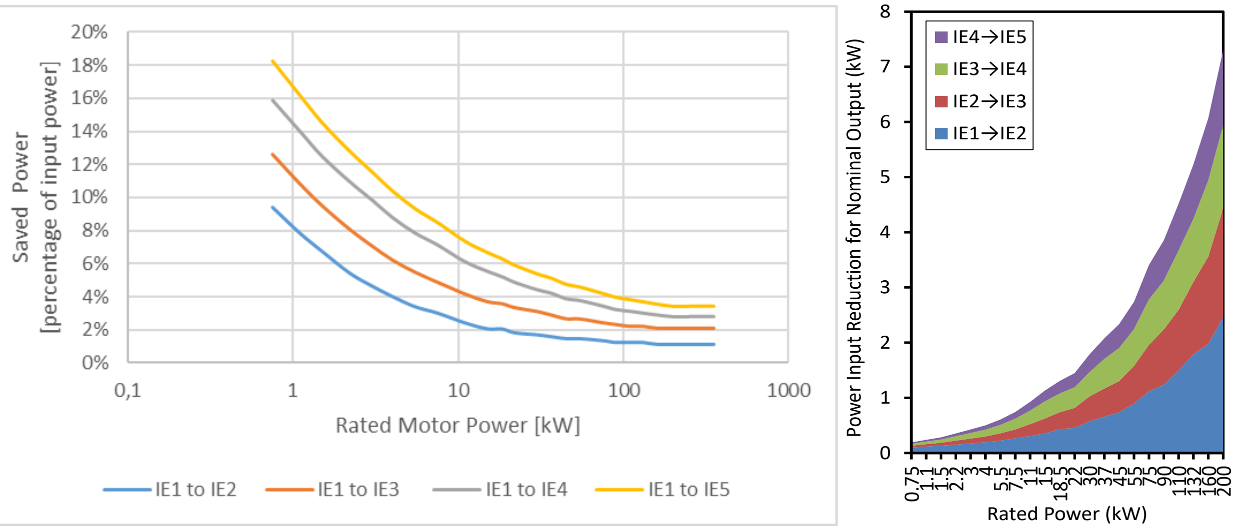


Figure 6. Potential power savings at full load by improvement of motor efficiency class (4-poles, 50 Hz) (Source: Authors).

Most SynRM and PMSM motors require a VSD to operate which makes them an alternative to induction motors in applications with variable speed needs. Some manufacturers have recently introduced line-start models.

Table 1 shows a comparison of motor technologies highlighting features which can be used to achieve IE4 and IE5 performance. In applications benefitting from variable speed operation (about 50% of all motor loads), a major technology transformation is likely to happen. Due to their low cost (IE5 SynRel motors cost about the same as IE3 Induction Motors), SynRel motors can be used in variable speed applications (e.g., pumps, fans, compressors) leading to large savings. IE5 PMSM have the highest torque to weight ratio and can be used in applications requiring large torque or dynamic performance, enabling in many cases the use of direct drive of the load, avoiding the mechanical transmission losses in applications such as cooling tower fans, cranes and motion control.

Additionally, these new motor technologies present improved operating characteristics in part-load operation. As can be seen in Figure 7 the part-load efficiency of SynRel motors is much improved when compared to induction motors which can translate into significant energy savings in applications operating at part load some time.

The savings achieved by replacing old inefficient motors can be potentiated if other associated measures are also implemented at the same time of the replacement, directed not only at the motor but at the entire motor system. This includes, most importantly, correcting for possible oversizing, equipping the motors with variable speed/torque control, as well as smart sensors/digital capabilities.

Motors are most efficient at between 70% and 80% of rated output, with efficiency dropping sharply below 50% of rated output. This means that extremely oversized motors are not operating at their best efficiency. Correcting for oversizing can minimise energy use and subsequently reduce the operation costs. Proper sizing can also improve the power factor of the installation leading to further energy and cost savings.

Table 1. Comparison of the main self-cooled three-phase radial-flux motor technologies for industrial applications Source: Authors with information from [22–24].

