

Review

Bridging Innovation and Sustainability: The Strategic Role of High-Efficiency Motors in Advancing Industry 5.0

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Abstract

High-efficiency electric motors represent a core enabling technology for sustainable industrial systems, providing substantial opportunities to reduce electricity consumption, operating costs, and associated greenhouse gas emissions across motor-driven processes. This paper presents a structured synthesis of recent progress in high-efficiency motor technologies within the IE3–IE5 efficiency classes, with emphasis on design innovations in electromagnetic optimization, advanced materials, and thermal management that collectively improve efficiency retention, reliability, and service lifetime under practical duty cycle conditions. Beyond component-level advances, the review analyses how high-efficiency motor–drive systems are being embedded within Industry 5.0 manufacturing environments, where human-centric automation and data-driven intelligence extend motor functionality toward adaptive, condition-aware operation. In this context, the integration of IoT-enabled sensing, AI-based analytics, and digital twin models supports predictive maintenance, real-time condition assessment, fault diagnostics, adaptive control, and duty cycle-responsive energy optimization, thereby improving both energy management and operational resilience. The paper also discusses implementation considerations that commonly constrain industrial adoption, including interoperability with legacy infrastructure, control architecture compatibility, data quality and model robustness, cybersecurity concerns, and lifecycle-oriented sustainability requirements such as material criticality and end-of-life pathways. Representative industrial case studies are synthesized to illustrate typical deployment architectures, observed implementation effects, and recurring technical challenges, together with practical mitigation strategies. This article advances the viewpoint that, under the Industry 5.0 paradigm, the value of high-efficiency motors is evolving from a component-level efficiency upgrade to a cyber-physical enabling asset that shapes lifecycle carbon performance and manufacturing resilience; realizing this shift requires integrated co-design spanning electromagnetics, thermodynamics, information science, and control.



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1. Introduction

Electric motors constitute a cornerstone of contemporary industrial, commercial, and residential energy infrastructures, representing nearly 45% of global electricity consumption. Their widespread application across diverse sectors—including manufacturing, transportation, and building services—underscores their critical role in facilitating mechanical energy

conversion and automation processes [1,2]. As global industrialization intensifies alongside rising energy demand, the imperative for advancing motor efficiency has emerged as a pivotal challenge to enhance both economic and environmental outcomes. High-efficiency motor technologies provide a strategic and technically feasible solution to substantially curtail electrical energy consumption [3]. These motors achieve superior performance by mitigating core losses, such as stator and rotor copper losses, iron losses attributable to magnetic hysteresis and eddy currents, mechanical frictional losses, and stray load losses, through the deployment of advanced magnetic materials, optimized electromagnetic topologies, and precision manufacturing methodologies. By elevating the electrical-to-mechanical energy conversion efficiency, high-efficiency motors directly contribute to reducing energy demand and improving system-level sustainability [4–8]. The adoption of high-efficiency motors yields pronounced economic advantages, especially in industrial contexts characterized by continuous or heavy-load operation cycles. The attendant reductions in electrical energy consumption translate into significant operational cost savings, bolstering industrial competitiveness and profitability. Concurrently, decreased electricity consumption correlates with reduced carbon emissions, thereby aligning motor technology deployment with global decarbonization targets and stringent regulatory frameworks such as the European Union’s Ecodesign Directive and the U.S. Department of Energy’s energy conservation standards [9–11]. In addition to energy and environmental benefits, high-efficiency motors demonstrate enhanced reliability, decreased maintenance requirements, and prolonged operational lifespans. These improvements derive from advanced thermal management techniques, reduced mechanical and electromagnetic stresses, and stringent quality controls inherent in their design and manufacturing [12,13]. Integration with variable frequency drives (VFDs) and digital control systems further optimizes motor operation by enabling dynamic speed and torque adjustment in response to variable load conditions, thus amplifying overall system efficiency. The convergence of high-efficiency motor technologies with Industry 4.0 innovations, such as digital twin modeling, real-time condition monitoring, and predictive maintenance facilitated by the Internet of Things (IoT) and artificial intelligence (AI), presents transformative opportunities for energy optimization and asset management [14–18]. These developments empower proactive fault detection, adaptive control, and lifecycle extension, positioning high-efficiency motors as a cornerstone of intelligent and sustainable industrial systems [19,20].

Figure 1 projects a continuous increase in the global electric motor market from 2020 to 2030, indicating sustained growth over the decade. The highlighted value of approximately USD 197.8 billion around the middle of the forecast horizon provides a reference point for the scale of the market during this expansion. The market structure remains dominated by AC motors across all years, implying that demand from core industrial drive systems and infrastructure applications continues to account for the majority of market value. In contrast, DC motors represent a smaller share but show a gradual rise over time, suggesting strengthening demand in applications that require higher controllability and closer integration with power electronic conversion and digital control. Hermetic motors remain the least represented category; however, their contribution increases modestly, consistent with steady demand in sealed-motor applications such as refrigeration and heating, ventilation, and air-conditioning systems. Overall, this indicates that projected market growth is primarily driven by the expansion of AC motor deployments, with DC and hermetic motor segments providing incremental contributions to the upward trend [21].

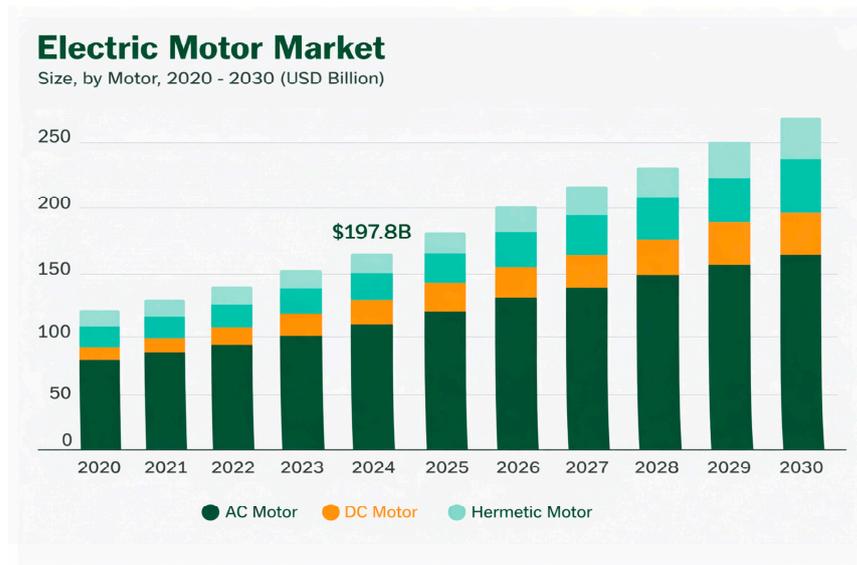


Figure 1. Global electric motor market–2020–2030 [21,22].

Figure 2 demonstrates a global implementation of minimum efficiency performance standards (MEPS) for electric motors which is structured around the International Efficiency (IE) classification system defined in IEC 60034–30–1 [23]. Over recent decades, regulatory frameworks have evolved from permitting IE1 (standard efficiency) and IE2 (high efficiency) motors toward mandating IE3 (premium efficiency) as the minimum standard across most industrialized regions. The European Union, North America, China, Japan, and South Korea have already established IE3 as a baseline requirement, with a growing policy emphasis on transitioning to IE4 (super-premium efficiency) for broader motor ranges. In contrast, several emerging economies in Latin America, Southeast Asia, and Africa continue to implement IE2 or are in the early stages of adopting IE3, reflecting disparities in market readiness and regulatory enforcement capacity. Collectively, these developments demonstrate a global convergence toward IE3 as the prevailing benchmark, while simultaneously indicating a forward trajectory toward the adoption of IE4 and the emerging promotion of IE5 (ultra-premium efficiency) technologies, aligning with long-term objectives of enhancing energy efficiency and reducing greenhouse gas emissions in motor-driven systems [23].

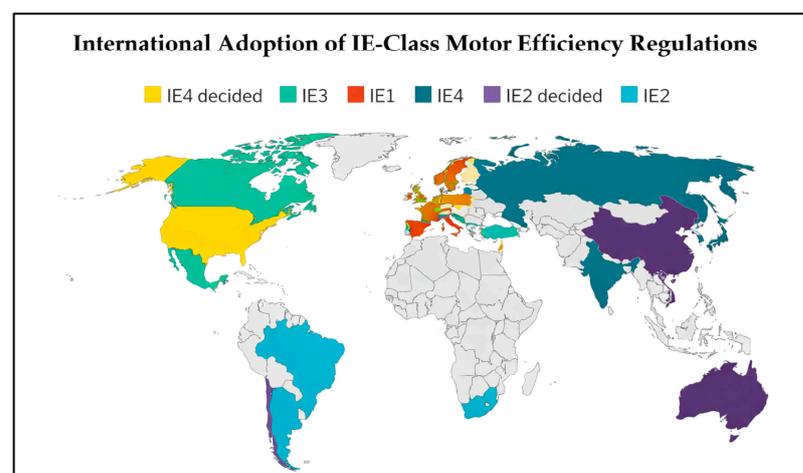


Figure 2. Global adoption of minimum efficiency performance standards (MEPS) for electric motors based on IE [24].

The integration of high-efficiency motor technologies, specifically those classified under the International Efficiency (IE) standards such as IE3, IE4, and the emerging IE5 motors, with Industry 4.0 advancements represents a transformative development in industrial energy management and asset optimization. IE motors are rigorously categorized based on their efficiency levels, with IE3 representing premium efficiency, IE4 denoting super-premium efficiency, and IE5, also known as ultra-premium efficiency, pushing the boundaries of energy savings through advanced design and materials. These motors typically employ state-of-the-art technologies, including permanent magnet synchronous motors (PMSMs), synchronous reluctance motors (SynRMs), and sophisticated power electronics, to achieve superior performance metrics compared to conventional induction motors [24,25]. Digital twin modeling, a key Industry 4.0 technology, creates precise virtual replicas of these IE motor systems, enabling comprehensive real-time simulation and performance evaluation under varying operational conditions. By continuously acquiring sensor data such as temperature, vibration, current, voltage, and rotational speed through IoT-enabled infrastructures, digital twins dynamically update to reflect motor health and operational status. This capability is particularly critical for IE5 motors, which, due to their complex design and advanced materials, require detailed monitoring to maintain optimal performance and prevent degradation. Real-time condition monitoring systems integrated with IE motors utilize high-resolution sensor arrays combined with edge computing to process large datasets locally, allowing for rapid fault detection and diagnosis [26,27]. Advanced machine learning and artificial intelligence algorithms, including neural networks, support vector machines, and ensemble methods, predict faults such as magnet demagnetization, bearing wear, and insulation breakdown. This predictive maintenance paradigm shifts industries from traditional time-based maintenance to condition-based approaches, significantly reducing downtime and maintenance costs while enhancing reliability [28,29]. Adaptive motor control strategies enabled by Industry 4.0 technologies facilitate dynamic optimization of IE motor operation. Variable frequency drives (VFDs) embedded with advanced control algorithms such as field-oriented control (FOC) and direct torque control (DTC) precisely regulate voltage, frequency, and torque to sustain peak efficiency across fluctuating load demands. These controls are essential for the sophisticated IE5 motors, which demand minimal energy loss and thermal stress management to maximize lifecycle and performance [30]. Moreover, IE motors, integrated within smart grid and microgrid systems, contribute significantly to grid resilience and energy optimization. Through standardized communication protocols like IEC 61850 and Modbus TCP/IP, IE motors participate actively in demand response programs, coordinating with distributed energy resources such as photovoltaic systems and battery storage. This integration supports ancillary grid services, including load balancing, peak shaving, and frequency regulation, further aligning with global decarbonization initiatives [31]. From a sustainability standpoint, IE motors combined with Industry 4.0 technologies enable compliance with stringent energy efficiency regulations and environmental standards. Enhanced power factor correction, reduced inrush current, and superior thermal management reduce energy consumption and greenhouse gas emissions. The extensive operational data collected facilitates lifecycle assessment, design improvements, and supports circular economy principles through maintenance optimization, refurbishment, and responsible end-of-life management. The convergence of IE motor technologies with Industry 5.0's human-centric automation emphasizes collaboration between intelligent systems and skilled operators. Integrating real-time analytics with augmented reality (AR) and sophisticated human-machine interfaces (HMIs) provides maintenance teams with actionable insights for faster fault diagnosis and repair, promoting safer, more efficient, and sustainable industrial environments. This holistic approach ensures IE motors remain at the forefront of driving

energy-efficient and resilient manufacturing ecosystems. The system provides a universal benchmark enabling manufacturers, end-users, and policymakers to assess, compare, and mandate motor efficiency levels with the objective of optimizing energy consumption in industrial and commercial sectors globally [31].

1.1. Classification and Efficiency Levels

The industrial sector is a major consumer of electricity, reflecting the breadth of electrically powered processes used in manufacturing and related activities. Electricity is required not only for thermal applications and lighting, but most prominently for motor-driven services, including pumping and fan systems for fluid transport, processing and conveying materials, compressed air generation, refrigeration, and auxiliary boiler operations [31,32]. In 2021, motor systems were estimated to account for roughly 70% of industrial electricity consumption [33,34]. Consequently, improving the efficiency of electric motor-driven systems is a central pathway for reducing industrial electricity use [35]. In addition to strengthening industrial cost competitiveness, efficiency improvements can lessen stress on power systems by reducing peak and total demand, thereby freeing grid capacity and potentially deferring investments in new capital intensive and long lead time infrastructure [35–38].

Since the early 1990s, many jurisdictions have introduced regulatory instruments that define minimum acceptable energy efficiency levels for energy using equipment, commonly referred to as Minimum Energy Performance Standards (MEPS) [39,40]. MEPS are designed to raise the minimum efficiency of products entering the market and to support purchasing decisions by making higher-efficiency options easier to identify and adopt, even when they involve higher upfront expenditure [41,42].

For electric motors, MEPS are typically implemented through efficiency classes that establish graded performance tiers and can be tightened over time as technologies mature and market penetration increases. At the international level, motor efficiency classification is largely harmonized through the International Efficiency or IE scheme defined in IEC 60034-3-1 and IEC 60034-30-2 [23], which facilitates cross-country comparability and is widely treated as a global reference framework [23]. The IEC scheme currently specifies classes from IE1 to IE4, with IE1 representing the lowest efficiency level and IE4 the highest standardized level [43]. In the United States, comparable tiers are commonly expressed using NEMA terminology as standard, high, premium, and super-premium efficiency [44]. A subsequent IE5 tier, often described as ultra-premium, has been discussed for future editions of the standards. While not yet formally defined, it is generally expected to target further loss reductions, on the order of about 20% relative to IE4, through advances in materials, design, and system integration [45]. Figure 3 presents the standardized efficiency performance of four-pole induction motors operating at 50 Hz across the IEC efficiency classes IE1-IE5 as a function of rated output power. The curves indicate a pronounced increase in efficiency at low power ratings, followed by a gradual approach to an asymptotic plateau as power increases, consistent with the reduced relative impact of fixed losses at higher ratings. For any given power level, higher efficiency classes (IE3-IE5) exhibit systematically higher efficiencies than IE1-IE2, reflecting lower total losses achieved through improved electromagnetic design, optimized materials, and reduced stray-load and mechanical losses. The shaded envelopes represent the typical dispersion/allowable range around each class curve due to design variability and standard tolerances. The vertical reference lines denote representative rated power points, facilitating comparison of efficiency requirements and expected performance differences among classes over commonly used motor sizes.

The IE classification spans five principal efficiency classes, which reflect continual improvements in motor design, materials, and manufacturing techniques to minimize electrical losses and improve overall performance:

IE1 (Standard Efficiency): Represents the baseline efficiency level for general-purpose motors, typically corresponding to older or legacy motor designs. These motors meet the minimum regulatory efficiency requirements in some regions but generally exhibit higher core and copper losses, leading to increased energy consumption over their operational life.

IE2 (High Efficiency): Reflects motors with moderate improvements achieved by enhancing electrical steel quality, winding methods, and rotor design. IE2 motors often represent the minimum efficiency standards currently enforced in many jurisdictions, offering a tangible reduction in energy usage and operational costs.

IE3 (Premium Efficiency): Denotes motors that incorporate advanced design elements such as optimized lamination stacks, higher grade electrical steels with lower hysteresis losses, and refined rotor bar geometries. These motors deliver significant efficiency improvements, especially under partial-load conditions, and are widely adopted in energy-conscious industries.

IE4 (Super-Premium Efficiency): Comprises motors that leverage emerging technologies such as permanent magnet synchronous motors (PMSMs) and synchronous reluctance motors (SynRMs). These designs enable drastically reduced rotor losses and enable higher power densities, although they typically require sophisticated control electronics for optimal operation.

IE5 (Ultra-Premium Efficiency): The highest recognized efficiency class to date, IE5 motors integrate cutting-edge design features such as high-performance rare earth magnets, advanced cooling technologies, and integrated inverter drives. These motors exhibit minimal iron and copper losses and are engineered to deliver peak performance in demanding applications, albeit at a higher capital cost and often requiring specialized manufacturing processes.

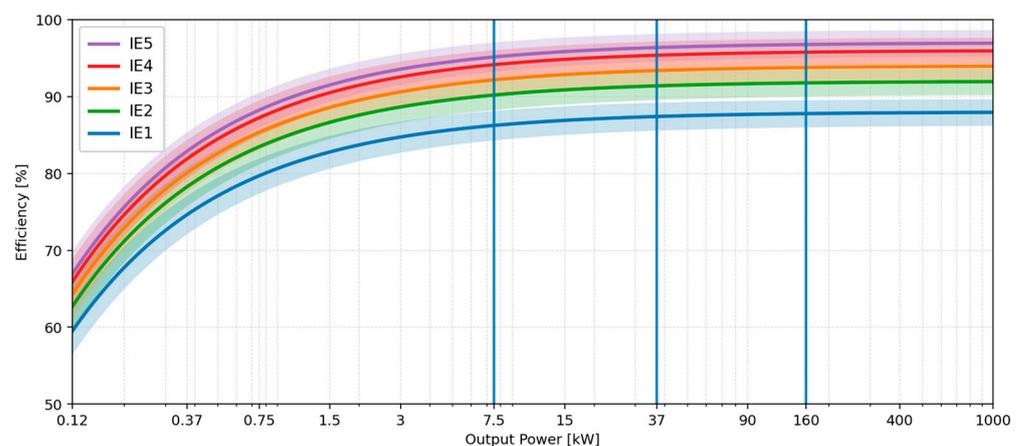


Figure 3. Efficiency classes for four pole motors at 50 Hz [46,47].

Improving energy efficiency in motor-driven systems has become a central objective in industrial energy management. Squirrel cage induction motors (SCIMs) continue to dominate industrial drive applications, reported at more than 95 percent. However, their operating principle inherently involves rotor current excitation, which produces unavoidable rotor losses. This fundamental constraint limits the extent to which conventional SCIM designs can be advanced toward the IE5 efficiency class [48]. Consequently, alternative motor technologies, particularly synchronous reluctance motors (SynRMs) and permanent magnet synchronous motors (PMSMs) have received increasing attention as

high-efficiency candidates capable of reducing electrical losses and supporting compliance with IE5 efficiency targets in appropriate duty profiles.

SynRMs are manufactured predominantly from material families comparable to those used in SCIMs, yet they differ in their torque production mechanism. Rotor currents are not required, and rotor losses associated with induced currents are therefore largely eliminated [49]. Reported differences in material composition are mainly attributable to rotor construction, including the absence of aluminum in the rotor assembly [49,50]. PMSMs also exhibit negligible rotor losses because the rotor magnetic field is provided by permanent magnets rather than induced currents [51,52]. In many industrial PMSM designs, Nd, Fe, and B permanent magnets are used due to their high magnetic energy density [53]. Nevertheless, reliance on rare earth elements, especially neodymium, introduces sustainability challenges related to resource criticality and supply vulnerability, environmental burdens from extraction and refining, the management of hazardous substances during magnet manufacturing, and persistent difficulties in achieving effective end of life recovery and recycling [53–55].

More broadly, improvements in electric motor efficiency are typically realized through one or a combination of the following approaches. First, increasing the quantity of active materials. Second, improving material quality and optimizing electromagnetic and thermal design. Third, adopting advanced or novel materials [56,57]. Because SCIM, SynRM, and PMSM technologies differ in both their loss mechanisms and material inventories, a technology comparison based solely on operational efficiency is insufficient. A systematic evaluation of environmental performance across the full lifecycle is therefore required to support technology selection for load drive systems in which environmental sustainability is considered alongside cost and technical performance.

Environmental assessments of electric motors have often emphasized the operational use phase due to its dominant contribution to lifetime energy consumption. However, manufacturing and end-of-life stages can also be significant, particularly for high-efficiency motors that may require higher material intensity or incorporate critical materials. Accordingly, cradle-to-grave lifecycle assessment is necessary to quantify impacts consistently across all stages of the product system [58]. As illustrated in Figure 4, the motor lifecycle can be structured into raw material extraction and motor production in the manufacturing phase, operation during the service life in the use phase, and end-of-life management, including recycling, recovery, and disposal pathways, in the end-of-life phase [59,60].