Indicator/Feature		**Self-Cooled Three-Phase Radial-Flux Motor Technology**							
		Variable-Speed Applications (Optimized Supply Voltage and Frequency)				**Fixed-Speed Applications (Rated Supply Voltage and Frequency)**			
		SCIM	**PMSM**	**SynRM**	**PMSynRM**	**SCIM**	**Line-Start PMSM**	**Line-Start SynRM**	**Line-Start PMSynRM**
Cross-sectional topology with identification of active materials: - orange areas: copper - light grey areas: aluminum - dark gray areas: steel - black areas: permanent magnets									
Line-start capability without VSD		yes	no	no	no	yes	yes	yes	yes
Requires VSD		yes	yes	yes	yes	no	no	no	no
Possibility of using an electronic soft-starter or Y-D starter		n.a.	n.a.	n.a.	n.a.	yes	no	no	no
Motor cost		$	$$$	$	$$	$	$$$	$$	$$
VSD cost		$	$	$$	$	n.a.	n.a.	n.a.	n.a.
Rated efficiency of the motor (best available technology)		●●●	●●●●●	●●●●	●●●●	●●●	●●●●	●●●	●●●●
Typical efficiency class range		IE1–IE4	IE4–IE5	IE3–IE5	IE4–IE5	IE1–IE4	IE3–IE4	IE3–IE4	IE4–IE5
Rated power factor of the motor		●●●	●●●●	●	●●●	●●●	●●●●	●	●●●●
Efficiency reduction at partial torque and/or speed		●●●	●●●●	●●●●	●●●●	●●	●●●●	●●●	●●●
Motor reliability and robustness		●●●●●	●●●●	●●●●●	●●●●	●●●●●	●●	●●●●●	●●
Power density (kW/kg) for standard frame sizes		●●	●●●●●	●●●	●●●●	●●	●●●●	●●●	●●●●
Overload capacity		●●●●●	●●●	●●●●●	●●●	●●●●●	●●●	●●●●	●●●
Field weakening		●●●●	●●●	●●●●●	●●●	n.a.	n.a.	n.a.	n.a.
Very high-speed capability		●●●●	●●●	●●●●●	●●●	n.a.	n.a.	n.a.	n.a.
Thermal limitations		●●●●	●●	●●●●●	●●●	●●●●	●●	●●●●●	●●●
Useful lifetime		●●●●●	●●●●	●●●●●	●●●●	●●●●●	●●●●	●●●●●	●●●●
Technology maturity		●●●●●	●●●●	●●●	●●	●●●●●	●●●	●	●
Active materials and parts	Electrical steel core	yes	yes	yes	yes	yes	yes	yes	yes
	Cooper winding	yes	yes	yes	yes	yes	yes	yes	yes
	Cooper or aluminum cage	yes	no	no	no	yes	yes	yes	yes
	Ferrite PMs in the rotor	no	no	no	yes	no	yes	no	yes
	Rare-earth PMs in the rotor	no	yes	no	no	no	yes	no	no

Symbols and abbreviations: "$" denotes lowest costs, "$$$" denotes highest cost, "●●●●●" denotes high; "●" denotes poor; "n.a." denotes not applicable or not required. Acronyms: SCIM—Squirrel-Cage Induction Motor; PMSM—Permanent-Magnet Synchronous Motor; SynRM—Synchronous Reluctance Motor; PMSynRM—Permanent-Magnet-Assisted Synchronous Reluctance Motor; SRM—Switched Reluctance Motor; PM—Permanent Magnet; VSD—Variable-Speed Drive (AC-AC converter).

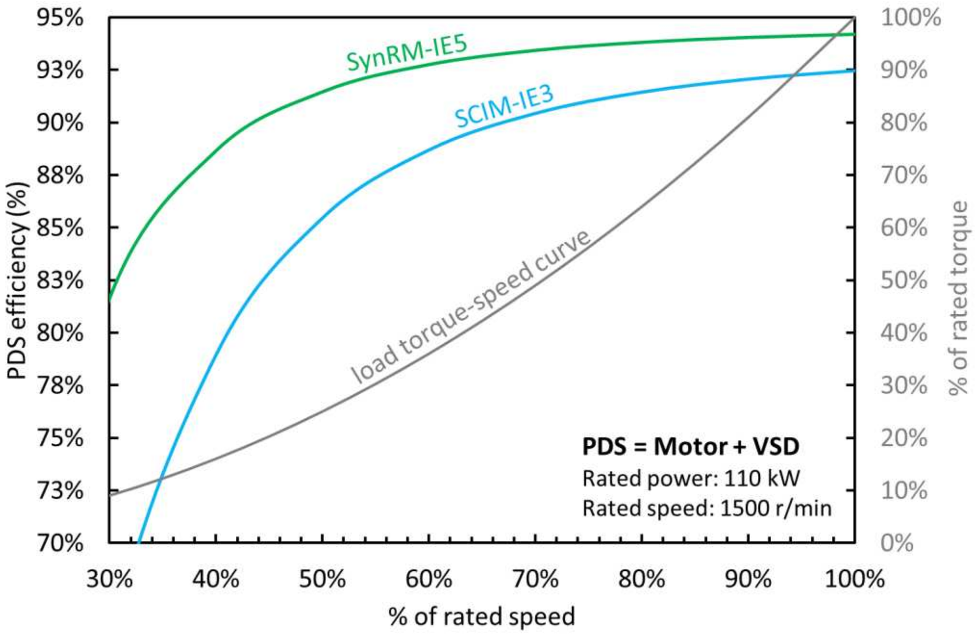


Figure 7. Efficiency comparison of an 110-kW PDS (Power Drive System) with IE3-class SCIM and with IE5-class SynRM considering a quadratic-torque load fan or pumping system without static head. (Source: Authors).

Most motor applications do not require the motor to run at full-speed for their entire operation. On the contrary, processes often operate at different load requirements (depending on required flow, throughput, etc.). In these cases, matching the speed of the motor-driven equipment to the load requirement using a VSD instead of, for example a throttling device, produces significant energy savings [25]. Additionally, the use of VSDs can lead to better process control, less wear in the mechanical equipment, less acoustical noise and the elimination of drive equipment such as gears and belts. Motor systems are made up of several components which all contribute to the overall efficiency of the system (e.g., controls, transmission, end-use equipment). Therefore, improvements in the entire motor system lead to the best technical solution and to much larger savings than replacing the motor alone [26]. Figure 8 shows the possible improvements in a pumping system.

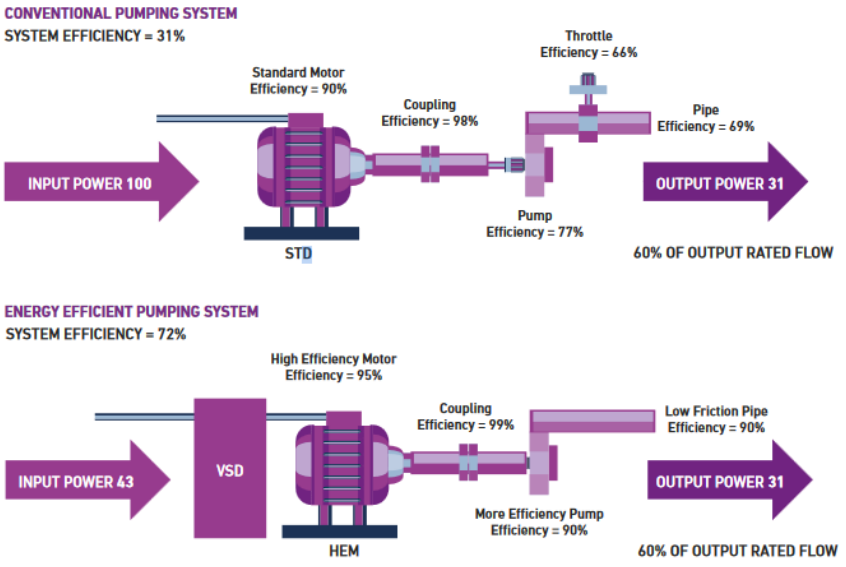


Figure 8. Efficiency of a pumping electric motor system, showing the energy saving potential [27].

Industry has recently witnessed an increase in the use of digital technologies (sensors and meters connected to a data analysis procedure) applied to electric motor driven systems [28,29]. Sensors and meters in motor systems can be used to monitor variables that can give valuable insights into the motor system components operating conditions and about the process performance (Figure 9), leading to increased efficiency in operations (operational cost, flexibility, procurement, footprint), energy, materials (circularity) and emissions. Data are collected or measured and then sent to a centralized cloud computing platform where information is collected and analyzed to be used to monitor and act in different industrial processes.