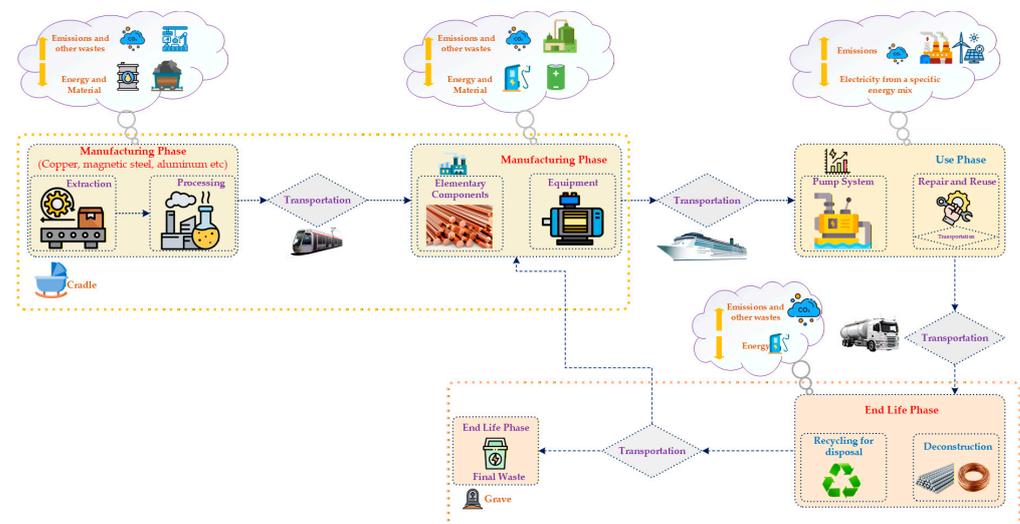


Figure 4. Lifecycle stages of electric motors [61,62].

Figure 5 summarizes the material composition of the three motor technologies considered in this study, namely, the squirrel cage induction motor (SCIM), classified as IE3, the synchronous reluctance motor (SynRM), classified as IE5, and the permanent magnet synchronous motor (PMSM), also classified as IE5. The inventory is reported by principal material categories, comprising electrical steel, other steels, cast iron, aluminum, copper, and, in the case of the PMSM, permanent magnets. Across the assessed designs, the SynRM is characterized by the highest overall material demand, which is primarily associated with a comparatively greater contribution from electrical steel. Conversely, the PMSM exhibits the lowest overall material demand and is the only technology that includes permanent magnets as a distinct material input.

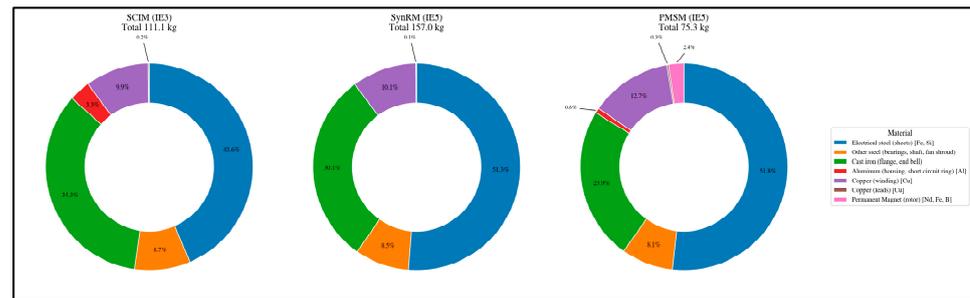


Figure 5. Bill of materials for 11 kW motor manufacturing for each technology.

Differences in material volume across the technologies investigated are reflected in their mechanical form factors. The PMSM, in particular, is associated with a smaller material volume and consequently a smaller frame size. This disparity constrains direct functional substitution in retrofit applications, since replacement may require modifications to couplings and mounting interfaces. Such adaptation measures can introduce additional labor requirements and incremental material and energy inputs beyond those attributable to the motor unit alone. In contrast, the SynRM and SCIM generally share comparable frame dimensions, which improves mechanical interchangeability and reduces the scope of integration work during replacement.

The relative distribution of material shares, illustrated in Figure 5, further clarifies technology-specific patterns when expressed as mass fractions. For the SCIM, electrical steel accounts for 43.6 percent of total mass, followed by cast iron at 34.3 percent and copper at 10.1 percent. The SynRM exhibits a higher dependence on electrical steel, representing 51.3 percent of total mass, while cast iron and copper contribute 30.1 percent and 10.1 percent, respectively. Aluminum is absent from the SynRM material breakdown, indicating a distinct rotor construction compared with the SCIM.

In lifecycle environmental assessments of electric motors, annual operating hours are a pivotal input because they determine cumulative electricity consumption and, consequently, most impact categories linked to energy use. For the 11 kW motor examined in this study, an average operating time of 3236 h·yr⁻¹ has been reported for the U.S. industrial sector [63]. This value was therefore adopted as the reference operating profile and applied consistently across the assessed motor technologies to maintain a uniform basis for comparison, as summarized in Figure 6.

The service life of industrial motors can extend well beyond typical design expectations; nevertheless, the effective lifetime is highly dependent on the duty cycle, maintenance practices, installation quality, and ambient operating conditions [63,64]. In addition, IEC 60034-30-1 and IEC 60034-31 [23] provide reference assumptions for motor lifetime as a function of shaft power [65]. To ensure methodological consistency and avoid overly optimistic assumptions, a conservative lifetime of 15 years was selected for the 11-kW motor and used throughout the analysis, as reported in Figure 6.

In real industrial environments, motors frequently operate below rated load and outside their maximum-efficiency region due to non-ideal mechanical and electrical conditions, including misalignment, variable ambient temperature and humidity, and voltage unbalance [66–71]. However, because the objective of this work is a comparative evaluation of motor technologies rather than a site-specific performance assessment, the modeling assumes standardized operating conditions for all cases. Accordingly, each motor was evaluated at a representative 75% load factor, and performance was based on the corresponding best efficiency at that load, as presented in Figure 6, thereby isolating technology-related differences in use-phase impacts.

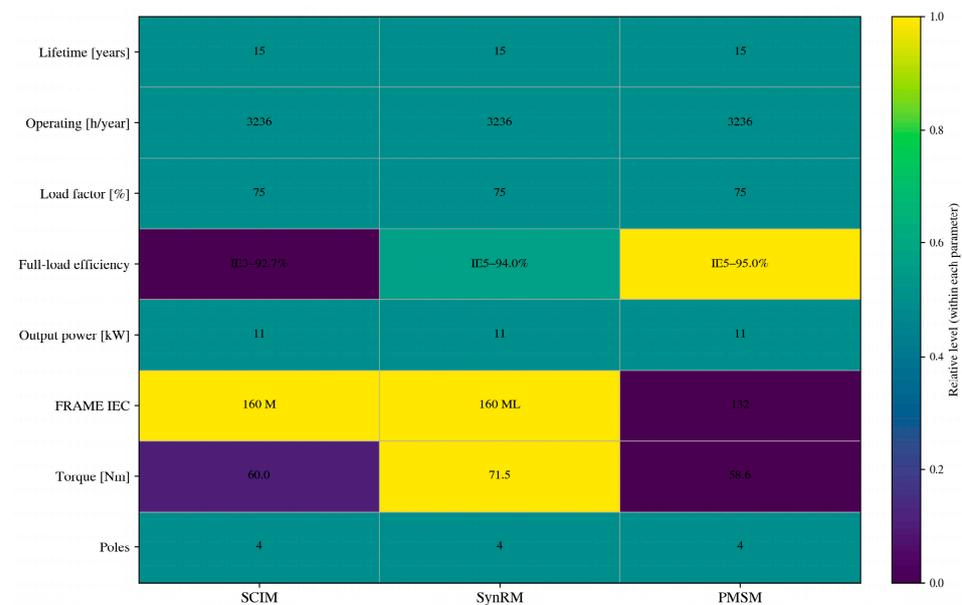


Figure 6. Motor specifications for SCIMs, SynRMs, and PMSMs.

1.2. Technical Attributes and Design Innovations

The enhanced performance of modern IE-class motors is driven by coordinated advances across multiple domains of motor engineering. Key contributions include improved electromagnetic design and machine architectures to increase torque capability while reducing loss mechanisms, the adoption of advanced materials and components to lower copper and core losses, improved thermal management to control hotspot temperatures and sustain higher continuous loading, and integrated drive systems that optimize operation through precise control and monitoring. These four aspects are discussed in the following subsections.

1.2.1. Electromagnetic Design/Architecture

Advanced electromagnetic design architectures are an effective route to increase power density and efficiency in electric traction machines. Coordinated rotor–stator optimization can address key performance constraints and reduce dominant loss components [72–74]. A commonly adopted unifying design [75,76] variable is the slots-per-pole-per-phase ratio, as it consolidates several limitations associated with the maximum fundamental frequency (f_{max}) and high-speed loss mechanisms [77]. Traction motors are generally realized as radial-flux or axial-flux machines. Radial-flux machines establish the main flux path perpendicular to the rotation axis, whereas axial-flux machines align the flux parallel to the axis, typically enabling a shorter flux path. Each topology therefore presents distinct tradeoffs in packaging, thermal behavior, and achievable torque/power density. In current EV traction systems, radial-flux machines remain prevalent, including induction machines (IMs), switched reluctance motors (SRMs), and permanent magnet synchronous machines (PMSMs). PMSMs are

commonly classified as interior permanent magnet (IPM) and surface-mounted permanent magnet (SPM) types [78]. Among these, IPM synchronous machines (IPMSMs) are widely preferred for traction because Nd, Fe, and B magnets enable high torque/power density and efficiency, albeit at higher cost than IM solutions [78,79]. Consequently, significant research is directed toward reducing heavy rare earth content or adopting alternative magnet/material systems while retaining EV-level performance [80,81].

Recent studies increasingly emphasize axial-flux traction machines, particularly where axial length constraints and tight drivetrain integration are critical [82,83]. Compared with radial-flux designs, axial-flux machines often offer favorable torque-to-weight characteristics and compact packaging [84]. Prior comparisons indicate that, within a specified envelope and rating, both radial- and axial-flux machines can deliver similar torque, while axial-flux machines may achieve this with lower active mass/volume, supporting higher torque/power density and potentially improved heat removal due to their flatter geometry. The principal findings from [85] are summarized in Table 1 in terms of power density (kW/kg), efficiency (η , %), and cost (\$/EUR/INR). With continued progress in topology and materials, axial-flux concepts have also evolved toward flux-switching machines (FSMs), where torque is produced by redirecting flux paths within the stator, improving controllability and torque density [86]. Conventional FSMs typically employ rare earth magnets, motivating alternatives such as high-temperature superconductors (HTSs) to further enhance torque/power density and efficiency over wider speed ranges; however, reported HTS-FSM development is currently concentrated on aerospace/electric aircraft propulsion under cryogenic operation. Materials within the REBa₂Cu₃O _{γ} (REBCO) family are frequently discussed [87], with YBCO commonly used [88] and Bi2212 highlighted for high-field capability and aircraft relevance. The literature further reports dual-rotor, air-core stator arrangements to avoid saturation and reduce losses, while noting thermal management as a critical challenge [89]. Although axial-flux motors are not yet widely adopted in mass-market EVs, industrial interest is increasing such as Daimler's planned acquisition of YASA and Renault's collaboration with WHYLOT for hybrid applications from 2025 [90]. In addition, the comparatively straight flux paths in axial-flux machines may enable the use of grain-oriented electrical steels to improve efficiency, as identified in automotive roadmaps, while compact structures can reduce back-iron requirements and support higher power density.

Table 1. Comparison of radial- and axial-flux machines.

Parameters	Power Density (kW/kg)	Efficiency (% η)	Cost (\$/EUR/)
Traditional radial-flux machines	Can be optimized to achieve relatively high power density, but typically lower than axial-flux alternatives.	Limited by inherent design constraints and associated high-speed loss mechanisms.	Generally lower due to mature designs and well-established manufacturing processes.
Emerging axial-flux motors	Typically, higher power density than traditional radial-flux machines, aided by compact geometry and improved torque-to-weight potential.	Higher due to greater design flexibility and favorable thermal utilization.	Generally higher because of structural complexity and less mature (emerging) manufacturing/assembly technologies.

1.2.2. Materials and Components

Advanced materials are increasingly critical for achieving the power density and efficiency targets of next-generation traction motors and for enabling newer machine architectures. Recent developments show that material upgrades can improve performance

even in conventional topologies by reducing dominant losses and supporting higher magnetic loading [91].

Core Material:

In electrical machines, the main opportunities for material-driven improvements lie in the magnetic core, stator windings, and rotor magnets. This subsection focuses on core materials. Improving core materials, primarily stator and rotor laminations, can reduce hysteresis and eddy-current losses and thereby increase machine efficiency. Commercial machines typically use non-grain-oriented electrical steels with ~3.2 wt.% silicon and lamination thicknesses of about 0.35–0.50 mm [92]. Further thickness increases the effective resistivity and helps suppress eddy-current losses, particularly at higher frequencies. Grain refinement approaches such as grain boundary strengthening (GBS) are also used to improve mechanical strength and manufacturability by limiting dislocation motion, leading to higher yield strength [93]. High-silicon steels (~6.5 wt.% Si) with thinner laminations have been proposed to further reduce losses [94,95], although increased brittleness can raise manufacturing complexity and cost. To balance magnetic performance and processability, alternative alloy systems containing Si, Cr, Al, and Mn are being explored [95]. Fe–Ni alloys offer high permeability and low losses but are limited by lower saturation and higher cost; however, compositions near 48% Ni have been reported as potentially cost-competitive with 6.5% silicon steels [95]. Fe–Co alloys such as Hiperco-50 provide a high saturation flux density (~2.4 T) and mechanical strength, enabling higher power density and improved efficiency through reduced core losses, though their cost restricts use mainly to aerospace applications [96]. Grain-oriented steels can also be beneficial in machines with largely unidirectional flux paths, including segmented/modular designs and certain flux-switching machines, but cost–reliability tradeoffs remain important [97–99]. Furthermore, dual-phase laminations can locally tailor magnetic properties to reduce leakage and improve efficiency and power density, albeit with lower saturation and higher cost than standard M19 steel [100,101]. Table 2 summarizes advanced core materials and their expected influence on traction motor performance. The comparison is based on key material parameters, magnetic permeability (μ), electrical resistivity (ρ), saturation flux density (B_{sat}), and temperature capability (T), and relates these properties to qualitative trends in achievable power density, efficiency, and core material cost.

Table 2. Advanced materials for the core of a machine.

Parameters	Magnetic Permeability, μ (H/m)	Electrical Resistivity, ρ (Ωcm)	Magnetic Saturation, B_{sat} (T)	Temperature, T ($^{\circ}\text{C}$)	Power Density (kW/kg)	Efficiency (% η)	Cost of the Core with the Given Materials (\$/EUR)
Si content: 3.2% to 6.5%	High	High	1.6–1.8	-	Improves	Higher than 3.2% Si	More than conventional
Fe-Ni alloys	High	-	-	High	Not much impact	More than Si content steel	More
Fe-Co alloys (Permendur)	High	-	2.4	High	Improves	Increases	More
Dual-Phase Materials	Medium	Same as Si	Low—1.6	Low	Improves	Increases	Relatively less

Stator Winding:

Recent developments in conductor engineering have intensified interest in carbon nanotube (CNT)-modified copper (Cu) windings for electric traction machines [102]. Owing to their high specific strength and favorable electrical and thermal transport characteristics, CNTs are being investigated as reinforcement phases or surface layers to enhance the

performance of conventional copper (and aluminum) conductors. Prior studies report that CNT-coated or CNT-incorporated Cu conductors can increase current-carrying capability and improve effective electrical/thermal behavior relative to baseline Cu, thereby enabling reduced resistive losses and supporting higher power density in traction machines [103]. Moreover, CNT-Cu conductors have been reported to exhibit reduced temperature dependence of resistance, which is advantageous for maintaining efficiency under elevated winding temperatures typical of traction duty cycles [104]. A complementary strategy involves graphene-enhanced copper conductors, as demonstrated by the U.S. DOE's Pacific Northwest National Laboratory (PNNL) [105]. PNNL reports that graphene additions at parts-per-million levels can lower the temperature coefficient of resistance while preserving room-temperature conductivity, indicating improved stability of winding resistance with temperature and a potential efficiency benefit at the motor level [105]. The associated microstructural characterization (Figure 6), based on electron microscopy and atom probe techniques, indicates carbon-rich nanoscale features within the copper matrix that are consistent with the proposed Cu-graphene extrudate architecture [105]. Despite these promising results, CNT- and graphene-enabled conductors remain in an early stage of technological maturation. Further work is required to demonstrate scalable manufacturing routes, long-term reliability, and cost competitiveness for automotive deployment. The advanced winding materials discussed in this subsection are summarized in Table 3, along with their anticipated implications for traction motor performance.

Table 3. Advanced materials for stator windings.

Parameters	Power Density (kW/kg)	Efficiency (% η)	Cost (\$/EUR)
Carbon Nanotubes (CNTs)	Improves significantly	Very High	More
Nano-Structured Interconnected Carbon Conductors (NICCs)	Improves significantly	Increases	More
Aluminum Windings	Improves significantly	Not as good as copper	Less

Figure 7 illustrates the concept of a carbon nanotube-reinforced copper (CNT Cu) composite conductor intended for motor windings. The schematic shows copper as the primary current-carrying matrix, while CNTs are incorporated as a coating layer or dispersed reinforcement to enhance conductor performance. Owing to their high intrinsic electrical and thermal conductivity and exceptional mechanical strength, CNTs can improve the current-carrying capability, reduce temperature-dependent resistance rise, and facilitate heat spreading from the winding region. As a result, CNT Cu conductors are expected to lower winding losses and support higher current density, contributing to improved motor efficiency and power density.

Rotor Magnets:

Sintered neodymium-iron-boron (NdFeB) magnets are the prevailing choice for permanent magnet (PM) traction drives due to their high energy density (≈ 50 MGOe) and suitability for compact, high-performance machines [106]. To improve demagnetization resistance at elevated temperatures, heavy rare earth elements (HREEs) such as dysprosium (Dy) and terbium (Tb) are often added, improving the knee-point behavior of the B-H demagnetization curve and enabling robust operation under thermal loading [107]. However, Dy/Tb additions significantly increase magnet cost, prompting research that targets either higher energy product grades or reduced rare earth content through engineered and composite magnet systems [108]. Consistent with supply risk and price volatility concerns emphasized by the UK APC and the U.S. DOE, a key objective is to minimize or eliminate HREE usage without sacrificing traction-level performance [109,110]. Reported strategies

include combining Dy-free magnet grades with rotor geometry optimization, since material substitution alone typically does not yield optimal machine-level outcomes [111]. From an industrial perspective, grain boundary diffusion (GBD) magnets provide a practical low-Dy option by concentrating HREEs near magnet surfaces to enhance coercivity while limiting bulk Dy content. In contrast, some Dy-free commercial grades (e.g., NEOREC45mhf) are constrained to operating temperatures of ~150–160 °C, increasing demagnetization susceptibility above this range [112]. Additional approaches include partial substitution of Nd with more abundant rare earth materials (Ce and La) and the development of high-performance magnets from recycled feedstock to reduce critical material dependence. Bonded (polymer-bonded) magnets are also being considered because of their higher resistivity and reduced eddy-current losses; however, they generally exhibit lower maximum energy products than sintered magnets despite comparatively high coercivity. Candidate alternatives to HREE-rich magnets are consolidated in Table 4. In parallel, magnet recycling is gaining attention as a complementary pathway to improve sustainability and supply security. Several processes have been proposed to recover rare earth elements from pre-consumer and post-consumer products, including routes that convert NdFeB scrap into bonded magnets. The rotor magnet candidates are summarized in Table 4, using permeability (μ), resistivity (ρ), saturation flux density (B_{sat}), and temperature capability (T), while their implications for motor power density, efficiency (η), and cost are reported in Table 5.

Table 4. Magnet materials found suitable replacements for heavy rare earth elements (HREEs) [113–116].

Magnet Materials	Operating Temperatures	Applications	Challenges	Opportunities
Iron ferrite magnets	Medium temperatures (up to 250 °C)	Lower-powered motor	Given the lower flux density, the magnets are considerably heavier and cannot act as a direct drop-in for NdFeB	Automobiles, washing machines, and electric fans
Samarium cobalt (SmCo) magnets	High temperatures (up to 500 °C)	48 V-based motors	Price premium	Considered more suitable for aerospace applications
Polymer-bonded NdFeB magnets	Low temperatures (up to 150 °C)	Both low- and medium-powered motors	Low-energy product, susceptible to corrosion, and limited temperature stability	With improvement in performance, they find a suitable possibility of getting employed in EV applications

Table 5. Potential advanced materials for rotor magnets [117].