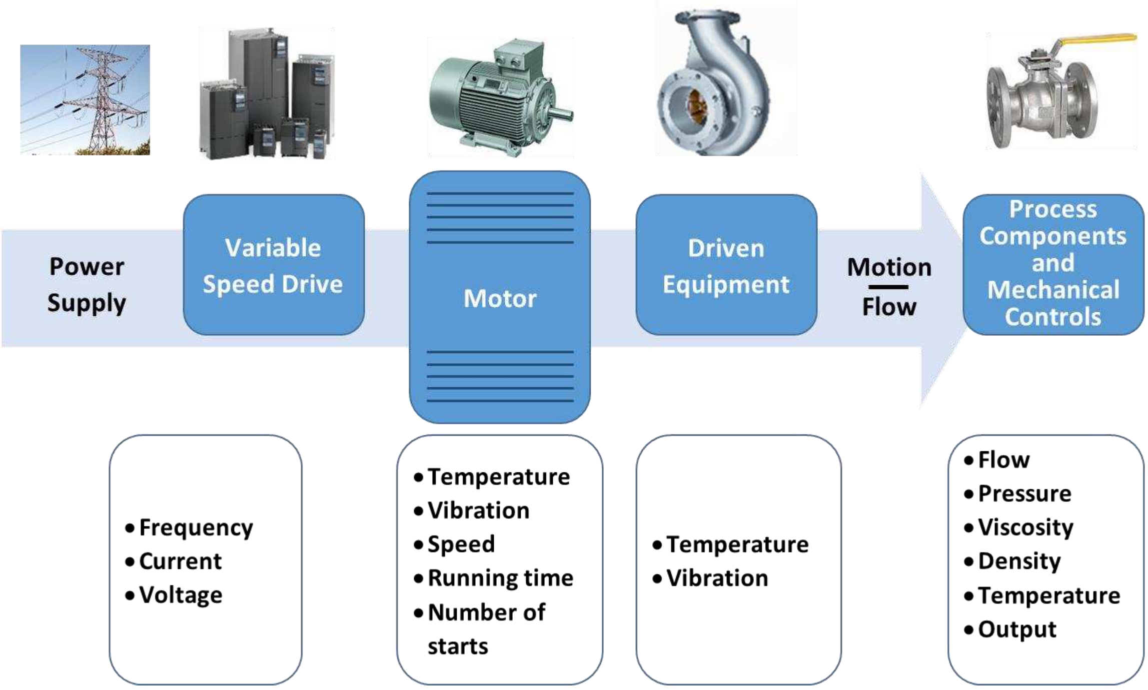


Figure 9. Potential areas of measurements and of application of sensors in motor driven systems (Source: Authors adapted from [30]).

Digitisation enables motor systems to the following:

- Detect if, how much and how long the motor/fan/pump/compressor is operating at suboptimal conditions (low efficiency, stall conditions, frequent on/off switching, vibrations etc.).
- Detect abnormal operation conditions (e.g., leaks in compressed air systems, dirty filters).
- Allow for system integration throughout plants, allowing multiple pieces of machinery to be networked together, optimizing resources.
- Real-time monitoring of the energy consumption of motors. Information can, on the one hand, give a better understanding of how and when the energy is being used and, on the other, provide hints on energy efficiency practices leading to optimization.

These capabilities can provide significant process improvements and, in turn, deliver energy savings. Furthermore, knowing what the process needs are in real-time and feeding this information back to the motor system enables its operation at optimal operating points at all times. This allows, for example, to adjust equipment speed to meet real-time production demands. Furthermore, processes can be tuned to match predicted production demands.

Energy efficiency improvements in motor systems bring not only energy savings (and the associated financial savings), but also several co-benefits such as reduced maintenance, reduced down-time, improved reliability, higher flexibility, reduced production time, reduced production loss, increased productivity and quality control. They also come with benefits at societal or macro-economic levels. These societal benefits include impacts on public health, job creation, poverty alleviation, energy security, public budget or climate change mitigation. Taking into account these co-benefits can greatly improve the possibilities for action, by tipping the scale for decision-makers.