Parameters	Magnetic Permeability, μ (H/m)	Electrical Resistivity, ρ (Ωcm)	Magnetic Saturation, B_{sat} (T)	Temperature, T (°C)	Power Density (kW/kg)	Efficiency (% η)	Cost (\$/EUR)
Dy-free magnets	-	Medium	<1	Low	Increases	Decreases	Low cost
Polymer-bonded magnets	-	High	<1	-	Improves	Can be improved	Low cost
Blending of new magnets	Medium	Medium	~1	Low	Can be improved	Can be improved	Low cost
Iron nitride phases—the α'' -Fe ₁₆ N ₂	-	-	2T	-	Expected to be more	Expected to be more	Expected to be more

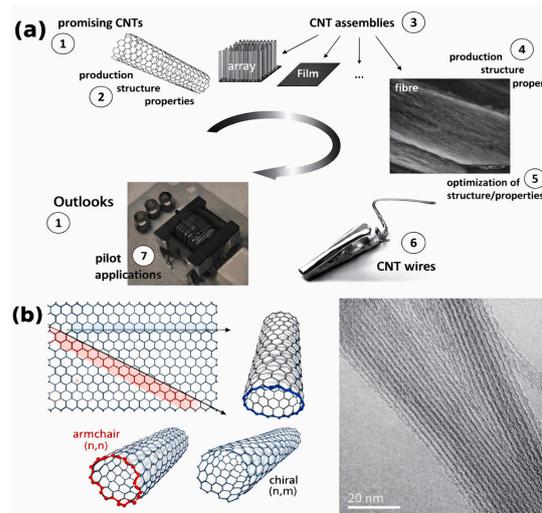


Figure 7. Concept of CNT-Cu composite conductor used for motor windings [102]. (a) Roadmap from CNT synthesis to assembled forms (arrays/films/fibres) and CNT wires/applications. (b) CNT structure and alignment: chirality schematics (left) and TEM of aligned CNT bundles in a fibre (right, 20 nm).

1.2.3. Thermal Management

Thermal management is a key design constraint in high-power-density traction machines and IE5-class motors because allowable electromagnetic loading is often limited by hotspot temperature rather than torque production alone. Heat generation is dominated by copper loss (I^2R), core loss associated with hysteresis and eddy currents, and inverter-related contributions, such as harmonic-induced iron losses and alternating current effects in conductors arising from skin and proximity phenomena. Inadequate heat rejection elevates local temperatures beyond permissible limits, accelerating insulation aging and, in permanent magnet machines, reducing demagnetization margin and torque capability.

The thermal design objective is to reduce the effective thermal resistance between internal heat sources and the cooling boundary while maintaining acceptable transient temperature rise during overload conditions. In first order form, the temperature rise can be approximated as

$$\Delta T \approx P_{\text{loss}} R_{\text{th}},$$

where P_{loss} is the generated loss and R_{th} is the equivalent thermal resistance from the dominant hotspot to the coolant or ambient air. Critical hotspots are commonly located in the slot copper and end windings due to conductive bottlenecks introduced by insulation layers and limited convective surface area. Accordingly, effective strategies shorten the conduction path and enhance convection. Integrated liquid cooling through stator jackets or embedded channels improves heat extraction from the active stack, and direct cooling schemes targeting the slot region and end windings further reduce winding hotspot temperature. Heat pipes and vapor chamber elements can redistribute concentrated heat to larger heat exchange surfaces, improving temperature uniformity. In air-cooled configurations, optimized flow passages and guided ventilation increase convection, although effectiveness decreases as loss density rises. Maintaining temperatures within design limits improves efficiency and reliability. Lower winding temperature restrains resistance rise and associated copper loss escalation at load, while reduced magnet temperature increases demagnetization margin. Limiting thermal stress also slows insulation degradation, enabling higher continuous current density and improved overload capability. Thermal management should therefore be treated as an integrated component of machine design alongside electromagnetic and mechanical considerations, particularly for compact, high-efficiency

traction applications. Figure 8 illustrates thermal management techniques in electric traction motors, including liquid cooling, heat pipes/vapor chambers, and air cooling. These methods help reduce motor operating temperatures. Lower temperatures lead to higher efficiency, improved reliability, increased current density, and better overload capability, enabling safer and more compact motor operation.

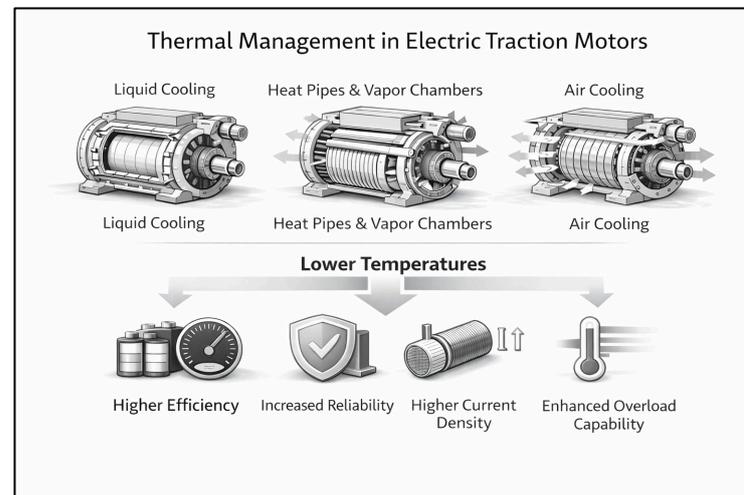


Figure 8. Thermal management and cooling techniques in electric motors.

1.2.4. Integrated Drive Systems

Integrated drive systems are increasingly used with modern IE-class motors, reflecting a shift toward treating the motor and the variable frequency drive as a single, jointly engineered subsystem. By synthesizing the required stator excitation, the drive regulates speed and torque through controlled adjustment of voltage magnitude, electrical frequency, and phase relationship. In practice, this capability is commonly implemented using vector control frameworks, such as field-oriented control and direct torque control, enabled by high-bandwidth current measurement and real-time computation. Compared with fixed-speed operation, the integrated approach provides improved transient response and accurate torque production across a wide operating range, supporting functions such as controlled starting, programmable acceleration and deceleration, torque limiting, and energy recovery during braking when the application permits. Motor–drive integration also offers efficiency advantages under variable load conditions. Matching the electrical input to the instantaneous mechanical demand improves part load performance and reduces energy waste associated with throttling or mechanical regulation in loads such as pumps, fans, and compressors. In addition, integrated drives enable advanced supervisory and protection functions, such as overload detection, stall recognition, phase-loss monitoring, and temperature-dependent derating, ensuring safe and reliable operation. These functions may rely on embedded sensors or on thermal and electrical models, and they support reliable operation near design limits while protecting the insulation system and magnetic materials.

Advances in power electronics further strengthens the case for integration. Increased switching frequencies and the adoption of wide bandgap semiconductors, including silicon carbide and gallium nitride, enable higher converter power density, reduce passive component size, and improved conversion efficiency. At the same time, inverters supplied waveforms introduce harmonic content that can increase iron losses, rotor surface losses, and alternating current copper losses associated with skin and proximity effects. Preserving high efficiency therefore requires coordinated design of the machine electromagnetic structure, the converter switching and modulation strategy, and the thermal management

system, while also controlling torque ripple, acoustic noise, and electromagnetic emissions. In industrial automation environments, integrated drives increasingly incorporate deterministic communication protocols such as EtherCAT and PROFINET to enable low latency, synchronized data exchange with controllers and supervisory systems. This connectivity supports Industry 4.0 capabilities, including real-time monitoring of electrical and mechanical variables, condition monitoring, predictive maintenance, and adaptive control. It also simplifies commissioning and lifecycle management through electronic nameplate functions, remote diagnostics, and firmware updates. Overall, integrated motor–drive systems provide improved controllability, enhanced efficiency under variable operating conditions, and increased operational intelligence, making them a central enabler for high efficiency motor deployment in modern industrial and traction applications.

1.3. Operational and Environmental Implications

The deployment of International Efficiency (IE)-class motors plays a pivotal role in advancing industrial energy efficiency initiatives, owing to their demonstrated capacity to substantially reduce electrical energy losses during operation. These efficiency gains directly translate into lower operational expenditures and a corresponding decline in carbon dioxide and other greenhouse gas emissions, thereby addressing both economic and environmental imperatives. Empirical studies consistently show that upgrading from lower efficiency classes such as IE1 (standard efficiency) or IE2 (high efficiency) motors to IE3 (premium efficiency) and higher levels (IE4 and IE5) yields energy savings typically ranging between 10% and 20%, although this figure varies depending on specific application conditions, duty cycles, and load characteristics. Beyond energy conservation, IE motors contribute to enhanced reliability and decreased maintenance overheads by virtue of their improved design and superior materials, which enable operation at reduced winding and bearing temperatures. This thermal efficiency minimizes wear and tear on critical motor components, leading to fewer unscheduled downtimes and prolonged maintenance intervals, an especially valuable advantage in industries characterized by continuous process operations, such as chemical manufacturing, petrochemicals, and food processing. Such reliability gains not only optimize production throughput but also enhance overall equipment effectiveness (OEE), thereby supporting broader operational excellence initiatives. From a regulatory and sustainability perspective, the adoption of high-efficiency electric motors is strongly aligned with global and regional policy frameworks aimed at climate change mitigation and energy system decarbonization. Within the European Union (EU), the Ecodesign Directive, currently embodied in Regulation (EU) 2019/1781, establishes Minimum Energy Performance Standards (MEPS) for electric motors and variable-speed drives. This legislative framework has accelerated the diffusion of IE3 and IE4 efficiency classes, while also creating market incentives for the deployment of IE5 ultra-premium motors. Comparable initiatives are being pursued in other jurisdictions, underscoring the global convergence of regulatory efforts and the increasing role of electric motors in achieving both binding climate targets and voluntary corporate sustainability commitments. The EU has outlined progressively ambitious objectives under the European Green Deal and the Fit for 55 legislative packages, which seek to reduce greenhouse gas (GHG) emissions by at least 55% by 2030 and achieve climate neutrality by 2050. In this context, the forthcoming transition from the Ecodesign Directive to the Ecodesign for Sustainable Products Regulation (ESPR) represents a significant regulatory milestone. The ESPR will broaden the scope of performance requirements to encompass a wider range of motor-driven systems, introduce more stringent efficiency thresholds, and integrate circular economy principles, including durability, reparability, recyclability, and the introduction of digital product passports. Moreover, policy frameworks increasingly encourage the integration of high-efficiency

motors with power electronic drives, advanced condition monitoring, and smart grid platforms, thereby enhancing system-level efficiency and facilitating the integration of variable renewable energy sources. Although the IEC 60034-30-1 and IEC 60034-30-2 standards formally defines efficiency classes up to IE5, emerging academic and industrial discourse has begun to conceptualize future efficiency classes (IE6–IE9). These prospective categories are associated with near-lossless energy conversion enabled by advanced materials, wide bandgap semiconductor-based power electronics, novel electromagnetic topologies, and AI-assisted predictive maintenance strategies. Within this framework, an IE9 classification may be envisioned as a future benchmark encompassing not only unprecedented energy efficiency, but also compliance with circularity, digital interoperability, and seamless compatibility with renewable-based and decentralized power systems. Accordingly, the trajectory of IE-class motor development, from the current IE3–IE5 technologies to future conceptual IE6–IE9 categories, illustrates the central role of motor systems in enabling the EU’s transition toward a low-carbon, resource-efficient, and digitally integrated industrial economy. While their immediate benefits lie in reducing electricity demand, the broader significance of these technological developments rests in their capacity to accelerate the transition toward integrated, efficient, and renewable-based energy systems, thereby reinforcing the European Union’s commitment to climate neutrality by 2050.

The environmental impact patterns observed for SCIMs, SynRMs, and PMSMs in Figure 9 can be interpreted primarily through differences in material composition and total material demand during manufacturing, as reported in Figure 5, and will be discussed within the broader context of use phase dominance over the motor lifecycle. The SynRM exhibits the highest material intensity, particularly for electrical steel, requiring 80.5 kg compared with 48.4 kg for the SCIM and 39.0 kg for the PMSM. This higher material demand is reflected in energy related indicators, with the SynRM showing the largest cumulative energy requirement (GER 7095 MJ) and primary electricity use (1086 MJ). The SynRM also records the highest greenhouse gas emissions (493 kg CO₂ equation) and acidification emissions (6005 g SO₂ equation), indicating that its production phase impacts are strongly driven by energy and emissions embodied in material processing and fabrication. Waste results reinforce this interpretation, as the SynRM generates the greatest amount of non-hazardous waste (1.15 t) compared to the other technologies, consistent with increased upstream processing burdens and higher manufacturing losses associated with greater steel inputs.

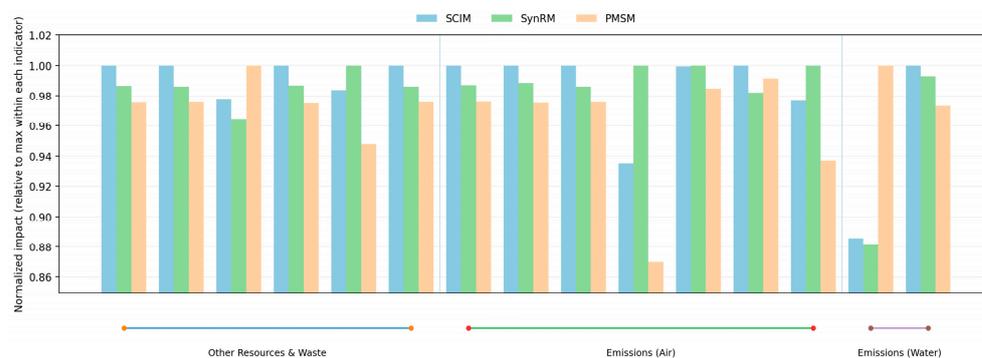


Figure 9. Environmental impacts of electric motor manufacturing phase.

The SCIM represents a useful reference technology because its material composition is comparatively conventional and does not rely on rare earth permanent magnets. Relative to the SynRM, the SCIM requires substantially less electrical steel (48.4 kg versus 80.5 kg), which is consistent with a generally lower burden in indicators that are strongly influenced by steel production and processing. At the same time, several SCIM results remain close

to the SynRM, indicating that differences in manufacturing impacts are not determined solely by electrical steel mass, but also reflect contributions from other materials, processing routes, and the underlying lifecycle inventory assumptions. In comparison with the PMSM, the SCIM tends to exhibit higher impacts in categories where bulk material demand and associated processing energy dominate, while avoiding the pronounced water and toxicity burdens linked to permanent magnet supply chains. Overall, the SCIM represents an intermediate profile, with moderate manufacturing impacts and without a single indicator disproportionately driving its footprint.

The PMSM generally exhibits lower impacts in categories dominated by bulk material demand. However, it demonstrates clear tradeoffs in indicators associated with permanent magnet production. Despite the lowest total motor mass (75.3 kg), the PMSM shows a substantially higher process water requirement (1172 L) and the highest release of heavy metals to water (2949 mg Hg equivalent), which is consistent with the inclusion of Nd, Fe, and B permanent magnets (1.8 kg) and the resource-intensive upstream operations typically associated with rare earth supply chains. At the same time, the PMSM requires less cooling water (246 L), which may reflect improved efficiency and thermal performance linked to its electromagnetic design and material configuration. These results highlight that relatively small quantities of specific materials can dominate selected water and toxicity-related indicators, even when the overall material mass is reduced.

From a mitigation perspective, increasing recycled content in motor components provides a direct opportunity to reduce manufacturing burdens. While electrical steel laminations and Nd, Fe, and B permanent magnets remain challenging to recycle due to stringent functional requirements and complex separation constraints, other materials used in motor construction, including structural steels, cast iron, aluminum, and copper, have established recycling routes. Substituting primary feedstock with secondary materials for these components reduces impacts associated with extraction and energy intensive refining, complementing strategies aimed at lowering overall material demand.

Importantly, manufacturing stage differences must be interpreted within a full lifecycle context because the use phase typically dominates the environmental footprint of electric motors. Numerous LCAs indicate that operational electricity consumption accounts for approximately 80% to 90% of total impacts, particularly for motors operating under continuous industrial duty. Ferreira et al. [118] estimates that industrial motors are responsible for roughly 65% to 70% of total electricity consumption in the European Union, underscoring the substantial mitigation potential associated with efficiency improvements and control strategies such as variable-speed drives. Consistent with this, Boughanmi et al. [119] show that, while production and end-of-life stages contribute to the footprint, electricity consumption during operation remains the principal driver for induction motors. Deprez et al. [120] further note that the lifetime operational energy expenditure for three-phase induction motors can reach up to 100 times the initial purchase cost, reinforcing the centrality of operational performance.

The literature also indicates that incremental manufacturing burdens associated with higher-efficiency designs are typically offset rapidly by reduced electricity consumption during operation. Auer and Meincke [121] report that the environmental breakeven point for high-efficiency motors is achieved in less than one month for most impact categories, despite the use of additional materials such as copper and rare earth elements. Cassoret et al. [122] similarly report that higher manufacturing impacts for copper cage rotors relative to aluminum cage rotors are compensated quickly by operational energy savings, and that up to 95% of lifetime energy use occurs during the operational stage. Broader policy and system-level assessments corroborate these findings. The EuP Lot 30 study indicates that the use phase contributes around 70% of the total environmental impact

for most electric motors [123], while Jocanovic et al. [124] report that 93% to 94% of lifecycle costs and energy consumption in pump motor systems are attributable to the operational phase. Overall, while material selection, recycled content, and end-of-life strategies remain important for addressing production phase hotspots and toxicity-related categories, the largest reductions in total lifecycle impacts are generally achieved by minimizing operational electricity consumption through higher-efficiency motor designs and appropriate control strategies [124–128].

1.4. Integration with Emerging Technologies

IE motors serve as foundational components in the ongoing evolution toward smarter, more interconnected, and sustainable industrial ecosystems. Their inherent high efficiency and operational reliability make them ideal candidates for seamless integration within the framework of Industry 4.0, where advanced digitalization and automation technologies are transforming traditional manufacturing and industrial processes at a fundamental level. The convergence of IE motors with sophisticated Industry 4.0 innovations, including digital twin modeling, Internet of Things (IoT)-enabled sensor networks, and artificial intelligence (AI)-driven predictive maintenance systems, enables unprecedented levels of operational transparency, control, and optimization.

Digital twin technology plays a pivotal role in this integration by creating precise virtual replicas of physical motor assets. These digital twins allow for real-time simulation, monitoring, and analysis of motor behavior under a wide array of operational conditions. By continuously comparing real-world data with simulation outputs, operators and maintenance teams can identify inefficiencies in energy consumption, detect early signs of mechanical or electrical faults, and predict future performance degradation. This facilitates timely and targeted interventions, minimizing unscheduled downtime and enhancing overall system availability. The deployment of IoT-enabled sensors embedded within motor assemblies further enhances the granularity and fidelity of data acquisition. These sensors capture a multitude of critical parameters, such as temperature, vibration, electrical current, torque, and rotational speed, which are transmitted to centralized analytics platforms. The rich data environment enables detailed condition monitoring and supports real-time diagnostics, thus allowing for continuous health assessments of motor systems. This data-driven approach not only ensures optimal operational performance but also enhances safety by enabling early detection of abnormal operating conditions.

AI-driven predictive maintenance represents a transformative advancement in the management of IE motor assets. Leveraging machine learning and advanced analytics, these systems process vast amounts of historical and real-time sensor data to identify subtle patterns and anomalies indicative of wear, imbalance, misalignment, bearing degradation, or insulation failures. By predicting potential failures well in advance, maintenance activities can be scheduled proactively, optimizing resource allocation, extending motor service life, and reducing both maintenance costs and production interruptions. This predictive capability shifts the paradigm from reactive to proactive maintenance, thereby improving overall equipment effectiveness (OEE) and significantly lowering the total cost of ownership. In addition to maintenance optimization, the integration of these Industry 4.0 technologies facilitates the dynamic performance tuning of IE motors. Adaptive control algorithms enabled by AI can adjust motor parameters in real-time to match changing load demands and environmental conditions. Such adaptability not only maximizes energy efficiency across varying production cycles but also stabilizes process control, improves product quality, and reduces mechanical stress on motor components. These performance enhancements contribute directly to operational excellence and support sustainable manufacturing practices.

Beyond immediate operational gains, the integration of IE motors with Industry 4.0 tools fosters enhanced asset utilization and comprehensive lifecycle management. Continuous condition monitoring and data-driven analytics enable industrial stakeholders to make informed decisions regarding capital investments, prioritizing upgrades and replacements based on asset health and performance metrics. This strategic approach supports sustainability by optimizing the use of resources and minimizing waste generated through premature equipment replacement. Furthermore, detailed lifecycle insights aid compliance with evolving environmental regulations and corporate sustainability mandates. Collectively, these advancements underscore the critical role of IE motors as enablers of energy-efficient, resilient, and intelligent industrial operations. Their deployment aligns with global sustainability objectives by significantly reducing energy consumption and greenhouse gas emissions across manufacturing sectors. Moreover, these technologies support the transition toward Industry 5.0, which emphasizes human-centric automation, collaborative robotics, and circular economy principles. By empowering operators with intelligent tools and real-time insights, IE motors integrated within Industry 4.0 and 5.0 frameworks contribute to the creation of manufacturing environments that are not only economically competitive but also socially responsible and environmentally sustainable.