5. The Case of the European Union

In the EU-27, Minimum Energy Performance Standards (MEPS) for electric motors (0.75 kW to 375 kW) were introduced through Commission Regulation 640/2009 [31] under the Ecodesign Directive (2009/125/EC) [32] in 2009. The regulation followed the international approach setting efficiency limits at IE2 level in an initial phase (from 2011) and raising the level to IE3 from 2015 onwards for motors over 7.5 kW and from 2017 onwards for all motor powers covered by the regulation. There was also the possibility of purchasing IE2 motors if equipped with a VSD.

From July 2021, the regulation was updated by Regulation (EU) 2019/1781 [33] which expanded the scope of motors covered (e.g., power range, number of poles, inclusion of brake motors and certain explosive-proof motors). MEPS at IE4 level for motors between 75 kW and 200 kW were also introduced.

The Ecodesign regulation for electric motors has effectively transformed the market towards higher-efficiency products (Figure 10). Low-efficiency IE1 and IE2 motors have essentially been removed from the market remaining only in applications where efficiency is not relevant (e.g., applications with a high number of starts and stops where rotor inertia is a concern). Most of the motors sold in Europe are now IE3 (69%) and higher-efficiency IE4 motor sales is growing (4% in 2021).

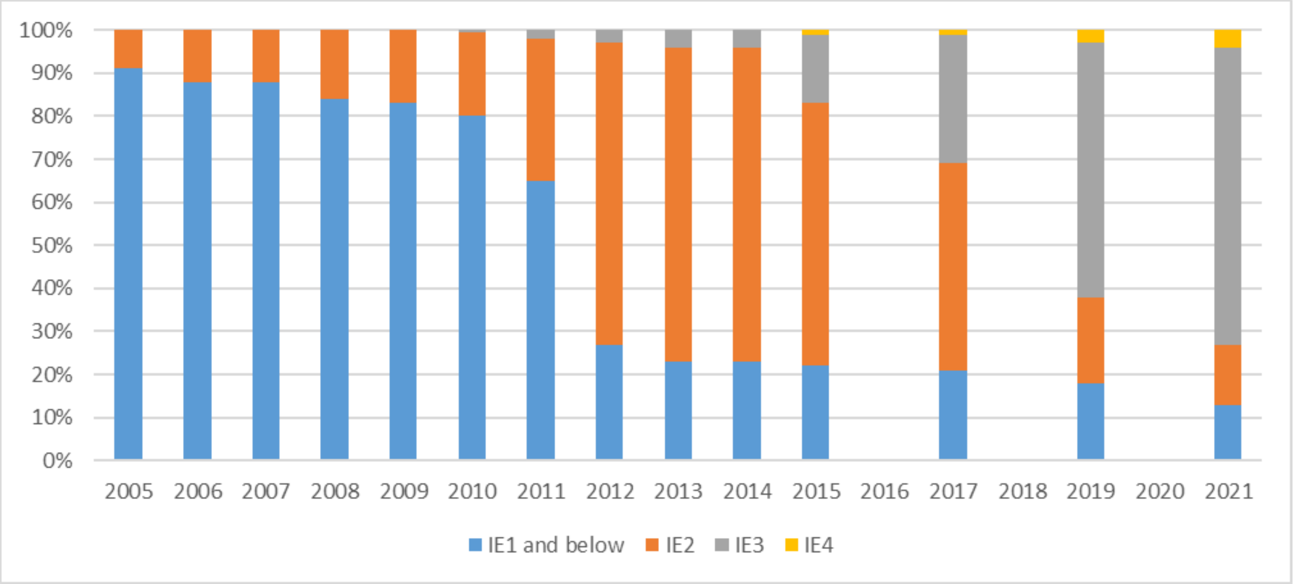


Figure 10. EU motor sales by efficiency class (CEMEP data), 2021.

Although the introduction of efficiency regulation was a most important step in raising the efficiency of motors sold in the European Union, the long lifetime of motors means that the installed base is still very inefficient. A preliminary estimate based on the conservative average lifetimes of 12, 15 and 20 years, depending on the power range (small, medium and large motors), shows that the current stock of motors is still very inefficient, with over 70% of the motors installed in the EU-27 were still IE2 efficiency class or below in 2020, and about 40% with IE1 or lower efficiency, as shown in Figure 11. The numbers would be higher if the average lifetime of motors is greater than assumed, as the recent US and Swiss studies seem to indicate. For example, considering a lifetime of 20 years across the entire power range (0.75 kW to 375 kW) would translate into over 80% of the installed base remaining below the IE2 efficiency class.