1.5. Review Scope and Objectives

This article provides a structured synthesis of technological progress in high-efficiency electric motors and examines how these motor systems can be deployed as enabling assets within Industry 5.0 manufacturing environments. The discussion is anchored in the International Efficiency (IE) classification framework, with focus on IE3-IE5 motor systems and ultra-premium efficiency concepts, together with the associated enabling technologies—particularly power electronic drives, digital monitoring, and human-centered automation.

To support a comprehensive and transparent review, relevant publications were collected from major scholarly databases (including IEEE Xplore and ScienceDirect) with a primary emphasis on literature published between 2005 and 2025. In addition to peer-reviewed research, this study incorporates standards and policy documents and publicly accessible industrial documentation such as technical reports and manufacturer materials, thereby connecting academic findings with industrial deployment practices. Figure 10 summarizes the temporal evolution of research output on high-efficiency motors in the Elsevier and IEEE literature from 2005 to 2025. The bar series reports the annual publication counts, while the dashed lines indicate the underlying growth trends for each database. Overall, both sources show a sustained increase in publication activity across the period, with more pronounced growth in the later years, underscoring the expanding research emphasis on high-efficiency motor technologies in response to industrial energy-efficiency and decarbonization priorities.

The collected evidence was organized and analyzed across the following themes:

- Efficiency classification schemes and regulatory drivers.
- Machine topologies and electromagnetic design strategies.
- Materials innovations for stators, rotors, conductors, and magnets.
- Thermal management solutions and integrated motor–drive configurations.
- Environmental and lifecycle considerations.
- Digital integration pathways involving IoT, AI-based analytics, and digital twins in Industry 4.0/5.0 contexts.

The purpose of this manuscript is not to introduce new experimental results or modeling frameworks. Instead, it aims to integrate and evaluate existing research and industrial evidence, clarify technical and sustainability tradeoffs, and highlight practical constraints that influence adoption in smart manufacturing. On this basis, the paper is positioned

as a review and synthesis contribution intended to inform researchers and practitioners working on energy-efficient, resilient, and human-centric manufacturing systems.

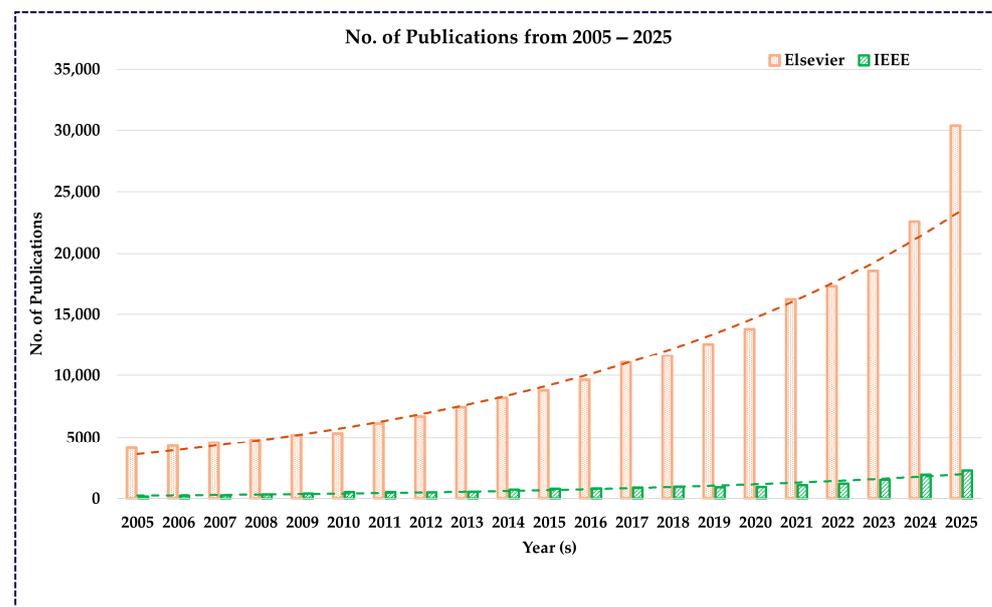


Figure 10. No. of publications on high-efficiency motors during 2005 to 2025.

Literature Search Strategy and Selection Criteria

The primary contributions of this work are

- A technology-focused synthesis of high-efficiency motor types, squirrel cage induction motors (SCIMs), synchronous reluctance motors (SynRMs), and permanent magnet synchronous motors (PMSMs), emphasizing differences in design rationale, performance behavior, and implementation contexts across IE classes.
- A system-oriented discussion that extends beyond rated motor efficiency to include motor–drive coupling, inverter-related losses, control methods, and the implications of part-load and variable-speed operation.
- A consolidated assessment of current IE5 industrial offerings, drawing together publicly reported performance indicators and application positioning to highlight prevailing design directions and practical deployment patterns.
- A critical examination of sustainability and lifecycle aspects, including rare earth dependence and material supply risks, recyclability and end-of-life options, and the shifting balance between manufacturing impacts and operational benefits as efficiency levels increase.
- An integration perspective aligned with Industry 5.0, outlining how condition monitoring, predictive maintenance, digital twins, and human-in-the-loop decision support can jointly enhance energy management, reliability, and system resilience.
- Identification of implementation barriers and open research problems, such as legacy system interoperability, control architecture constraints, scalability, and techno-economic limitations affecting adoption in industrial settings.

1.6. Conceptual Framework

The conceptual framework illustrated in Figure 11 establishes a unifying analytical perspective for this review by positioning high-efficiency electric motor–drive systems as central cyber-physical assets within Industry 5.0 manufacturing environments. Rather than treating motors, drives, materials, and digital technologies as isolated elements, the framework emphasizes their system-level interdependence and collective influence on

energy efficiency, operational reliability, and lifecycle sustainability. At the foundation of the framework is the physical actuation layer, comprising high-efficiency electric motors (IE3–IE5) and associated power electronic drives. Design-level considerations, including electromagnetic configuration, material selection, and thermal management, define baseline efficiency, loss distribution, and reliability characteristics. These factors critically affect performance under variable-speed and partial-load operating conditions typical of modern industrial processes. The framework further incorporates a digital intelligence layer, where sensing, IoT connectivity, and data-driven analytics enable continuous monitoring of electrical, thermal, and mechanical states. Artificial intelligence and digital twin models support predictive maintenance, fault diagnosis, and adaptive control, thereby preserving efficiency gains achieved at the design stage throughout the operational lifecycle. Consistent with Industry 5.0 principles, a human-centric interaction layer is explicitly included. Operator-oriented decision-support tools, interpretable diagnostics, and augmented maintenance interfaces facilitate transparent human–machine collaboration, enhancing safety, trust, and operational resilience. Finally, the lifecycle and sustainability layer links system operation to environmental performance, material sustainability, and regulatory compliance. Feedback mechanisms across all layers enable continuous improvement and alignment with circular economy objectives. This conceptual framework serves as the organizing structure for the remainder of the review, guiding the synthesis of technological developments and clarifying how high-efficiency motor systems enable sustainable, resilient, and human-centric industrial systems.

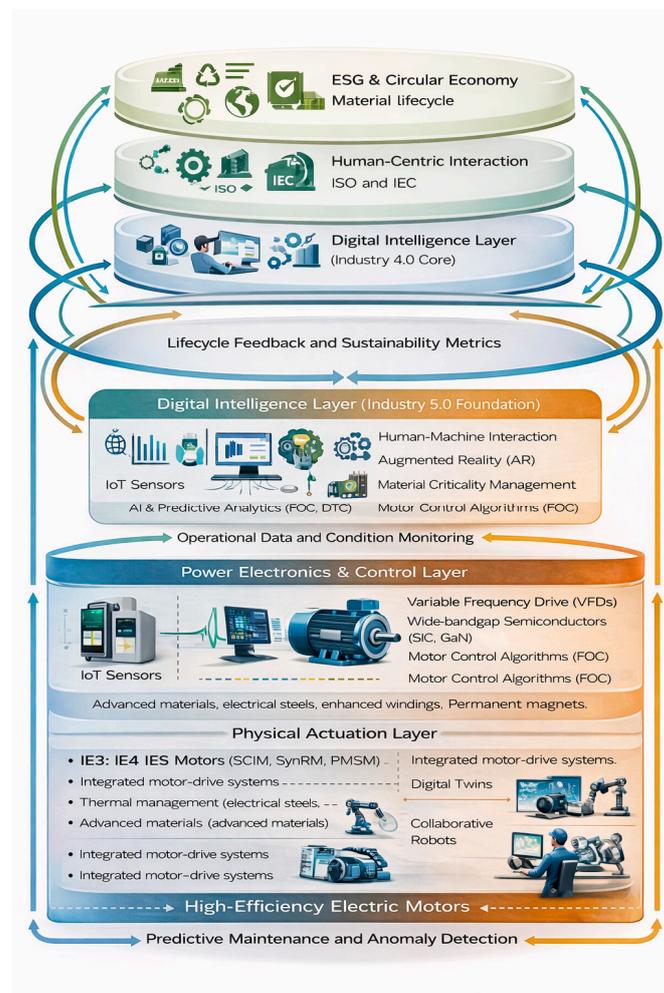


Figure 11. Conceptual framework for integrating high-efficiency electric motors into Industry 5.0 manufacturing systems.

2. The Role of Electric Motors in Industry 5.0

Electric motors constitute essential components in contemporary industrial infrastructure, serving as the primary drivers of mechanical motion in diverse manufacturing and process automation applications. Within the evolving paradigm of Industry 5.0, which emphasizes the symbiotic integration of human expertise, advanced digital technologies, and sustainable manufacturing practices, electric motors transcend their traditional role as mere energy conversion devices to become critical enablers of adaptive, intelligent, and efficient production systems. Industry 5.0 focuses on fostering human-centric automation, wherein collaborative robots (cobots), artificial intelligence (AI), and the Internet of Things (IoT) converge to create flexible and responsive manufacturing environments. In this context, electric motors equipped with embedded sensors, smart drives, and real-time communication capabilities play a pivotal role in facilitating enhanced system interoperability and operational transparency. These smart motors support advanced functionalities, such as predictive maintenance, dynamic load management, and energy optimization, which collectively enhance system reliability, reduce downtime, and contribute to cost-effective operations. Furthermore, the deployment of high-efficiency motors aligns directly with Industry 5.0's sustainability objectives by minimizing energy consumption and reducing greenhouse gas emissions, thereby mitigating the environmental impact of industrial activities. The integration of electric motors with digital twins and cyber-physical systems enables continuous performance monitoring and adaptive control strategies, ensuring that manufacturing processes remain agile and resilient amidst fluctuating demand and supply conditions. The essential role of electric motors in contemporary industrial processes necessitates a rigorous understanding of the diverse motor technologies employed across various manufacturing sectors to maximize their utility within the evolving Industry 5.0 paradigm. Each motor type exhibits distinct operational characteristics, efficiency metrics, and performance attributes that influence its suitability for specific industrial applications.

A systematic evaluation of these factors is critical for the strategic selection and deployment of motor technologies that enhance productivity, energy efficiency, and system responsiveness in advanced manufacturing systems. Industry 5.0's emphasis on flexibility, sustainability, and enhanced human-machine collaboration further underscores the importance of motor technologies that seamlessly integrate with digital control architectures, support predictive maintenance frameworks, and adapt to dynamic operational requirements. Therefore, a comprehensive analysis of predominant high-efficiency industrial motors, including IE5-rated designs, becomes imperative. The IE5 efficiency class, defined by the IEC 60034-39-1 and IEC 60034-30-2 standards [23], represents the current benchmark for ultra-premium energy performance, delivering up to 20% lower energy losses compared to IE3 and 14% compared to IE4 motors. This class encompasses a variety of advanced designs, such as permanent magnet synchronous motors (PMSMs), synchronous reluctance motors (SynRMs), and hybrid configurations optimized for reduced rotor losses, enhanced power density, and precise speed control. Within this domain, leading global manufacturers, such as ABB, Siemens, WEG, Nidec, Danfoss, Nord Drivesystems, SEW-Eurodrive, Bosch, and Toshiba, have introduced highly specialized IE5 motor solutions tailored for diverse industrial sectors. These motors are engineered not only to achieve top-tier efficiency but also to integrate seamlessly with advanced drive systems, digital twins, IoT-based monitoring platforms, and AI-enabled predictive maintenance tools. Their design innovations encompass optimized rotor and stator geometries, high-grade lamination steels, improved cooling architectures, and advanced insulation systems to ensure consistent performance under demanding operational conditions. The forthcoming sections provide a comparative review of IE5 motor offerings from these manufacturers, examining their efficiency ratings, design characteristics, drive integration capabilities, control system com-

patibility, and targeted industrial applications. By detailing both technical specifications and application-specific advantages, this analysis will enable stakeholders to align motor selection with operational goals, sustainability strategies, and Industry 5.0 readiness.

2.1. Criteria for Technology and Manufacturer Selection

The motor technologies and manufacturers included in this review were selected using predefined, objective criteria to ensure technical relevance, industrial representativeness, and consistency with the scope of the study. This review is not intended as an exhaustive survey of all commercially available solutions; instead, it concentrates on technologically mature and industrially significant approaches that reflect current directions in high-efficiency motor system development.

2.1.1. Motor Technology Selection

Motor technologies were selected based on the following criteria:

- Relevance to ultra-high efficiency: Alignment with IE4–IE5 efficiency classes and/or a technically substantiated pathway toward ultra-premium efficiency.
- Industrial applicability: Demonstrated adoption or strong suitability across key sectors, including manufacturing, automotive, and process industries.
- Technical evidence: Sufficient documentation in peer-reviewed literature and/or reputable public industrial sources to enable rigorous analysis.
- Representation of design tradeoffs: Ability to capture key engineering tradeoffs involving efficiency limits, material selection, thermal constraints, and control and drive complexity, including major motor families such as SCIMs, SynRMs, and PMSMs.

2.1.2. Manufacturer Selection

Manufacturers were included based on the following criteria:

- Market relevance and technological capability: Demonstrated industrial presence and/or recognized capability in high-efficiency motor and drive technologies.
- Transparency of publicly available information: Availability of accessible datasheets, technical notes, application guidance, or documented implementations that support verifiable discussion.
- Evidence of IE5-class solutions: Documented deployment of IE5 or equivalent ultra-high-efficiency motor–drive systems supported by technical performance information.
- System-level integration focus: Relevance to integrated system design, including advanced control, digital monitoring and diagnostics, and compatibility with data-enabled operation aligned with Industry 5.0-oriented objectives.

2.1.3. Scope and Intent

The selection is intended to enable a technically rigorous and system-oriented discussion of prevailing design methodologies, integration architectures, and implementation constraints associated with ultra-efficient motor–drive systems. Emphasis is placed on approaches that make the underlying engineering rationale explicit, particularly the ways in which ultra-high efficiency is pursued through electromagnetic design choices, material and topology selection, thermal management strategies, and the increasing reliance on advanced control and power electronic interfacing. This framing supports an analysis of how design decisions translate into measurable performance under industrial duty cycles, including implications for reliability, manufacturability, cost, and operational robustness. The review is not structured to support direct cross manufacturer comparison or product ranking. Such evaluation would require harmonized testing procedures, standardized operating points, consistent application contexts, and comprehensive access to propri-

etary validation data, conditions that are rarely satisfied across publicly available sources. Moreover, reported performance and efficiency values are often dependent on specific configurations, such as inverter selection, control parameters, cooling conditions, and load profiles, which further limits the validity of direct comparisons. Instead, the selected technologies and manufacturers provide a representative basis for examining recurring engineering tradeoffs and common integration patterns at the system level, including motor and inverter coordination, control and hardware interactions, and the incorporation of digital functions such as monitoring, diagnostics, and data enabled optimization. By adopting this evidence-based and application-oriented perspective, the review aims to reflect contemporary industrial practice while maintaining analytical rigor, avoiding over-generalization, and emphasizing the system-level factors that ultimately govern efficiency, deployability, and lifecycle performance.

2.2. ABB—SynRM IE5 Ultra

ABB's SynRM IE5 Ultra motor represents a pivotal advancement in sustainable industrial motor technology. Historically, synchronous reluctance motors were explored as early as the 1920s, but early designs suffered from poor torque characteristics and manufacturing complexity. ABB's breakthrough came through innovative rotor design using flux barriers and sophisticated finite element analysis (FEA), combined with advanced power electronics in their ACS880 drives. The motor achieves IE5 ultra-premium efficiency with efficiency levels exceeding 96%, primarily by eliminating rotor copper losses and avoiding rare earth permanent magnets. This is crucial, as it reduces supply chain risks related to magnet sourcing. In industries like cement, pulp and paper, and district heating, continuous operation with high reliability is demanded, and ABB's SynRM provides superior thermal performance and extended maintenance intervals compared to traditional induction motors. ABB also focuses on integrated digital solutions, enabling remote condition monitoring and predictive maintenance via the ABB Ability™ platform, reducing unplanned downtime and optimizing asset lifecycle costs. The motor's low noise emission and vibration levels further contribute to worker safety and environmental compliance [129]. Figure 12 shows the ABB IE5 synchronous reluctance motor (SynRM). The motor uses a reluctance-based rotor without windings or permanent magnets, reducing rotor losses. When driven by a frequency inverter, the stator's rotating magnetic field aligns the rotor along the path of minimum reluctance, enabling synchronous operation. This design achieves IE5 efficiency with low heat generation, high reliability, and improved energy performance compared to conventional induction motors.



Figure 12. ABB IE5 SynRM [129].

- Power range: 0.75 kW to 500 kW.
- Efficiency: Up to 96.5% (IE5 ultra-premium).
- Torque density: Approx. 1.3–1.5 Nm/kg.
- Speed range: 750 to 3600 rpm (variable frequency drives supported).
- Weight: Typically 20–350 kg, depending on size.
- Temperature class: Class F insulation (up to 155 °C).
- Typical applications: Pumps, fans, compressors, HVAC.
- Energy savings: Up to 15–20% compared to IE4 motors in typical operation.

2.3. Siemens—SIMOTICS SD IE5

Siemens' SIMOTICS SD IE5 motor is emblematic of the shift toward Industry 4.0, where energy efficiency meets digital intelligence. Building on a century of expertise in electromechanical systems, Siemens developed this motor to integrate seamlessly within their Totally Integrated Automation (TIA) portfolio, enabling smart manufacturing ecosystems. The motor uses a hybrid rotor design with permanent magnets and reluctance elements to reduce rare earth magnet content while maximizing performance. This hybrid approach delivers excellent torque linearity, minimal cogging torque, and stable operation across a wide speed range, which is critical for automotive assembly lines and high-speed packaging machinery. The embedded digital nameplate technology allows for instant access to motor specifications and real-time operating data via QR codes, enabling rapid commissioning and maintenance planning. In addition, Siemens leverages edge computing and cloud analytics to provide condition-based maintenance alerts and energy usage optimization. The SIMOTICS SD IE5 motor's compliance with ISO 9001 and ISO 14001 [130] underscores Siemens' commitment to delivering not only cutting-edge technology but also sustainable and responsible manufacturing solutions [131]. Figure 13 shows the Siemens SIMOTICS SD IE5 permanent-magnet synchronous motor together with its associated drive unit. The motor features a compact, finned housing for effective cooling and an integrated permanent-magnet rotor that enables ultra-premium IE5 efficiency. The drive unit supplies controlled power to the motor, allowing precise speed and torque regulation. This combination results in reduced energy losses, lower heat generation, and high-power density compared to conventional induction motor systems.



Figure 13. Siemens—SIMOTICS SD IE5 [131].

- Power range: 0.75 kW to 400 kW.
- Efficiency: Up to 96.8% (IE5).
- Torque density: About 1.4 Nm/kg.
- Speed range: 500 to 4500 rpm.

- Weight: 25–320 kg depending on frame size.
- Noise level: ≤ 65 dB(A) at 1500 rpm.
- Integrated features: Digital nameplate, real-time monitoring.
- Typical applications: Automotive manufacturing, packaging, machine tools.

2.4. WEG—W22 Magnet IE5

WEG's W22 Magnet IE5 motor builds on a rich heritage of delivering durable, energy-efficient electric motors to the most demanding industrial environments. The W22 family is renowned for its ruggedness, with features such as H-class insulation, epoxy resin coatings for corrosion resistance, and robust cast iron frames designed to withstand harsh ambient conditions. WEG's IE5 motor incorporates high-performance neodymium magnets and optimized rotor topology, enabling a peak efficiency of around 96–97%, which translates into substantial energy savings and reduced greenhouse gas emissions for industrial operators. In industries such as mining and petrochemicals, where downtime and energy costs are significant, the W22 Magnet IE5's enhanced torque density and reliability simplify mechanical systems by reducing gearbox sizes and maintenance frequency. WEG's extensive global manufacturing and service network ensures rapid spare parts delivery and local support, which is essential for minimizing production interruptions in remote or challenging locations. Additionally, the motor is designed for compatibility with variable frequency drives (VFDs), further enabling precise speed control and energy optimization [132]. Figure 14 shows the main parts and magnetic flux of the WEG W22 Magnet IE5 motor. A three-phase, inverter-fed stator creates a rotating field, while permanent magnets on the rotor remove rotor copper losses. The rotor runs synchronously with the stator field, giving IE5 efficiency, lower heat, and higher power density than an induction motor.