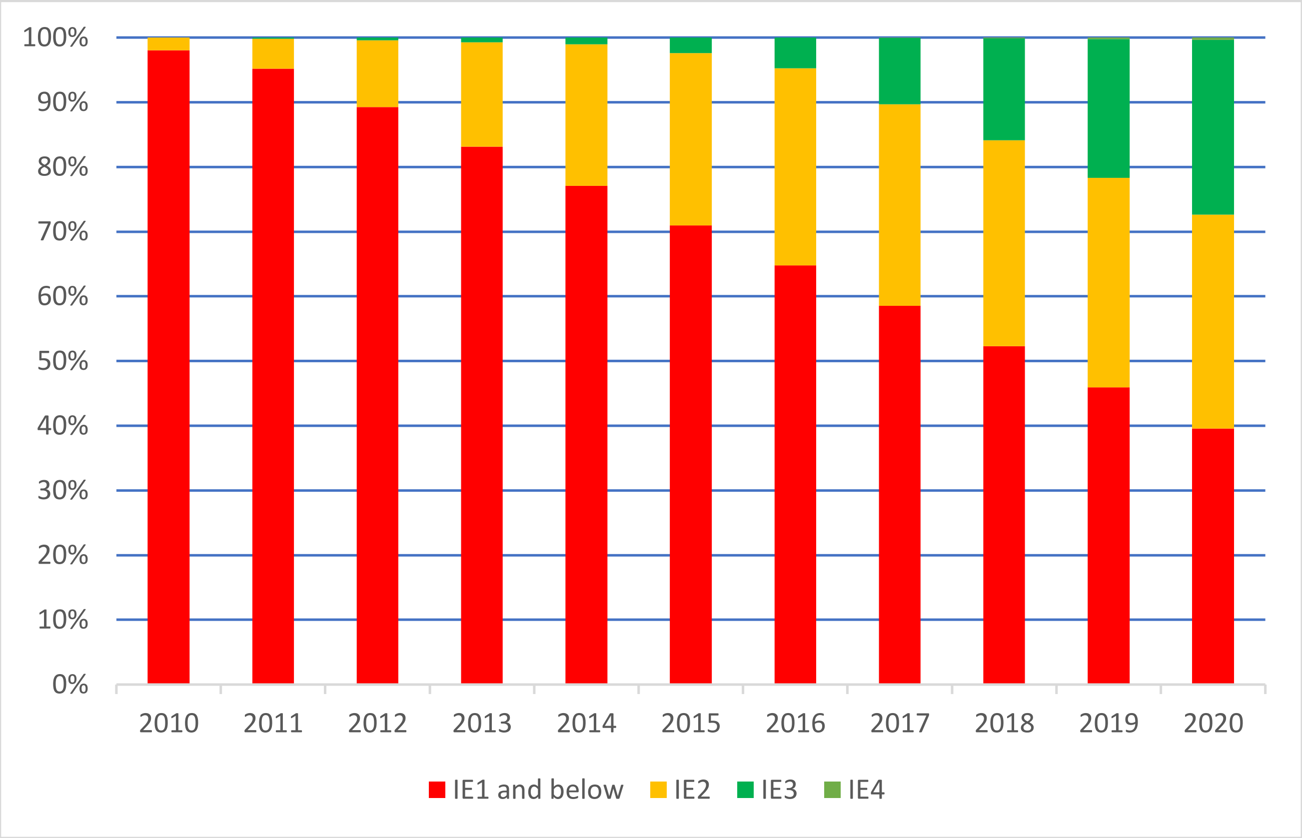


Figure 11. Estimation of EU-27 motor stock by efficiency class (Source: Authors).

6. Estimation of Potential Impact of Large-Scale Application of Energy-Efficient Motor Systems

In the EU-27, in 2021, electric motors represented around 900 TWh/year of electricity consumption [34]. Replacing the persisting inefficient motors still in use in the EU, despite the Motors Ecodesign Regulations (estimated 70% of the installed base below IE3), would result in significant savings.