- Power range: 0.37 kW to 355 kW.
- Efficiency: 96.3% to 96.9% (IE5).
- Torque density: Around 1.5 Nm/kg.
- Speed range: 750 to 3600 rpm.
- Weight: 15–300 kg.
- Insulation class: H-class (180 °C) for high durability.
- Typical applications: Mining, petrochemical, heavy industry.
- Energy savings: Approx. 12–18% over IE3 motors.



Figure 14. WEG—W22 Magnet IE5 [132].

2.5. Nidec Leroy-Somer—Dyneo+ IE5+

Nidec Leroy-Somer's Dyneo+ IE5+ motor exemplifies a versatile solution that bridges the gap between traditional motor operation and cutting-edge digital control. The Dyneo+ line, with origins in the 1990s, has evolved through multiple iterations to achieve IE5+ efficiency by combining high-energy rare earth magnets with a sophisticated rotor design and integrated sensor technology. Unique to Dyneo+ is its ability to operate both as a direct-on-line (DOL) motor and as a variable-speed drive motor, providing flexibility for retrofitting legacy systems while enabling energy savings in new installations. The motor's embedded temperature sensors and encoder compatibility allow for real-time thermal monitoring and speed feedback, reducing the risk of overheating and improving dynamic performance. Industries such as marine propulsion and industrial refrigeration benefit from Dyneo+'s high starting torque and robust construction, which ensure reliable operation under variable load conditions and harsh environments. Nidec's emphasis on digital integration supports Industry 4.0 initiatives, offering remote monitoring and fleet management to optimize asset utilization and maintenance scheduling [133]. Figure 15 shows the Nidec Dyneo IE5+ permanent-magnet synchronous motor. The motor uses a high-efficiency permanent-magnet rotor with an inverter-fed stator to operate synchronously. This design minimizes losses, achieving IE5+ efficiency, lower heat generation, and high torque density compared to conventional induction motors.

- Power range: 0.5 kW to 90 kW.
- Efficiency: Up to 97.0% (IE5+).
- Torque density: ~1.3 Nm/kg.
- Speed range: 1500 to 3000 rpm.
- Weight: 10–80 kg.
- Starting torque: Up to 2.5× rated torque.
- Applications: Marine propulsion, refrigeration, industrial automation.



Figure 15. Nidec—Dyneo IE5+ motor [133].

2.6. Danfoss—EC+ IE5 Motor System

Danfoss's EC+ IE5 motor system is a flagship product in the field of building automation, HVAC, and refrigeration, where partial load efficiency and noise reduction are paramount. With a background steeped in refrigeration and climate control technologies, Danfoss developed the EC+ motor as a highly efficient brushless DC (BLDC) solution that excels under variable-speed and partial-load conditions, which typically dominate HVAC operation cycles. The motor integrates directly with Danfoss's VLT and VACON variable-frequency drives and supports common communication protocols like BACnet and Modbus for seamless integration into building management systems. The EC+ system's compact design and quiet operation make it ideal for applications in hospitals,

laboratories, and cleanrooms, where environmental control is critical. Advanced features such as automatic fan balancing and filter clog detection reduce maintenance costs and improve system reliability, while VAV optimization helps building owners reduce energy consumption significantly. Moreover, the EC+ system supports certification compliance for green building standards, such as LEED and BREEAM, aligning with the growing market demand for sustainable construction and operation [134]. Figure 16 shows the Danfoss EC+ IE5 motor system, which integrates a high-efficiency motor with an electronic drive. The inverter-fed motor operates synchronously to optimize speed and torque control. This integrated system reduces energy losses, lowers heat generation, and achieves IE5 efficiency, making it suitable for high-performance and energy-efficient industrial applications.

- Power range: 0.1 kW to 15 kW.
- Efficiency: Up to 96.7% (IE5).
- Torque density: ~1.2 Nm/kg.
- Speed range: 100 to 5000 rpm.
- Noise level: ≤55 dB(A) typical.
- Communication: BACnet, Modbus, CANopen.
- Applications: HVAC, refrigeration, building automation.

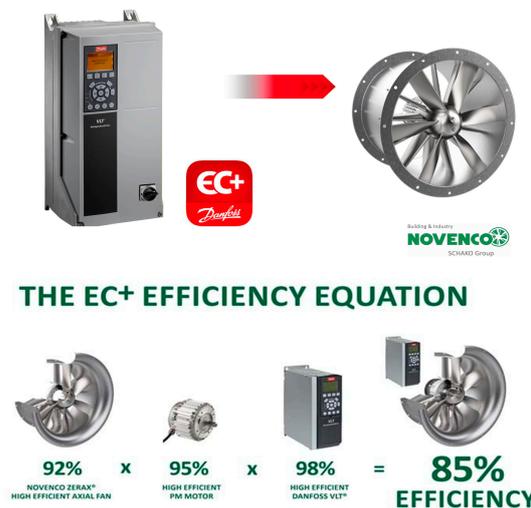


Figure 16. Danfoss—EC+ IE 5 motor systems [134].

2.7. Nord Drivesystems—IE5+ Synchronous Motor

Nord Drivesystems' IE5+ synchronous motor addresses the specialized requirements of hygiene-sensitive industries such as food and beverage, pharmaceuticals, and intralogistics. The motor's IP69K-rated stainless steel housing with smooth surfaces minimizes contamination risks by eliminating crevices and cooling fins, which are common bacteria traps. This design facilitates stringent washdown procedures required by regulatory bodies such as the FDA and EHEDG. The use of permanent magnets ensures high torque output at low speeds, enabling direct-drive solutions that eliminate gearboxes and reduce mechanical losses, improving system efficiency and reliability. Nord's integrated decentralized drive units combine the motor, controller, and safety functions within a compact form factor, reducing installation complexity and wiring. These units support safety protocols like PROFIsafe and STO, allowing machine builders to comply with ISO 13849 [135] and IEC 62061 [136] safety standards. By reducing the bill of materials and speeding up certification, Nord's IE5+ motor supports OEMs and end-users in achieving cost-effective and high-performance automation solution [137]. Figure 17 shows the Nord Drive Systems IE5+ synchronous motor. The motor operates with synchronous technology and is designed for inverter supply, enabling precise speed control. This design minimizes losses, reduces heat

generation, and delivers IE5+ efficiency with high power density compared to conventional induction motors.

- Power range: 0.37 kW to 90 kW.
- Efficiency: 96.5% to 97.2% (IE5+).
- Torque density: ~1.4 Nm/kg.
- Speed range: 0 to 3000 rpm.
- Ingress protection: IP69K.
- Housing: Stainless steel for hygiene.
- Applications: Food processing, pharma, packaging.
- Weight: 15–90 kg.



Figure 17. Nord Drive systems—IE5+ synchronous motor [137].

2.8. SEW-Eurodrive—MOVIGEAR® Performance IE5

SEW-Eurodrive's MOVIGEAR® Performance IE5 represents a revolutionary approach to material handling and intralogistics drives by integrating motor, gearbox, and inverter in a single compact, sealed unit. This integrated design reduces energy losses from cabling and electromagnetic interference, boosting overall system efficiency. The motor features IP65 ingress protection and hot-swap capability, enabling rapid replacement and minimizing downtime in demanding environments such as cold storage and automotive assembly lines. The system supports multiple industrial communication protocols including PROFINET, EtherCAT, and AS-i, facilitating decentralized control, diagnostics, and remote maintenance. Its lightweight construction and flexible mounting options ease installation on overhead conveyors and complex conveyor systems, allowing for dynamic reconfiguration of plant layouts. SEW's MOVI-C automation platform further empowers users with centralized control, simulation, and predictive maintenance capabilities, reinforcing the MOVIGEAR® system as a cornerstone of Industry 4.0-compliant logistics automation [138]. Figure 18 shows the SEW-Eurodrive MOVIGEAR® integrated motor and gear unit. The system combines a high-efficiency synchronous motor, integrated inverter, and gearbox in a compact housing. This integrated design reduces energy losses, improves thermal performance, and enables high system efficiency, making it suitable for energy-efficient drive applications.

- Power range: 0.12 kW to 15 kW.
- Efficiency: Up to 96.5% (motor component).
- Torque output: 0.4 to 40 Nm.
- Speed range: 0 to 4000 rpm.
- Weight: 8–40 kg.
- Protection class: IP65.
- Communication: PROFINET, EtherCAT, AS-i.

- Applications: Material handling, conveyor systems.



Figure 18. SEW-Eurodrive—MOVIGEAR® [138].

2.9. Bosch Rexroth—IE5-Class cyber® Motors

Bosch Rexroth's cyber® IE5-class motors are designed for next-generation high-precision automation systems, including robotics, 3D printing, and pharmaceutical manufacturing. Drawing on decades of expertise in motion control and drive technology, these motors offer ultra-low energy losses combined with rapid dynamic response and precise torque control. They integrate with the IndraDrive Mi decentralized servo platform, allowing for power and communication to be transmitted through a single hybrid cable, reducing the cabinet size by up to 85% and simplifying wiring. The motors support real-time industrial Ethernet protocols such as Sercos III and EtherCAT, enabling sub-millisecond closed-loop control critical for high-speed, high-accuracy tasks. The IP65-rated housing supports cleanroom and semi-harsh environments, while integrated absolute encoders provide exact positioning essential for complex motion profiles. Bosch Rexroth's cyber® motors advance Industry 4.0 goals through built-in predictive diagnostics, energy profiling, and rapid commissioning tools, boosting productivity and lowering operational costs in sophisticated manufacturing settings [139]. Figure 19 shows the Bosch Rexroth IE5-class cyber® motors. These motors use high-efficiency synchronous technology and are designed for precise motion control with inverter supply. The compact design minimizes losses, reduces heat generation, and achieves IE5-class efficiency with high torque and power density for advanced automation applications.



Figure 19. Bosch Rexroth—IE5-class cyber® motors [139].

- Power range: 0.1 kW to 20 kW.
- Efficiency: 96.8% to 97.5% (IE5).

- Torque density: Up to 1.6 Nm/kg.
- Speed range: 0 to 6000 rpm.
- Weight: 8–50 kg.
- Communication: EtherCAT, Sercos III.
- Applications: Robotics, pharma, additive manufacturing.

2.10. Toshiba—IE5 Synchronous Reluctance Motor

Toshiba's IE5 synchronous reluctance motors mark a strategic evolution in the company's extensive portfolio of industrial electric machines. With roots in the 1930s, Toshiba has historically been a leader in reliable motor design for heavy industries such as steel production and water treatment. Their IE5 line employs advanced rotor lamination techniques and optimized flux barriers to maximize magnetic flux guidance, achieving ultra-high efficiency while entirely avoiding permanent magnets. Power ratings typically range from 1.5 kW up to 250 kW, covering diverse applications from HVAC systems to large industrial pumps. Integration with Toshiba's own variable frequency drives allows for highly optimized energy use and dynamic speed control. The magnet-free design supports Toshiba's sustainability goals by reducing dependency on rare earth materials and improving end-of-life recyclability, aligning with increasing industrial demands for circular economy principles [140]. Figure 20 shows the Toshiba IE5 synchronous motor combined with its drive system. The inverter-fed synchronous motor operates at high efficiency by minimizing electrical and mechanical losses. This integrated motor–drive solution achieves IE5 efficiency, reduces heat generation, and provides precise speed and torque control compared to conventional induction motor systems.

- Power range: 1.5 kW to 250 kW.
- Efficiency: 96.0% to 96.7% (IE5).
- Torque density: 1.2–1.4 Nm/kg.
- Speed range: 750 to 3600 rpm.
- Weight: 25–400 kg.
- Insulation class: F-class.
- Applications: Steel mills, water treatment, HVAC.



Figure 20. Toshiba—IE5 synchronous motor and drive system [140].

2.11. Regal Rexnord—IE5 Permanent Magnet Motors

Regal Rexnord's IE5 permanent magnet synchronous motors target high-performance industrial sectors requiring compactness and precision, such as robotics, automated guided vehicles (AGVs), and precision machining. With efficiencies surpassing 96.5%, these motors feature innovative rotor designs that reduce cogging torque and thermal buildup, enabling smooth and consistent torque delivery over wide speed ranges. Their high torque density,

approximately 1.5 Nm/kg, allows OEMs to downsize mechanical components, reducing machine footprint and weight, which improves overall system efficiency. Advanced thermal management techniques and optimized magnetic circuit designs ensure prolonged motor life under demanding duty cycles. Communication interfaces including CANopen and EtherCAT facilitate integration within Industry 4.0 frameworks, enabling real-time condition monitoring, fault diagnostics, and predictive maintenance. Regal Rexnord's modular design approach accelerates product development and customization, helping manufacturers quickly adapt to evolving automation needs [141]. Figure 21 shows the Regal Rexnord IE5 permanent magnet motor. The motor employs a permanent-magnet rotor and an inverter-fed stator to achieve synchronous operation. This design minimizes rotor losses, resulting in IE5 efficiency, reduced heat generation, and high-power density compared to conventional induction motors.

- Power range: 0.5 kW to 50 kW.
- Efficiency: Up to 97.2% (IE5).
- Torque density: 1.5 Nm/kg typical.
- Speed range: 0 to 5000 rpm.
- Weight: 12–100 kg.
- Thermal class: F or H depending on model.
- Applications: Robotics, AGVs, CNC machines.



Figure 21. Regal Rexnord—IE5 permanent magnet motor [141].

2.12. SEW-Eurodrive—IE5 Electric Motors (Standalone)

In addition to its MOVIGEAR® integrated solutions, SEW-Eurodrive offers a comprehensive lineup of standalone IE5 electric motors designed for robust industrial use across multiple sectors including manufacturing, logistics, and process industries. These motors feature premium insulation systems rated for H-class temperatures, advanced cooling technologies, and modular mounting options that accommodate various mechanical configurations. Designed to withstand harsh conditions, the motors possess IP55 to IP65 protection and conform to global efficiency standards, helping users meet stringent energy regulations such as IE5. Compatibility with multiple inverter types offers flexibility for new installations or retrofits. SEW-Eurodrive's extensive global service network provides comprehensive technical support and rapid spare parts supply, ensuring minimal downtime and optimized asset utilization. Their focus on reliability, low lifecycle costs, and energy efficiency makes these motors well-suited for continuous operation in heavy-duty industrial environments [142]. Figure 22 shows the SEW-Eurodrive standalone IE5 motor. The motor uses high-efficiency synchronous technology and is designed for inverter operation. This configuration reduces energy losses, lowers heat generation, and achieves IE5 efficiency while providing high torque density compared to conventional induction motors.

- Power range: 0.25 kW to 355 kW.
- Efficiency: Up to 96.5% (IE5).

- Torque density: Approx. 1.3 Nm/kg.
- Speed range: 500 to 3600 rpm.
- Weight: 20–320 kg.
- Protection: IP55 to IP65.
- Applications: General industrial use, pumps, compressors.



Figure 22. SEW—Eurodrive—IE5 motor (standalone) [142].

Table 6 provides a structured comparison of commercially available IE5 and IE5+ ultra-premium efficiency motor families from major manufacturers, emphasizing parameters that are relevant to energy performance, operational capability, environmental suitability, and integration into digitally enabled industrial systems. Reported peak efficiencies are typically around 96% to 97.5%, reflecting reduced electromagnetic and thermal losses relative to lower efficiency classes and implying potential benefits in lifecycle energy consumption, heat generation, and reliability under continuous operation. The wide coverage of rated power, extending from sub-kilowatt units for building services and small automation to several hundred kilowatts for heavy industrial drives, indicates that IE5-level performance is implemented across both low-power and high-power domains. The mechanical and electromechanical specifications enable assessment of power density and controllability. Torque density, considered together with motor mass, serves as a proxy for compactness and is particularly relevant for applications where space constraints or dynamic response are critical, such as robotics, automated guided vehicles, and high-performance machine tools. The stated speed ranges further indicate suitability for variable-speed operation under inverter control, where broader ranges generally correspond to greater flexibility across multiple operating points. Electrical ratings, including rated voltage and starting torque as a percentage of rated torque, provide insight into compatibility with industrial supply standards and the capability to accelerate high-inertia or high-load torque systems, with implications for start-up robustness and potential motor sizing margins. Thermal and environmental attributes are included to support evaluation of continuous duty performance and operational resilience. Insulation class, thermal rating, and maximum operating temperature define allowable thermal stress and offer an indication of overload headroom and endurance in elevated ambient conditions or constrained convection environments. Cooling configurations influence attainable continuous torque and decreasing behavior and should be interpreted alongside enclosure sealing requirements. Ingress protection classifications indicate resistance to dust and water exposure and differentiate designs intended for standard industrial settings from those engineered for harsh environments or hygienic washdown regimes, where sealing requirements may impose additional thermal design constraints. In addition, the table highlights digital and system integration features that increasingly differentiate high-efficiency motor platforms. Embedded sensing, condition monitoring, predictive maintenance functions, and support for industrial com-

munication protocols facilitate commissioning, diagnostics, and data-driven maintenance within Industry 4.0 architectures. Protocol compatibility with real-time Ethernet networks supports deterministic control in automation systems, while building-oriented interfaces enable integration into supervisory control and energy management platforms.

Table 7 demonstrates that IE5 motor technologies deliver their highest practical benefit when evaluated as an integrated motor–drive system. Although many IE5 motors exhibit nameplate efficiencies in the upper 96% to 98% range, the overall system efficiency is governed by the combined performance of the motor and its converter, with drive efficiencies typically spanning 96% to 99% depending on the topology, control, and operating conditions. The table also highlights an industry trend toward tightly matched motor–drive ecosystems, where application-specific control features and integrated diagnostics improve real-world efficiency retention across variable-speed duty cycles rather than only at rated conditions.

- Drive efficiency range (96–99%): As reflected in Table 2, the efficiency of the drive stage is primarily determined by inverter topology and semiconductor technology, the implemented control approach (for example, field-oriented control or direct torque control), switching frequency and modulation strategy, and the effectiveness of thermal management. These factors jointly influence both switching and conduction losses, as well as the ability of the converter to operate near its optimal efficiency point across a given duty cycle.
- Servo drive platforms (Bosch Rexroth cyber): High-performance servo drives typically occupy the upper end of the reported range (approximately 98–99%) because they employ fast current control, highly optimized modulation, and advanced power electronic designs. Under favorable operating conditions, such drive efficiencies can raise the combined motor–drive efficiency to roughly 96–97%, highlighting the advantage of tightly engineered servo-grade converter platforms for high-efficiency motion and process applications.
- Permanent magnet motors (PM): PM motor systems often benefit from dedicated drive parameter sets and machine-specific control tuning, which support accurate torque production with reduced loss contributions from current harmonics and sub-optimal excitation. In practice, these tailored configurations commonly sustain drive efficiencies around 97–98%, contributing to consistently high system efficiency over a broad speed range.
- Synchronous reluctance motors (SynRMs): SynRM technologies can also achieve high overall energy performance, particularly when paired with sensorless control strategies that reduce sensor related complexity. However, their reliance on flux regulation and sensitivity to operating point can impose additional control demands, which may slightly reduce drive efficiency in certain implementations, typically to the 96–97% range.
- Integrated motor–drive systems (SEW MOVIGEAR, Danfoss EC+): Integrated architectures emphasize coordinated motor–drive communication, simplified commissioning, and compact thermal integration. Although peak converter efficiency may be marginally below that of specialized servo platforms, system integration can improve real-world performance by reducing mismatched configurations, stabilizing thermal operation, and enabling consistent parameterization, thereby sustaining high efficiency in industrial deployments.

Table 6. Technical specifications and performance characteristics of high-efficiency electric motor models [143–146].

Company & Model	Power Range (kW)	Efficiency (%)	Torque Density (Nm/kg)	Speed Range (rpm)	Weight (kg)	Rated Voltage (V)	Starting Torque (% Rated)	Insulation Class	Protection Rating	Thermal Rating (°C)	Max Operating Temp (°C)	Cooling Type	Digital Features	Typical Applications	Remarks
ABB—SynRM IE5 Ultra	0.75–500	Up to 96.5	1.3–1.5	750–3600	20–350	380–690	150%	Class F	IP55	155	155	TEFC/IC411	Integrated temperature sensors, remote monitoring, ABB Ability cloud	Pumps, compressors, HVAC, continuous processes	Magnet-free design reduces rare earth dependency
Siemens—SIMOTICS SD IE5	0.75–400	Up to 96.8	~1.4	500–4500	25–320	230/400/690	180%	Class F	IP55	155	155	TEFC/IC411	Digital twin, predictive maintenance, QR code commissioning	Automotive, packaging, machine tools	Hybrid rotor combining PM and reluctance torque
WEG—W22 Magnet IE5	0.37–355	96.3–96.9	~1.5	750–3600	15–300	230–690	180%	Class H	IP66	180	180	TEFC/IC411	VFD compatible, high overload capacity, robust housing	Mining, petrochemical, heavy industry	Designed for harsh environments with IP66 protection
Nidec Leroy-Somer—Dyneo+ IE5+	0.5–90	Up to 97.0	~1.3	1500–3000	10–80	400–690	200%	Class F	IP55	155	155	TEFC/IC411	Encoder compatibility, thermal sensors, software inertia tuning	Marine propulsion, refrigeration, industrial automation	Dual operation (DOL & inverter), versatile applications
Danfoss—EC+ IE5 Motor System	0.1–15	Up to 96.7	~1.2	100–5000	3–30	230–480	140%	Class F	IP54–IP65	155	155	Air-cooled	BACnet/Modbus, VAV optimization, automatic fan balancing	HVAC, building automation	Compact design, optimized for partial loads
Nord Drivesystems—IE5+	0.37–90	96.5–97.2	~1.4	0–3000	15–90	230–690	160%	Class F/H	IP69K	180	180	Air-cooled	Integrated safety (STO, PROFIsafe), condition monitoring	Food, pharma, packaging	Hygienic design with smooth housing for washdown
SEW-Eurodrive—MOVIGEAR® IE5	0.12–15	Up to 96.5	-	0–4000	8–40	230–480	150%	Class F	IP65	155	155	Integrated fan	PROFINET, EtherCAT, AS-i communication protocols	Material handling, conveyors	Compact motor-gear-inverter unit for distributed automation
Bosch Rexroth—cyber® IE5	0.1–20	96.8–97.5	Up to 1.6	0–6000	8–50	230–480	180%	Class F	IP65	155	155	Air-cooled	Real-time Ethernet (Sercos III, EtherCAT), absolute encoder	Robotics, pharma, additive manufacturing	Hybrid cable integration reduces installation complexity

Table 6. Cont.

Company & Model	Power Range (kW)	Efficiency (%)	Torque Density (Nm/kg)	Speed Range (rpm)	Weight (kg)	Rated Voltage (V)	Starting Torque (% Rated)	Insulation Class	Protection Rating	Thermal Rating (°C)	Max Operating Temp (°C)	Cooling Type	Digital Features	Typical Applications	Remarks
Toshiba—IE5 SynReluctance	1.5–250	96.0–96.7	1.2–1.4	750–3600	25–400	380–690	160%	Class F	IP55	155	155	TEFC	Optimized cooling, rugged frame construction	Steel mills, water treatment, HVAC	Focus on robust industrial applications
Regal Rexnord—IE5 PM Motor	0.5–50	Up to 97.2	~1.5	0–5000	12–100	230–480	180%	Class F/H	IP55	155	155	Air-cooled	Advanced thermal management, digital integration	Robotics, AGVs, CNC machines	High torque and thermal efficiency
SEW-Eurodrive—IE5 Standalone	0.25–355	Up to 96.5	~1.3	500–3600	20–320	230–690	150%	Class F	IP55–IP65	155	155	TEFC	Modular mounting, wide voltage range	Pumps, compressors, general industry	Flexible for retrofits and new installations
Johnson Electric—IE5 High-Efficiency Motor	0.1–20	96.7–97.3	1.3–1.6	1000–6000	5–40	110–480	160%	Class F	IP54	155	155	Air-cooled	IoT-enabled monitoring, integrated inverter option	HVAC, small industrial equipment	Focus on compact design and IoT readiness

- Partial load behavior and duty cycle relevance: Importantly, drive efficiency is not constant across load conditions and can decline at partial loads or low-torque operation due to fixed losses, switching loss dominance, and reduced power factor. Accordingly, advanced control functions, adaptive modulation, and variable switching strategies are critical for maintaining system-level energy savings over realistic industrial duty cycles, rather than only at rated operating points.

Table 7. IE5 Motors in terms of drive efficiency.

Manufacturer & Motor	Motor Efficiency (%)	Typical Driver Efficiency (%)	System Efficiency (%) (Motor × Driver)	Driver Type & Features
ABB—SynRM IE5 Ultra	Up to 96.5	97–98	~93.6–94.6	ACS880 drives, sensorless control, optimized for SynRM operation
Siemens—SIMOTICS SD IE5	Up to 96.8	97–98	~94.0–94.8	SINAMICS S120 drives, advanced field-oriented control (FOC)
Siemens—Sinamics G220	up to 98%	97–98%	~88–94%	Compact design optimized for single-axis applications with integrated safety functions.
Siemens—Sinamics S120	up to 98%	97–99%	~89–95%	Modular and scalable multi-axis drive system with advanced vector control and comprehensive safety features.
WEG—W22 Magnet IE5	96.3–96.9	96–97	~92.6–93.7	WEG CFW11/CFW700 inverters, PMSM optimized
Nidec Leroy-Somer—Dyneo+ IE5+	Up to 97.0	97–98	~94.1–95.1	Leroy-Somer Unidrive M/Unidrive SP inverters
Danfoss—EC+ IE5 Motor System	Up to 96.7	96.5–98	~93.3–94.8	Danfoss VLT/VACON drives with dedicated BLDC control profiles
Nord Drivesystems—IE5+	96.5–97.2	97–98	~93.6–95.2	Nord frequency inverters with integrated safety and diagnostics
SEW-Eurodrive—MOVIGEAR® IE5	Up to 96.5	96.5–97.5	~93.1–94.2	MOVIGEAR® integrated drives, optimized motor–drive communication
Bosch Rexroth—cyber® IE5	96.8–97.5	98–99	~94.8–96.5	IndraDrive Mi servo drives, single cable power & communication
Toshiba—IE5 SynReluctance	96.0–96.7	96–97	~92.2–93.6	Toshiba dedicated SynRM inverters, sensorless vector control
Regal Rexnord—IE5 PM Motor	Up to 97.2	97–98	~94.1–95.2	Advanced PM motor drives with thermal and overload protections
SEW-Eurodrive—IE5 Standalone	Up to 96.5	96.5–97.5	~93.1–94.2	Standard SEW inverters, scalable for general industry
Johnson Electric—IE5 High-Efficiency Motor	96.7–97.3	97–98	~93.8–95.3	Custom IoT-enabled drives, energy profiling & optimization

3. Industry Impact of Drive Efficiency on IE5 Motor Systems

3.1. Significant Energy and Operational Cost Reductions: The Economic Imperative

Electric motors are the largest consumers of industrial electricity, with estimates attributing nearly 50% of global industrial electricity consumption to motor systems. However, the efficiency gains from IE5 motors alone are insufficient without highly efficient

drives. The motor–drive system (motor + inverter/drive) must operate with minimal power losses to fully realize potential savings.

- Advanced IE5 motor drives use state-of-the-art power semiconductor materials (e.g., silicon carbide and SiC) and switching topologies to minimize conduction and switching losses.
- Drives commonly achieve power conversion efficiencies between 98% and 99.5%, a marked improvement over older-generation drives with efficiencies around 95–96%.
- For example, a large manufacturing plant operating 100 motors of 30 kW each for 8000 h/year can save upwards of 150,000 kWh annually by upgrading to IE5 motor–drive systems, equivalent to reducing CO₂ emissions by approximately 100 metric tons per year (assuming grid emission factor ~0.67 kg CO₂/kWh).
- These savings directly improve a company’s EBITDA margins and reduce exposure to volatile energy markets, which is critical amid rising energy prices and carbon taxes.
- Furthermore, reduced heat dissipation from drives lowers cooling demands on HVAC systems in control rooms and motor enclosures, generating secondary savings.

3.2. Enabling and Accelerating Corporate Sustainability and Regulatory Compliance

With environmental regulations becoming increasingly stringent worldwide, industrial companies face mounting pressure to reduce carbon footprints and energy consumption.

- IE5 motor drives help industries comply with tough regulations such as the EU’s Ecodesign Directive Tier 3 and Tier 4, U.S. DOE efficiency standards, and China’s MEPS.
- Beyond compliance, these systems contribute to companies’ Environmental, Social, and Governance (ESG) goals, allowing transparent tracking and reporting of energy use and emissions reductions.
- The elimination of permanent magnets in some IE5 motors reduces dependency on critical raw materials (rare earth elements), helping companies meet supply chain sustainability goals and avoid resource scarcity risks.
- This compliance also opens doors to incentives like grants, tax rebates, and preferential financing for energy-efficient investments.
- Industrial sectors that have traditionally been energy-intensive, such as cement, steel, mining, and oil and gas, are using IE5 motor drives as key enablers for their carbon-neutral transition roadmaps.

3.3. Enhanced Process Control and Product Quality Through Precise Drive Technology

Industrial manufacturing increasingly demands tighter control over production processes to achieve higher quality standards and minimize waste.

- IE5 motor drives integrate advanced vector control algorithms (field-oriented control and direct torque control) that enable highly precise and rapid adjustments to torque and speed.
- This reduces mechanical oscillations, vibrations, and electrical noise, critical in high-precision sectors such as semiconductor manufacturing, pharmaceuticals, and food processing.
- Drives with real-time feedback loops and sensor integration optimize energy usage during transient load conditions, ensuring that power is only supplied as needed.
- For example, packaging lines using IE5 motors and drives experience smoother operation with less product damage, fewer rejects, and higher throughput.
- These drives also facilitate adaptive manufacturing by integrating with AI and machine learning systems to predict process deviations and self-correct in real time.

- The ability to maintain stable operation even under fluctuating supply voltages enhances product consistency in regions with unstable grids.

3.4. Increased Reliability, Reduced Downtime, and Optimized Maintenance

Unplanned downtime is one of the costliest risks in industrial operations, often resulting in lost production, missed delivery deadlines, and costly emergency repairs.

- IE5 motor drives incorporate a suite of built-in diagnostic and protection features, including thermal monitoring, insulation resistance measurement, current and voltage imbalance detection, and vibration sensors.
- This allows for maintenance teams to implement condition-based and predictive maintenance regimes, scheduling repairs before catastrophic failures occur.
- Drives also support soft start and stop capabilities, mitigating mechanical stresses such as torque spikes and electrical inrush currents that typically shorten motor and gearbox lifetimes.
- In industries like water/wastewater treatment, food processing, or pharmaceuticals, where continuous operation is essential, this translates to improved process uptime and product safety.
- Remote monitoring and cloud connectivity enable rapid troubleshooting and expert support, reducing the need for costly onsite visits.
- These improvements significantly lower lifecycle costs of motor–drive systems, boosting return on investment.

3.5. Facilitating Industry 4.0 and Digital Transformation Initiatives

The modern industrial landscape is evolving into a connected, data-driven environment where real-time information is essential for decision making.

- High-efficiency IE5 drives are equipped with advanced communication protocols (e.g., EtherCAT, PROFINET, and Modbus TCP) that enable seamless integration into factory automation and digital twin ecosystems.
- They provide detailed energy consumption and performance data that feed into Energy Management Systems (EMS), enabling plant-wide optimization of power usage and demand response strategies.
- This digitalization supports smart grid interaction, where industrial facilities can adjust their energy consumption dynamically based on grid conditions or tariff signals, contributing to grid stability and resilience.
- The drives' capability to communicate faults, performance degradation, and operational parameters facilitates remote asset management and predictive analytics, reducing downtime and maintenance costs.
- By serving as smart nodes in the Industrial Internet of Things (IIoT) network, IE5 motor drives accelerate the transition to fully automated, self-optimizing plants with minimal human intervention.

3.6. Sustained High Efficiency Under Partial Load and Variable Operating Conditions

Industrial motors frequently operate under variable load and speed conditions, making partial load efficiency critical.

- IE5 motors combined with vector-controlled drives maintain high efficiency (>90%) even at 20–50% load, unlike older motors that can experience steep efficiency drops.
- This is particularly relevant for HVAC systems, centrifugal pumps, compressors, and conveyor systems, where load variability is common.

- Drives implement advanced control methods such as pulse width modulation (PWM), synchronous rectification, and adaptive cooling to optimize losses across all operating points.
- Efficient operation across varying loads reduces cumulative energy consumption and thermal stress on components, extending motor and drive lifespan.
- This adaptability is essential for industries with fluctuating production schedules or batch processing, such as chemical manufacturing and food processing.

3.7. Flexibility, Scalability, and Modular Integration for Diverse Industrial Applications

The IE5 motor–drive ecosystem supports a broad range of power ratings, configurations, and control architectures.

- From small servo drives for precision robotics (fractional kW) to large motors exceeding several megawatts for heavy industry, IE5 systems can be tailored to virtually any industrial application.
- Modular drive platforms allow OEMs and system integrators to build customized solutions quickly and cost-effectively, reducing design complexity and speeding time to market.
- The ability to integrate safety functions (e.g., Safe Torque Off and Safe Stop) and industry-standard communication protocols simplifies global certification and compliance.
- This modularity also future-proofs installations, allowing for easy upgrades or expansions without complete system overhauls.
- Such versatility accelerates adoption across sectors, from food and beverage, pharmaceuticals, and automotive manufacturing to mining, oil and gas, and utilities.

Figure 23 compares the efficiency of two motor–drive configurations, SCIM meeting IE3 and SynRM meeting IE5, when operated as a complete power drive system with a variable-speed drive. The results show that the SynRM IE5 configuration maintains higher efficiency than the SCIM IE3 configuration throughout the operating range. The advantage is particularly evident under low- and intermediate-speed operations, where induction motor-based systems typically experience a larger relative contribution of losses under partial-load conditions. In contrast, the SynRM IE5 system exhibits a more stable and consistently high-efficiency profile, indicating reduced loss sensitivity across a broad set of operating points.

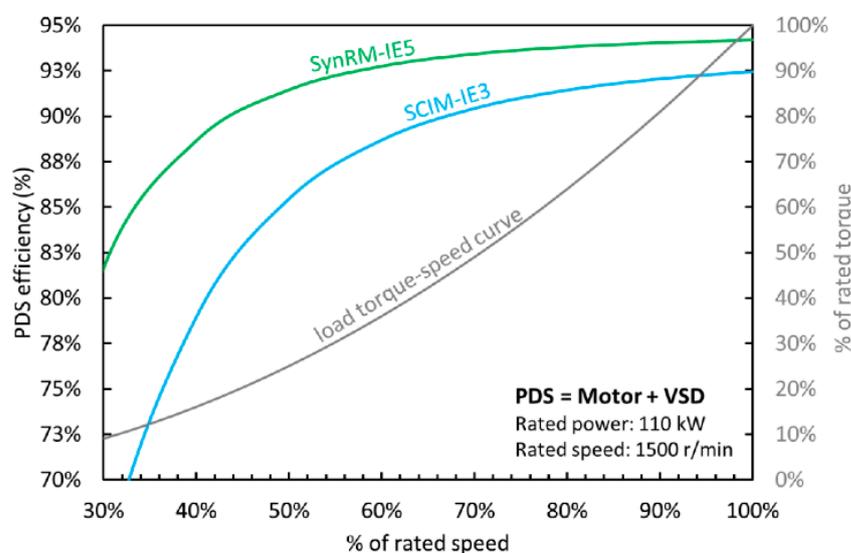


Figure 23. Efficiency vs. rated speed for IE3 and IE5 motors [147].

As operation approaches nominal conditions, both configurations tend toward similarly high efficiency levels, yet the SynRM IE5 system retains a systematic benefit. For applications characterized by frequent operation below rated speeds, such as pumps, fans, compressors, and many variable-torque industrial processes, the superior partial load efficiency of the SynRM IE5 is expected to translate into measurable reductions in electricity consumption. Consequently, the figure supports the broader conclusion that deploying IE5-class SynRM technology in variable-speed drive applications constitutes an effective strategy for improving operational energy efficiency and reducing associated environmental impacts over the use phase.

4. Industry Standards and Certifications for IE5 Motors

4.1. IEC 60034-30-2: A Pillar for Defining IE5 Efficiency [148]

The International Electrotechnical Commission (IEC) plays a central role in harmonizing motor efficiency standards worldwide. The IEC 60034–30–2, published in 2017, was the first global standard to specifically address ultra-premium efficiency motors such as synchronous reluctance motors (SynRMs) and permanent magnet synchronous motors (PMSMs) that qualify as IE5 class.

4.1.1. Historical Development

- Before IEC 60034-30-2, the IEC 60034-30-1 standard focused mainly on drive-controlled variable-speed operation and single-speed directly grid-connected motors with efficiency classes of IE1 through IE4. With the rise of new motor technologies, especially synchronous reluctance and PM motors, there was a clear need to define consistent efficiency classes and testing procedures. IEC 60034-30-2 fills this gap, promoting transparency and innovation.

4.1.2. Technical Highlights

- Efficiency Measurement: Testing is performed at multiple load points (25%, 50%, 75%, and 100%) and at rated voltages and frequencies. Efficiency is calculated based on mechanical output power versus electrical input power, incorporating stray load losses and additional losses from advanced rotor topologies.
- Loss Allocation: The standard carefully categorizes losses into stator copper, rotor copper (if applicable), core losses, mechanical losses, and stray losses. IE5 motors push these losses to minimal levels through advanced materials and optimized designs.
- Variable Frequency Drive (VFD) Compatibility: IE5 motors are often paired with sophisticated inverters. IEC 60034–30–2 accounts for inverter-fed operation, which can affect losses due to harmonic currents and switching losses. This is crucial for applications requiring variable speed.

4.1.3. Impact on Motor Design and Testing

Motor manufacturers must invest in precision measurement labs and advanced simulation tools. Manufacturers leverage Finite Element Analysis (FEA), Computational Fluid Dynamics (CFD), and magnetic flux optimization to reach IE5 efficiency without compromising reliability.

4.2. ISO 50001: Driving Systematic Energy Efficiency Across Industries [149]

ISO 50001, first published in 2011 and updated in 2018, has become a cornerstone for industrial energy management. It defines a structured approach using the Plan–Do–Check–Act (PDCA) cycle to continually improve energy performance.

4.2.1. Why ISO 50001 Matters for IE5 Motors

- Given that electric motors often consume the majority share of industrial electricity (estimated at 45–70% in manufacturing sectors), upgrading to IE5 motors is often a strategic lever to meet ISO 50001 objectives.

4.2.2. Benefits for Organizations

- Quantifiable Energy Savings: Companies report typical energy reductions of 10–25% after motor upgrades.
- Cost Reduction: Beyond energy, reduced maintenance costs and longer motor lifespan translate into significant operational savings.
- Sustainability Reporting: ISO 50001 [149] supports compliance with global frameworks like the CDP (Carbon Disclosure Project) and Science-Based Targets Initiative (SBTi).

4.2.3. Implementation Challenges

- ISO 50001 [149] requires data transparency and continuous monitoring. IE5 motors equipped with digital monitoring and communication protocols (e.g., Modbus and BACnet) ease compliance by enabling real-time energy tracking.

4.3. EN 61800-9-2/EN 50598-2 Energy Efficiency of Power Drive Systems [150]

EN 50598-2, developed by CENELEC, defines standardized methods for assessing the energy efficiency of Power Drive Systems (PDSs), comprising the motor, converter, and their combined operation. Unlike the EN/IEC 60034-30 [148] series, which classifies motor-only efficiency, this standard introduces IES (IE System) classes—IES0, IES1, and IES2—to evaluate system-level performance under variable-speed conditions. Applicable to systems rated 0.12–1000 kW, EN 50598-2 provides a consistent framework for comparing total system losses, supporting ISO 50001 energy management objectives and ensuring compliance with the EU Ecodesign Regulation (EU) 2019/1781 [151]. It promotes a holistic approach to energy optimization and facilitates the adoption of high-efficiency technologies such as IE5 motors.

4.3.1. Why EN 50598–2 Matters for IE5 Motors

- The EN 50598-2 standard, issued by the European Committee for Electrotechnical Standardization (CENELEC), establishes a comprehensive methodology for evaluating the energy efficiency of Power Drive Systems (PDSs), which include the motor, converter, and their integrated operation. Unlike the EN/IEC 60034-30 series, which focuses solely on motor efficiency (IE classes), EN 50598-2 assesses the complete drive system under realistic operating conditions through the introduction of IES (IE System) efficiency classes—IES0, IES1, and IES2—representing progressive levels of system performance.
- The standard applies to variable-speed electrical drive systems within the 0.12 kW to 1000 kW power range and provides standardized methods to determine and compare total system losses. By doing so, it enables manufacturers and end-users to quantify the true energy performance of motor–drive combinations, facilitating the design and selection of high-efficiency systems.
- EN 50598-2 also supports ISO 50001 energy management frameworks and ensures compliance with the EU Ecodesign Regulation (EU) 2019/1781, which mandates minimum efficiency requirements for motors and drives. Overall, this standard contributes to a system-level approach to energy optimization, advancing the integration of high-efficiency technologies such as IE5 motors in sustainable industrial applications.

4.3.2. Benefits for Organizations

- Comprehensive System Evaluation: Assesses the efficiency of the entire motor–drive setup, providing a realistic measure of energy performance.
- Energy and Cost Optimization: Identifies opportunities for higher-efficiency configurations, thus reducing electricity consumption and operating costs.
- Facilitates ISO 50001 Compliance: Offers a standardized approach to track, measure, and verify energy performance within energy management systems.
- Regulatory Alignment: Supports adherence to EU Ecodesign regulations, ensuring drive systems meet required efficiency levels.
- Enables Digital Monitoring: Supports integration with smart monitoring technologies for real-time energy tracking and predictive maintenance.