The potential savings achieved by just replacing the motor, correcting for oversizing, equipping it with a VSD and taking advantage of digitisation are the following:

- Assuming an average 4% gain in efficiency, equal to the average difference between IE1 class and IE3 class motors, translates into savings of 25 TWh/year for the full replacement of the old inefficient motors (IE2 and below) still in use today. The savings would be even larger if the replacement is made with the best available technology motors (IE4 or IE5).
- Correct sizing of the motor can reduce energy consumption by up to 5%. Considering a conservative gain of 2% from replacing old motors with appropriately sized new units would bring additional savings of 12 TWh/year.
- Electronic speed control, achieved by equipping motors with VSDs, can also produce large savings, typically in the range 15–35%, in applications with variable load profiles. These applications represent approximately 50% of all applications [10]. CEMEP, the European industry association of motor manufacturers, estimates the market penetration of VSDs to be approximately 45% in 2020 [35]. However, in 2012 VSDs only represented 22% of all motors sold. This means that a large part of existing motors with variable loads, estimated to be around 35%, are still operated under inefficient

control methods. If VSDs are installed in these motors alongside motor renovations, and considering an average saving of 25%, the savings would amount to 26 TWh/year.

- Electricity savings from digitisation of electric motors were identified in the Preparatory study for the Ecodesign and Energy Labelling Working Plan 2020–2024 [36] to be in the 5–10% range. If digitisation techniques were applied to the replaced motors additional savings would be in the range of 31 to 63 TWh/year.

Therefore, the total energy savings which can be achieved by accelerating full motor replacement are about 100 TWh/year in Europe (approximately the electricity demand of Belgium). Using an emissions factor for future electricity generation of 200 g CO_2eq/kWh would mean the abatement of 20 Mton of CO_2eq per year.

Since the electricity consumption of electric motors in the EU is approximately one tenth of the worldwide consumption it can be conservatively estimated that the potential savings for replacing the global stock electric motors to be greater than 1000 TWh/year.

Energy-efficient motor systems present a major opportunity for cost-effective energy savings and reducing carbon emissions by about 2 Gtons per year [37]. Process industries are prime targets for large energy and carbon emissions with negative costs as shown in Figure 12 which presents the potential impact of efficient motor systems in the chemicals sector. In this sector, efficient motor system have the largest CO_2 abatement potential with a negative cost of −60€ per tCO_2eq abated.