4.3.3. Implementation Challenges

- EN 50598-2 implementation requires comprehensive system-level efficiency assessment. Motors and drives must be monitored accurately, and integration of IE5 motors with variable-speed drives demands careful design and control. Advanced digital monitoring and communication protocols (e.g., Modbus and BACnet) can facilitate compliance by providing real-time data on total system energy performance.

5. Regional and Global Regulatory Frameworks: Regulatory Landscape and Market Drivers

5.1. European Union Ecodesign Directive (2009/125/EC) [151,152]

- This directive, a critical element of the EU's climate policy, mandates the gradual phase-out of inefficient electric motors.
- Since 2017, motors from 0.75 kW to 375 kW must meet at least IE3 efficiency when operated DOL, or IE2 if used with a VFD.
- Proposals and consultations are underway to enforce IE4 and IE5 levels by 2030 in key industrial sectors, reflecting the EU's ambition for carbon neutrality by 2050.

5.2. US Department of Energy (DOE) Motor Efficiency Regulations

- The DOE enforces the Energy Policy Act (EPAAct) and subsequent updates that set minimum efficiency levels comparable to IE3 and IE4.
- IE5 adoption is encouraged through incentives and rebates, targeting heavy users in manufacturing, water utilities, and agriculture.

5.3. China's GB Standards (GB 18613) [153]

- China has aggressively implemented motor efficiency standards and incentives aligned with IE classifications to combat industrial pollution and reduce electricity consumption.
- China's vast manufacturing base creates significant demand and supply chain shifts toward IE5 motors.

5.4. Other Countries

Japan's METI program, South Korea's KEPCO policies, Australia's Minimum Energy Performance Standards (MEPS), and Brazil's PROCEL initiatives all contribute to a global mosaic pushing motor efficiencies higher.

5.5. Comprehensive Certification Landscape Beyond Efficiency

5.5.1. Safety and Electromagnetic Compatibility

Compliance with IEC 60204 (Electrical equipment of machines), IEC 61800 (Adjustable speed electrical power drive systems), and regional safety regulations ensure motors are safe for human operators and do not interfere with sensitive electronics.

5.5.2. Environmental Compliance and Material Restrictions

- RoHS and REACH compliance are increasingly mandatory for motors sold in the EU and many other regions.
- The transition to rare earth-free SynRM designs in IE5 motors is partially motivated by the environmental and geopolitical risks associated with rare earth mining.

5.5.3. Industry-Specific Certifications

Certain industries require additional certifications, such as

- ATEX and IECEx for explosive atmospheres (oil and gas, and mining).
- FDA and EHEDG compliance for food, beverage, and pharmaceutical industries to ensure hygienic design.

5.6. Strategic Industry Impact and Future Outlook

5.6.1. Accelerated Innovation Cycles

The stringent standards and certifications push motor manufacturers to innovate faster, leading to breakthroughs such as

- Use of wide-bandgap semiconductor-based inverters (SiC and GaN) to reduce drive losses.
- Advanced cooling methods like liquid cooling and heat pipes to improve thermal performance.
- Integration of AI-driven condition monitoring and predictive maintenance.

5.6.2. Economic and Environmental Payoff

- Adopting IE5 motors can reduce energy consumption by up to 20–30% compared to IE3, with payback periods of 2–5 years depending on operational hours and electricity costs. This yields significant CO₂ emissions reductions, supporting corporate net-zero goals.

5.6.3. Supply Chain and Manufacturing Impact

- As IE5 motors become mainstream, supply chains adapt by increasing production capacity for advanced materials and digital components. This also triggers upskilling of technicians for installation, commissioning, and maintenance of sophisticated motor–drive systems.

5.6.4. Global Trade and Harmonization

- Common standards lower technical barriers, enabling manufacturers to export IE5 motors globally with fewer certification hurdles, fostering a more integrated and competitive market.

5.6.5. Future Trends

- Continued push towards digitalization and smart motor systems embedded with IoT sensors for real-time performance optimization.
- Expansion of IE5-class motors into new sectors such as electric vehicles (EVs), robotics, and renewable energy.

- Evolution of standards to include circular economy principles addressing motor recyclability and end-of-life disposal.

Table 8 indicates that the adoption of IE5 (ultra-high-efficiency) motors is shaped by a converging set of technical standards, regulatory instruments, and conformity pathways that increasingly reflect a system-level perspective. At the technical core, IEC 60034-30-2 provides a harmonized efficiency classification framework for modern motor technologies, such as synchronous reluctance and permanent-magnet machines, enabling IE5 performance to be evaluated through standardized definitions and loss accounting principles. In parallel, recent industrial practice has placed greater emphasis on the fact that IE5 motors are frequently deployed in variable-speed, inverter-fed environments, where converter-induced effects, such as waveform distortion and associated additional losses, can influence measured and operational efficiency; consequently, efficiency assessment and selection are progressively framed in terms of motor–drive integration rather than motor nameplate performance alone. Regulatory drivers reinforce this transition: the EU Ecodesign regime and U.S. DOE efficiency requirements establish minimum performance thresholds and compliance routes that steer procurement toward higher-efficiency solutions, while regional schemes such as NEMA premium support market communication and purchasing standardization for high-efficiency products. At the organizational level, ISO 50001 strengthens the implementation rationale by embedding motor upgrades within a structured energy management cycle, supporting systematic monitoring, verification, and lifecycle-based investment decisions. Finally, Table 8 also emphasizes that successful industrial deployment depends on compliance beyond efficiency, including CE marking and UL/CSA safety certification, alongside RoHS/REACH substance requirements, which collectively enable market access, reduce operational risk, and align IE5 adoption with evolving sustainability and supply chain governance expectations.

Table 9 summarizes the main engineering issues that emerge when IE5 (ultra-high-efficiency) motor designs are scaled to high power levels, where practical limitations in heat removal, magnetic loading, and power electronic operation become tightly linked. Beyond roughly 500 kW, the ability to sustain IE5-level efficiency is often constrained by thermal behavior: total losses increase with rating and load, yet the motor does not gain heat transfer capability at the same pace, leading to higher winding and rotor hotspot temperatures. This thermal constraint can force reductions in current density and, in turn, limit continuous torque capability. For this reason, large IE5 machines frequently rely on enhanced cooling solutions, including liquid cooling and improved internal heat paths, combined with rotor design optimization to reduce loss concentrations and improve temperature margins. A second challenge is associated with inverter-fed operation. Large IE5 motors are commonly paired with variable-speed drives, and high-frequency switching introduces additional converter losses and electrical stress at the motor terminals. Steep voltage transitions and harmonic content can increase heating, electromagnetic interference, acoustic noise, and insulation aging, particularly in high-current systems and installations with long motor cables. Mitigation typically involves higher-performance drive technologies, including wide bandgap (SiC and GaN) devices to reduce switching losses, together with dv/dt filters and other output conditioning to moderate the applied waveform. Third, magnetic saturation becomes increasingly difficult to avoid at larger scales. High-power-density objectives can raise local flux densities in the stator and rotor toward saturation, increasing magnetizing current and core loss while degrading overall electromagnetic performance; this is commonly managed through magnetic circuit refinement and the use of low-loss, high-grade electrical steels. Finally, the drive platform itself can become a bottleneck at large scale. High-power IE5 systems often require specialized converter configurations to meet grid and harmonic requirements, which increases cost and reduces off-the-shelf

availability. In practice, active front-end drive topologies and harmonic filtering are widely used to improve power quality and compliance, enabling reliable deployment of large IE5 motor–drive systems in industrial settings.

Table 8. Key industry standards and certifications for IE5 motors [151,152].

Standard/Certification	Scope and Focus	Technical Requirements Related to IE5 Motors	Industrial Impact and Benefits
IEC 60034-30-2 [148]	Efficiency classes for synchronous reluctance and permanent magnet motors	Defines IE5 efficiency thresholds, test methods, and loss limits	Ensures consistent efficiency benchmarking, drives R&D
ISO 50001 [149]	Energy Management Systems (EnMSs)	Framework for energy performance improvement; drives IE5 adoption	Supports sustainable energy use, cost savings, and compliance
EU Ecodesign Directive [152]	Mandatory motor efficiency standards	IE3 mandatory with push towards IE4 and IE5	Accelerates IE5 market penetration, environmental targets
U.S. DOE Motor Efficiency Standards [154]	Energy conservation and efficiency regulations	Efficiency tiers aligned with IE classifications	Incentivizes high-efficiency motors, reduces energy costs
NEMA Premium Efficiency [155]	North American efficiency certification	Similar efficiency targets approaching IE4	Supports regional market acceptance and energy savings
CE Marking [156]	Safety, EMC, and environmental compliance	Compliance with LVD, EMC, and Ecodesign directives	Ensures market access and regulatory conformity
UL/CSA Certification [157]	Electrical and mechanical safety	Safety standards compliance for North America	Critical for operational safety and insurance requirements
RoHS/REACH [158]	Environmental and chemical safety	Limits hazardous substances and chemicals	Supports sustainable manufacturing and regulatory compliance

Table 9. Technical challenges of scaling IE5 motors [159].

Challenge	Description	Impact	Typical Mitigation
High-Power Scaling	Efficiency drops above 500 kW due to thermal and magnetic limitations	Reduced torque density, overheating	Advanced cooling (liquid), optimized rotor design
High-Frequency Switching	Increased heat and EMI at large scales	Inverter loss, noise, insulation breakdown	SiC-based drives, dv/dt filters
Magnetic Saturation	Difficulties maintaining high flux density in large motors	Core losses, performance degradation	High-grade lamination steel
Inverter Complexity	Custom drives required for large motors	Higher cost, low availability	Active front-end VFDs, harmonic filters

Table 10 identifies the principal cost-related barriers that constrain the diffusion of IE5 (ultra-high-efficiency) motors, emphasizing that economic feasibility is determined not only by motor price but also by system integration and operational capabilities. A primary limitation is the higher acquisition cost of IE5 motors, which is often reported to be approximately 1.5 to 2 times that of IE3 equivalents due to the use of higher-grade active materials, more complex rotor and stator designs, and tighter manufacturing tolerances required to achieve ultra-low loss levels. This capital premium can deter investment when procurement decisions are driven by upfront expenditure rather than lifecycle energy savings. Accordingly, mitigation strategies frequently involve policy and financial mechanisms,

such as targeted subsidies, tax incentives, or leasing and financing models that distribute initial costs and improve payback attractiveness. In addition, IE5 motors are commonly implemented within variable-speed, digitally controlled architectures, making drive system requirements a significant component of total installed cost. The need for VFD hardware, control integration, and associated filtering or protection increases project expenditure and complexity, particularly in retrofit scenarios; bundled motor–drive solutions are therefore increasingly adopted to reduce engineering effort, improve compatibility, and lower commissioning risk. Finally, successful deployment often depends on specialist expertise for commissioning, parameterization, and tuning, as well as ongoing monitoring to maintain expected efficiency gains. The resulting labor costs and reliance on external consultants can represent a further barrier, which is commonly addressed through vendor commissioning support, structured training, and remote or cloud-enabled diagnostic services that reduce on-site burden and support sustained operational performance.

Table 10. Cost barriers [160].

Cost Factor	Explanation	Effect	Mitigation Strategy
Initial Motor Price	IE5 motors cost 1.5–2× more than IE3 motors	Limits upfront investment	Government subsidies, leasing models
Drive System Requirements	VFDs and digital control systems needed for operation	Increased setup cost	Bundled motor + drive packages
Training and Expertise	Skilled personnel required for setup and tuning	Labor cost and dependency on external consultants	Vendor support, cloud-based diagnostics

Table 11 summarizes supply chain constraints that can hinder the scaling of IE5 motor–drive technologies by creating reliance on a limited set of critical materials and enabling components. A key dependency involves rare earth permanent magnets, particularly NdFeB, which are widely used in permanent magnet synchronous machines to achieve high torque density and high efficiency. However, supply concentration and strong price volatility introduce procurement risk and cost uncertainty for IE5 platforms. To reduce exposure, manufacturers and end-users increasingly consider alternatives such as synchronous reluctance designs that eliminate rare earth magnets, as well as ferrite-based magnet solutions where performance targets allow. A second constraint concerns high-grade electrical steel used for stator and rotor laminations. IE5 efficiency requires low iron loss and stable magnetic properties yet demand growth in sectors such as electric vehicles and renewable energy infrastructure can tighten availability and lengthen lead times. Mitigation approaches therefore include regional sourcing, qualification of equivalent steel grades, and dual-vendor procurement to improve resilience. Finally, high-efficiency inverter operation increasingly depends on wide bandgap devices such as SiC- and GaN-based power semiconductors, which enable lower switching losses and improved high-frequency performance, but remain costly and constrained by limited manufacturing capacity. In response, hybrid converter architectures that combine IGBT and wide bandgap devices are commonly adopted to balance efficiency improvements with component availability and overall system cost.

Table 12 shows that integrating IE5 motor technologies into existing industrial plants is frequently constrained by compatibility issues with legacy starting, protection, automation, and thermal infrastructure, largely because IE5 implementations are commonly associated with inverter supply operation and enhanced digital supervision rather than conventional direct on-line practice. Direct on-line starters, for example, are generally unsuitable for inverter-dependent motor configurations and applications requiring controlled voltage and

frequency, so retrofit projects typically require replacement with variable-frequency drives together with appropriate protection, interfacing, and installation measures. Protection coordination is also affected, since traditional relay schemes may not provide adequate sensitivity or selectivity under inverter-fed conditions and may not align with the electrical signatures of high-efficiency machines; accordingly, digital motor protection relays with drive-compatible measurement and configurable logic are often adopted. In addition, plant automation can present an integration barrier: older SCADA and PLC systems may rely on serial communication standards, whereas modern drives and diagnostic functions increasingly use industrial Ethernet protocols, necessitating controller upgrades and the use of protocol conversion gateways to ensure reliable data exchange. Finally, thermal integration must be addressed because existing ventilation arrangements may not be sufficient for enclosed or high-power density IE5 installations, which can require enhanced forced-air solutions or liquid cooling infrastructure to maintain temperature margins, avoid derating, and sustain expected performance in continuous operation.

Table 11. Supply chain constraints [160].

Material/Component	Dependency	Risk	Alternatives/Solutions
Rare earth magnets (NdFeB)	Used in PMSMs for high torque density	Geopolitical risk, price volatility	Synchronous reluctance motors, ferrite magnets
Electrical steel	Required for core laminations with low iron loss	Global supply tight due to EV & renewable sectors	Regional sourcing, dual-vendor strategies
SiC-based power semiconductors	High-frequency, efficient inverter operation	Expensive and limited global capacity	Hybrid drive designs using IGBT/SiC combinations

Table 12. Compatibility with existing infrastructure [161].

Legacy Element	Compatibility Issue	Required Upgrade
DOL Starters	Incompatible with inverter-only motors	Replace with VFD + protection circuitry
Protection Relays	Misalignment with low-current IE5 signatures	Install digital motor protection relays
SCADA/PLC Communication	Outdated protocols (e.g., RS485 vs. EtherCAT/Modbus TCP)	Upgrade control hardware and install protocol converters
Cooling Infrastructure	Existing ventilation insufficient for enclosed IE5 motors	Install forced air or liquid cooling systems

5.7. System-Level Synthesis and Implications

Standardized efficiency metrics provide a limited basis for technology selection in contemporary industrial applications, as operational performance is determined by system-level interactions among motor topology, power electronic drives, control strategies, duty cycles, and thermal boundary conditions. Consequently, high-efficiency motor systems should be considered within an integrated motor–drive–control design framework, with attention to efficiency retention under variable-speed and partial-load operation, as well as reliability and maintainability. From a technology standpoint, permanent magnet synchronous motors (PMSMs) typically achieve high efficiency and power density, particularly in variable-speed applications; however, these characteristics are associated with trade-offs related to rare earth material use, thermal sensitivity, and lifecycle considerations. Synchronous reluctance motors (SynRMs) offer a magnet-free pathway toward IE5-class efficiency and improved material sustainability, but their performance is often dependent

on inverter capability and advanced control to ensure stable operation across a wide operating range. Squirrel cage induction motors (SCIMs) remain widely applied in retrofit and cost-sensitive contexts due to robustness and established industrial practice, although inherent loss mechanisms limit their suitability for ultra-premium efficiency targets, especially under partial-load conditions. Thermal considerations further influence these tradeoffs. While reduced losses lower average heat generation, increased power density can introduce localized thermal stresses that affect insulation aging and long-term reliability. Within Industry 5.0 contexts, digital sensing, diagnostics, and adaptive control complement hardware efficiency improvements by supporting condition-aware operation and predictive maintenance. These observations indicate that motor selection is application-dependent and should account jointly for efficiency retention, controllability, thermal robustness, material sustainability, and readiness for digital integration.

Motor current characteristics vary substantially across motor types and operating regimes, with direct implications for copper losses, inverter thermal loading, and current rating and apparent power requirements. In PMSM and SynRM drive systems employing field-oriented control, the stator current is commonly resolved into torque-producing and flux-producing components. As torque demand increases, the torque-producing component rises accordingly, whereas operation in the field weakening region introduces a negative flux-producing components at higher speeds. This operating transition can increase the RMS current and, consequently, the required inverter current capability and thermal margin. In squirrel cage induction motor–drive systems, rotor slip and the presence of a magnetizing current component led to a comparatively larger reactive current contribution, particularly under partial-load conditions. This reduces the power factor and increases the RMS current for a given mechanical output, thereby elevating copper losses and inverter conduction losses. These distinctions indicate that system efficiency and thermal behavior cannot be interpreted solely from rated motor efficiency; instead, a power drive system perspective that jointly considers the motor, inverter, control strategy, and duty cycle is necessary for meaningful inverter sizing and performance assessment. Figure 24 presents a schematic comparison of normalized RMS stator current as a function of normalized speed for SCIM, SynRM, and PMSM drive systems, covering the constant torque region, a representative partial-load operating regime, and the constant power region typically associated with field weakening. The SCIM exhibits comparatively higher current demand at low speed and under partial load, primarily due to magnetizing current requirements and slip-related effects, which increased RMS current for a given torque. The SynRM displays an intermediate trend, reflecting reduced magnetizing demand relative to the SCIM while remaining dependent on inverter excitation and control settings to achieve the desired torque production. The PMSM generally maintains lower RMS current in the constant torque region, whereas current demand may increase at elevated speeds as field weakening introduces an additional flux producing current component, thereby increasing inverter current requirements. The schematic profiles are intended to highlight the qualitative differences relevant to loss distribution, thermal loading, and inverter sizing in variable-speed operation.

5.8. Motor and Drive Control Contributions to System Efficiency

For engineering design and deployment, it is important to distinguish efficiency improvements that are intrinsic to the motor from those primarily attributable to the drive and control layer, as these contributions affect technology selection, retrofit feasibility, and the efficiency achievable in field operation.

Motor intrinsic contributions arise from electromechanical design choices and their associated thermal implementation. Key mechanisms include reductions in (i) stator cop-

per losses through optimized winding configurations, conductor utilization, and reduced resistance; (ii) core losses through improved magnetic circuit design and the use of low-loss electrical steels; (iii) rotor related losses through topology selection, particularly the reduced rotor loss mechanisms in synchronous machines relative to induction machines; and (iv) stray load and mechanical losses through improved manufacturing quality, bearing selection, and mechanical design. Although thermal management and insulation design do not directly increase electromagnetic efficiency, they influence system performance indirectly by reducing operating temperature, stabilizing resistance and magnetic properties, and extending component lifetime, thereby supporting long term efficiency retention.

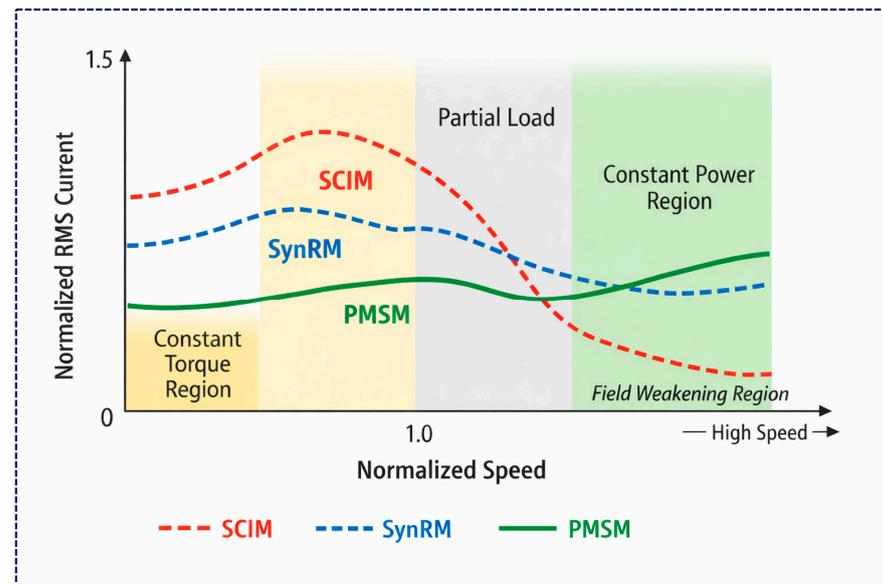


Figure 24. Normalized RMS current versus speed for SCIMs, SynRMs, and PMSMs.