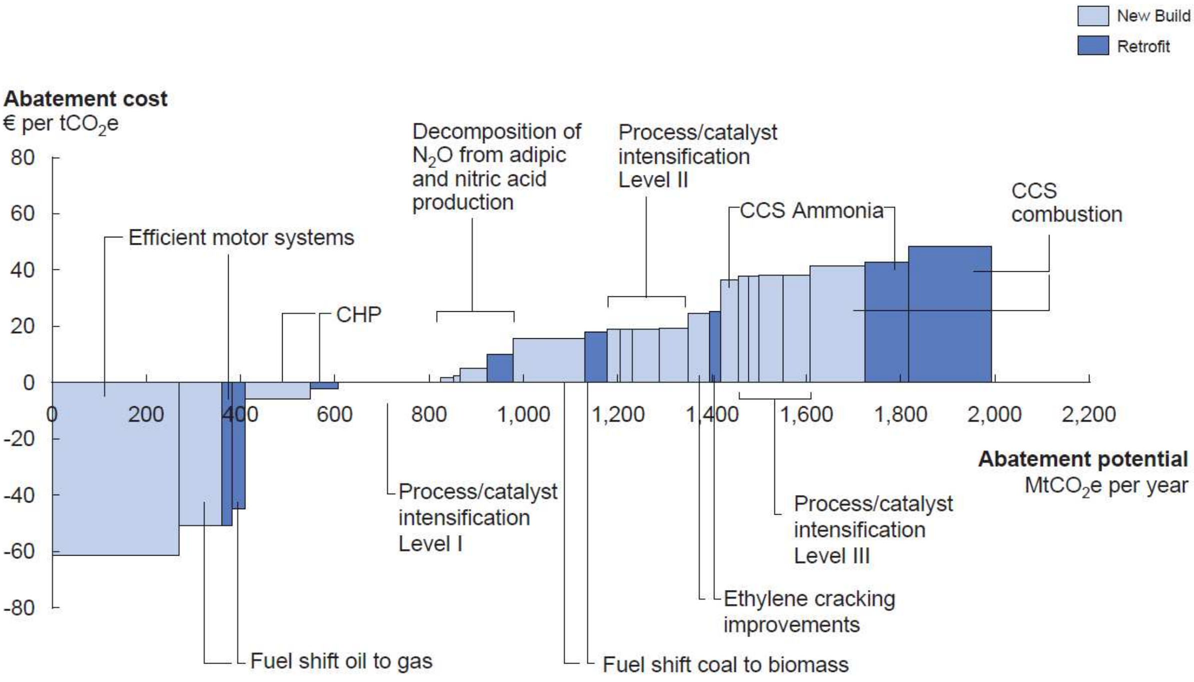


Figure 12. Global GHG abatement cost curve for the chemicals sector [38].

Improving the circularity of materials incorporated in electric motors, for example through trade-in schemes ensuring old motors are properly recycled, could also greatly improve the impact of energy savings and Green House Gases (GHG) reduction associated with motor renovation programmes. Electric motors are mainly built with materials that are recyclable and that have a high value (cast iron, electrical steels, plain carbon steels, aluminium and copper). Recycling requires much less energy than the production of virgin materials and, therefore, recirculating materials would greatly reduce emissions currently associated with primary material production. Steel recycling for example uses 10–15% of the energy required to produce primary steel and similar figures apply to copper. In Sweden, ABB and Stena Recycling recently signed a long-term agreement on the recycling of old electric motors, replacing them with modern high-efficiency motors coupled with motor systems optimization (IE5 with variable speed drives and IE4 for fixed speed). The estimated potential savings are of at least 4 TWh/year, which is about 3% of the total electricity consumption in Sweden [39].

Nevertheless, it should be noted that the lifecycle impact of electric motors is completely dominated by its use-phase. The Life-Cycle Analysis carried out in [13] showed that for motors working 4000 h per year the use phase accounts for over 97% of the total lifetime GHG emissions. The energy use is even higher at over 98%.

Therefore, the benefits of raising the efficiency of the electric motor stock by early replacement largely outweighs the initial production impact.

7. Conclusions

Despite the recognition of the importance of electric motors as major consumers of electricity, both in industry, agriculture and in the tertiary sector, and of the consequent efforts to promote energy-efficient electric motors by policy makers, manufacturers and other stakeholders, there is still a very large cost-effective savings potential that remains to be exploited. Major carbon emissions reduction is also possible, providing a significant contribution to climate change mitigation.

The savings potential triggered by the implementation of policies to accelerate the full replacement of old motors in Europe is estimated at 25 TWh/year if these old motors are replaced by at least IE3 class motors. If measures addressing oversizing, proper controls (VSDs) and digitisation, are also implemented along with the motor replacement by the highest efficiency classes, the additional savings triggered can be over 100 TWh/year in the same region. If similar measures were adopted globally, the savings triggered could be at least tenfold. These findings highlight the importance of improving the efficiency of electric motor systems. The large savings identified mean that energy-efficient motor systems present an opportunity for huge energy and carbon emissions cost-effective savings that cannot be forsaken. In emerging economies with fast growth of electricity demand energy-efficient motor systems can slow down the demand growth as well as the required investments.

However, the rate of replacement of old inefficient motors seems to be far lower than expected. Even when considering the commonly assumed lifetime of motors (between 12 and 20 years depending on power rating), over 70% of the motors installed in the EU-27 were still IE2 efficiency class or below in 2020. In other parts of the World, with exception of North America where minimum efficiency standards were earlier enforced in 1997, the situation is even worse, with the widespread use of old inefficient motors.

Further research is needed to identify innovative policies to bridge this gap and promote the uptake of highest efficiency motors, drives and motor systems that take into account past and current practices, identifying shortcomings and best-practices to develop innovative solutions that help capture these large potential savings and contribute to the ambitious climate targets set out for the next decades. Involvement of all stakeholders should be sought in order to achieve the best solutions in terms of reliability, energy, cost effectiveness and material efficiency.

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