By contrast, drive and control contributions are largely manifested under realistic duty cycles, especially during variable-speed operations. The drive introduces conduction and switching losses that depend on the semiconductor technology, switching frequency, modulation method, and operating point. Control strategies affect how closely the motor operates to its optimal efficiency region by shaping current excitation, flux level, and torque production. Under variable-speed conditions, realized efficiency is sensitive to factors such as field-oriented control accuracy, field-weakening behavior, torque ripple mitigation, sensor quality, and parameter identification. Within Industry 5.0 environments, supervisory control and data-driven optimization, such as adaptive setpoint scheduling and duty cycle awareness control, can further enhance energy performance by avoiding inefficient operating regions and enabling condition-aware operation.

From a system perspective, the appropriate performance metric is therefore the power drive system efficiency, which reflects the combined influence of motor losses and drive and control losses. Consequently, improvements at the motor design level, such as reduced rotor losses in synchronous reluctance and permanent magnet synchronous machines, may not yield proportional system-level gains if inverter losses and control constraints are not addressed. Conversely, advanced power electronics and control strategies can preserve efficiency under field conditions, but they cannot fully compensate for inherently high motor loss mechanisms. Explicit separation of these contributions improves the interpretability of reported performance gains and supports more informed engineering design and technology selection decisions.

5.9. Industrial Practice Versus Open Research Challenges

Current industrial practice primarily relies on IE4 and IE5 electric motors integrated within power drive systems (PDSs), consistent with IEC efficiency classification frameworks. These systems are typically realized using well-established machine topologies—namely, squirrel cage induction motors, synchronous reluctance motors, and permanent-magnet synchronous motors—combined with mature variable-speed drives (VSDs) employing field-oriented control. In practical deployments, such systems are commonly complemented by standardized condition monitoring functionalities, including temperature, vibration, and electrical signature measurements, together with rule-based diagnostics or simplified predictive maintenance schemes. Technology selection and implementation are largely guided by regulatory compliance, total cost of ownership, compatibility with existing automation and communication infrastructures, and the availability of validated manufacturer data for duty cycle-based sizing and performance evaluation. In parallel, ongoing research activities address limitations that arise under dynamic operating conditions, where variable load profiles and frequent transients can degrade PDS efficiency and accelerate thermal cycling. Current research directions include the development of higher-fidelity digital twins for PDS applications, improved diagnostic and prognostic methods that remain robust under domain shift, and mitigation of inverter-induced motor losses through coordinated motor–drive co-design. Additional efforts focus on sustainability-oriented challenges, such as reducing material criticality, improving recyclability, and establishing consistent lifecycle assessment methodologies. Distinguishing these research directions from established industrial practice clarifies which solutions are presently deployable within IEC-compliant frameworks and which require further validation, benchmarking, and standardization before broader adoption.

Figure 25 presents established industrial deployment patterns alongside key research directions in high-efficiency motor–drive systems. Current industrial practice is characterized by the use of IE4 and IE5 motors integrated with variable-speed drives and mature control strategies, supported by conservative loss management approaches and standardized condition monitoring with rule-based or simplified predictive maintenance. In parallel, ongoing research addresses system-level co-optimization of motor, inverter, and control; conceptual performance developments beyond current efficiency classes; emerging and hybrid machine concepts; adaptive and learning-enabled control strategies; mitigation of inverter-induced motor loss mechanisms; diagnostics and prognostics that remain reliable under changing operating conditions; and the development of higher-fidelity digital twin models that capture multi-physics behavior and degradation processes. This presentation clarifies which capabilities are currently deployable within IEC-oriented industrial frameworks and which remain research topics requiring further validation, benchmarking, and standardization.

5.10. Design and Implementation Tools

The practical design, verification, and deployment of motor–drive systems commonly rely on integrated tool chains that span electromagnetic design, thermal assessment, control development, and system-level evaluation. Consistent with a power drive system perspective, these tools enable the quantification of efficiency retention under duty cycle operation, assessment of inverter current and thermal margins, and evaluation of harmonic-related loss mechanisms that are not fully represented by rated efficiency values.

5.10.1. Electromagnetic Modeling and Loss Evaluation

Electromagnetic finite element analysis is widely applied to examine air-gap field distributions, torque production, magnetic saturation, and machine loss components,

including copper losses, core losses, and rotor-related losses. These analyses support topology screening and comparative evaluation of SCIM, SynRM, and PMSM architectures, as well as assessment of torque ripple and sensitivity to inverter-induced harmonic excitation. Representative commercial environments include ANSYS Maxwell, JMAG, Altair Flux, and electromagnetic modules within dedicated motor design suites, while research-oriented workflows may employ customized solvers coupled with calibrated loss models. Figure 26 illustrates the principal categories of design and implementation tools used for high-efficiency motor power drive systems, including electromagnetic and thermal modeling, drive and control simulation, real-time validation, and sizing and selection workflows, highlighting their complementary roles in system-level performance assessment and deployment.

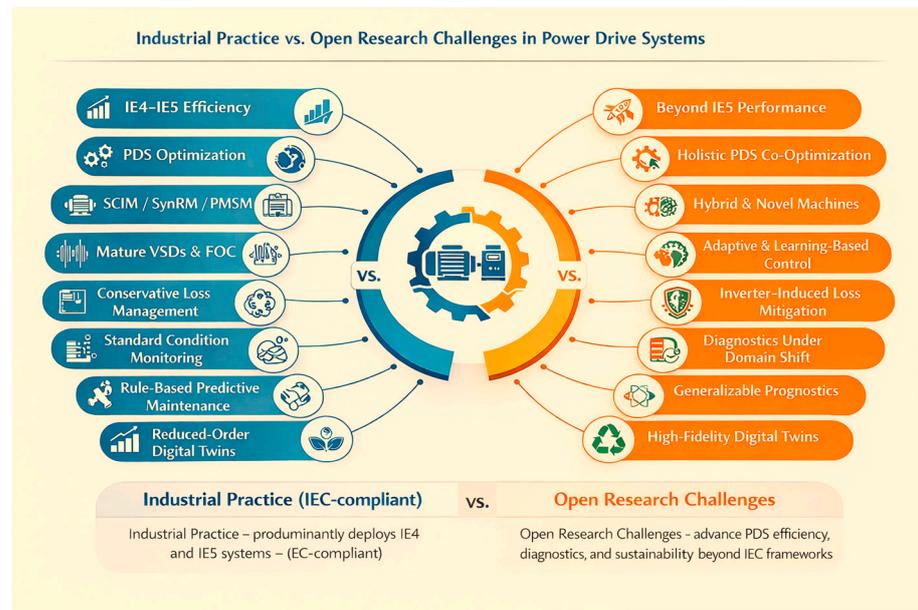


Figure 25. Comparison of IEC-compliant industrial practice and open research challenges for power drive systems (PDSs) incorporating high-efficiency electric motors.

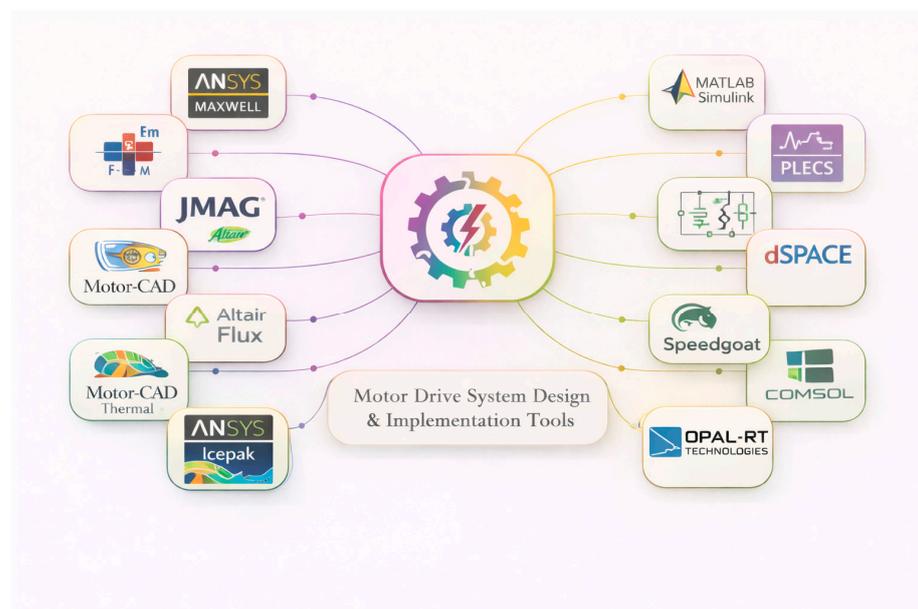


Figure 26. Overview of design and implementation toolchains for high-efficiency motor power drive systems.

5.10.2. Thermal Analysis and Cooling Assessment

Thermal network approaches and coupled electromagnetic–thermal simulations are used to estimate hotspot temperatures, thermal resistance paths, and cooling effectiveness under steady-state and transient loading. Such analyses are essential for evaluating insulation thermal margins, temperature cycling, and lifetime-related constraints. Commonly used platforms include Motor-CAD Thermal, ANSYS Icepak, and COMSOL Multiphysics for cases requiring detailed conjugate heat transfer modeling. These tools facilitate quantitative comparison of cooling strategies, including forced-air cooling, liquid jacket cooling, direct oil cooling, and heat-spreading solutions such as heat pipes and vapor chambers.

5.10.3. Drive, Control, and Power Electronics Simulation

System-level simulation environments are employed to develop control strategies, estimate inverter conduction and switching losses, and analyze interactions among modulation schemes, harmonic spectra, and motor loss behavior. Tools such as MATLAB Simulink, PLECS, and PSIM are frequently used for field-oriented control implementation, field-weakening analysis, and loss estimation under variable-speed operation. Co-simulation workflows, in which machine models are coupled with inverter and control models, support evaluation of power drive system efficiency and thermal loading under representative duty cycles.

5.10.4. Digital Implementation and Real-Time Verification

Controller development is often supported by rapid prototyping and real-time testing platforms that enable the validation of control robustness, sensor signal quality, and fault-handling strategies prior to full-scale prototype testing. Representative platforms include dSPACE, OPAL-RT, and Speedgoat. These workflows are increasingly relevant in Industry 5.0 settings, where monitoring, diagnostics, and adaptive control functions must remain reliable under operational variability.

5.10.5. Selection, Sizing, and Duty Cycle Assessment

In deployment and retrofit contexts, manufacturer sizing tools and selection platforms are commonly used to match motor and variable-speed drive ratings to load characteristics, operating cycles, and thermal constraints. These tools are typically complemented by duty cycle analysis based on plant data, such as speed–torque time series, enabling the estimation of RMS current demand, inverter headroom, thermal margins, and efficiency retention under partial-load operation. The coordinated use of electromagnetic, thermal, and control-oriented toolchains enables the translation of high-efficiency motor concepts into deployable power drive systems, supports performance assessment under realistic duty cycles, and clarifies constraints related to inverter sizing, harmonic-loss sensitivity, and cooling requirements.

5.11. *Industrial Case Studies: Deployment of High-Efficiency Motor Systems in Industry 5.0 Contexts*

To reinforce the technical synthesis developed in the preceding sections and to demonstrate the practical relevance of high-efficiency motor technologies within Industry 5.0 manufacturing settings, this section presents two illustrative industrial case studies. The cases are selected to represent common deployment pathways and to highlight the interaction between (i) high-efficiency motor–drive technologies, (ii) data-enabled monitoring and optimization, and (iii) human-centric operational support. In order to maintain general applicability and avoid reliance on confidential plant data, the discussion emphasizes system architectures, implementation processes, observable outcomes, and deployment challenges, rather than proprietary numerical results.

5.11.1. Case Study I: IE5 Permanent Magnet Motor Retrofits Supported by AI-Enabled Energy Management in Automotive Manufacturing

Operational Setting and Rationale

Automotive manufacturing plants typically operate extensive motor-driven infrastructures, including conveyors, robotic handling systems, and auxiliary utilities, where variable-speed operation is prevalent. In a representative implementation context, a performance audit indicated that legacy IE3 induction motor installations exhibited efficiency degradation under partial-load and intermittent duty cycles, motivating an upgrade toward IE5 permanent magnet synchronous motor (PMSM) solutions combined with plant-level digital energy management.

Technical Solution and Integration Approach

The retrofit strategy comprised the replacement of selected induction motors with IE5 PMSMs integrated with high-efficiency variable-frequency drives. The motor–drive assemblies were equipped with electrical and thermal sensing capabilities and connected through industrial communication protocols to a centralized analytics layer. A supervisory AI-enabled energy management platform was used to aggregate operational data, estimate subsystem energy performance under varying production states, and identify deviations from expected behavior. To support maintenance and operational decision making, digital twin representations of critical motor–drive assets were employed for state estimation (e.g., efficiency trends and thermal behavior), while machine learning models were applied to detect anomalies in current and temperature signatures consistent with early-stage degradation. Operator-facing dashboards were implemented to deliver interpretable indicators and maintenance recommendations, ensuring alignment with Industry 5.0 objectives related to transparency and human-centric oversight.

Observed Outcomes and Practical Challenges

The implementation yielded improved energy performance in targeted motor-driven subsystems, particularly under variable-speed regimes, and enhanced reliability through earlier identification of degradation phenomena. Practical challenges included increased capital expenditure, thermal operating constraints associated with PMSM designs, and integration complexity with legacy automation infrastructure. Mitigation measures included staged deployment, strengthened thermal monitoring and protection logic, and modular interface solutions to maintain interoperability with existing control architectures.

5.11.2. Case Study II: IE5 Synchronous Reluctance Motor Deployment with Predictive Maintenance in a Continuous-Process Facility

Operational Setting and Rationale

In continuous-process industries (e.g., pumping and compression systems), reliability and maintainability are primary requirements due to the high cost of unplanned downtime. In a representative facility context, sustainability considerations, particularly concerns regarding rare earth material dependency and end-of-life management, supported the selection of IE5 synchronous reluctance motors (SynRMs) as a magnet-free alternative to PMSM solutions.

Technical Solution and Integration Approach

The deployed SynRM systems were coupled with optimized drive control strategies to sustain efficiency across a wide operating envelope. Condition monitoring infrastructure was implemented using vibration sensing and electrical signature monitoring, with data transmitted to a centralized analytics platform. Machine learning-based diagnostic models were applied to identify early indicators of mechanical imbalance, insulation degradation, and cooling system performance decline. Human-centric integration was maintained through simplified alert mechanisms and trend visualization interfaces that supported maintenance planning by on-site personnel. This ensured that diagnostic outputs remained

actionable and interpretable, consistent with Industry 5.0 principles emphasizing human oversight and resilience.

Observed Outcomes and Practical Challenges

SynRM deployment supported high-efficiency operation while avoiding permanent-magnet materials, strengthening alignment with sustainability objectives. Predictive maintenance improved operational continuity by enabling earlier intervention. Nevertheless, stable performance under varying load conditions required careful controller tuning and iterative refinement of model parameters based on operational feedback, highlighting the importance of joint optimization of hardware selection and control strategy.

6. Future Trends and Discussions

As industrial sectors continue to prioritize energy efficiency, sustainability, and automation, the landscape of electric motor technology is rapidly evolving beyond the current IE5 benchmark. Several transformational trends are shaping the next generation of motor systems, emphasizing not only higher energy performance but also intelligent operation and seamless integration with future-ready manufacturing ecosystems.

6.1. Emergence of Ultra-Efficient Motor Technologies (Beyond IE5)

Moving from IE5 to IE6 and beyond requires addressing loss mechanisms that have already been reduced to very low levels. At this stage, incremental improvements demand breakthroughs in materials science, electromagnetic topology, and thermal management. Current research focuses on reducing core losses through amorphous or nanocrystalline laminations, lowering copper losses with high-conductivity alloys, and improving cooling efficiency to maintain low winding temperatures without increasing auxiliary energy consumption [162–165].

- One promising development is the axial-flux motor. Unlike traditional radial-flux designs, axial-flux machines position the magnetic flux path parallel to the shaft, resulting in shorter magnetic paths and reduced core material usage. This configuration inherently produces higher torque density, which is advantageous in weight- and space-constrained applications, such as electric aircraft propulsion, in-wheel EV drives, and high-precision robotics. Additionally, the larger surface area between rotor and stator facilitates more effective liquid or air cooling, allowing for higher continuous power output without thermal degradation.
- Halbach array magnet arrangements offer another avenue for efficiency gains, particularly in permanent magnet synchronous machines (PMSMs). By orienting individual magnet segments in a specific pattern, Halbach arrays concentrate magnetic flux on the working side of the motor while canceling it on the opposite side. This reduces leakage flux, improves torque production, and minimizes cogging torque, a source of vibration and acoustic noise that can impair precision manufacturing or medical device operation.
- Research into multi-phase motor architectures (e.g., six-phase, nine-phase, or even twelve-phase machines) is expanding due to their ability to offer redundancy and improved fault tolerance. If one phase fails, the motor can continue operating at reduced performance, making them attractive for aerospace, offshore wind, and critical process industries. Additionally, multi-phase systems inherently produce lower current ripple and torque pulsation, improving efficiency in variable-load conditions.
- At the experimental frontier, high-temperature superconducting (HTS) motors use cryogenically cooled superconducting windings that eliminate electrical resistance in the stator and rotor windings. These machines can achieve extremely high power densities and efficiencies, particularly in large-scale applications above 1 MW. However,

the capital and operational costs of cryogenic systems remain a barrier to commercialization, and research is ongoing to develop more cost-effective cooling solutions, such as compact closed-loop cryocoolers.

- Direct-drive torque motors, often based on permanent magnet or hybrid synchronous topologies, are gaining momentum in precision automation systems. By producing high torque at low rotational speeds, they eliminate the need for gearboxes, thereby reducing mechanical losses, improving motion control accuracy, and lowering maintenance requirements. This is particularly valuable in semiconductor fabrication, CNC machining, and robotic arm actuation.

Collectively, these developments suggest a clear trajectory toward motors that are smaller, lighter, quieter, more efficient, and more adaptable, with optimized designs tailored to specific industrial and transportation applications.

6.2. Integration of Artificial Intelligence and Machine Learning

Electric motors have traditionally been operated as “dumb” devices, relying on fixed-control strategies and periodic human inspection. The integration of AI and ML algorithms into motor control systems is transforming them into self-monitoring and self-optimizing assets. This transformation is facilitated by the increasing computational capacity of microcontrollers, the proliferation of low-cost sensors, and advancements in edge analytics [166–169].

- Predictive maintenance is one of the most impactful AI-enabled capabilities. By continuously analyzing data streams from embedded sensors—such as vibration accelerometers, current and voltage transducers, thermal probes, and acoustic microphones—ML models can identify anomalies indicative of early-stage faults. This allows for maintenance to be scheduled just before failure, minimizing unplanned downtime while avoiding the cost of overly frequent servicing. In high-throughput industries, even a few hours of avoided downtime can translate into substantial financial savings.
- AI also enables adaptive performance optimization. Instead of running motors at a fixed speed-torque profile, AI algorithms can dynamically adjust operational parameters in real time based on the load, process requirements, and energy pricing signals from the grid. For example, in a pumping application, AI can reduce speed during periods of low demand, thereby minimizing energy consumption without compromising output quality [170].
- With the rise of the Industrial IoT (IIoT), motors can be equipped with embedded processors capable of edge computing, allowing them to perform data analysis locally without constant cloud connectivity. This is crucial for latency-sensitive applications such as robotic welding, high-speed packaging, and precision assembly, where response times must be in the order of milliseconds [171].

Furthermore, digital twin technology—where a virtual model of the motor is continuously updated with live operational data—enables advanced simulation of performance under hypothetical scenarios. This can guide preventive actions, optimize energy usage, and validate control strategies before they are applied in the physical system.

6.3. Development of Integrated Motor–Drive Systems

The traditional separation of motors and drives introduces inefficiencies, such as electromagnetic interference (EMI) from long power cables, mismatched component sizing, and added installation complexity. The integrated motor–drive (IMD) approach consolidates the motor, inverter, control electronics, and sometimes sensors into a single enclosure, pre-calibrated for optimal performance [172].

- Efficiency improvements arise from eliminating cable-related transmission losses and ensuring that the motor and drive are matched for peak efficiency across the intended load profile. This is particularly advantageous for variable-speed applications where motors spend much of their operating life at partial load.
- From a mechanical and spatial standpoint, IMDs offer compact designs that reduce the need for large, centralized motor control cabinets. This makes them well-suited for decentralized manufacturing environments such as conveyor systems, automated guided vehicles (AGVs), and modular production cells. The reduction in cabling also improves system reliability by eliminating potential points of failure.
- Modern IMDs integrate fieldbus communication protocols (e.g., PROFINET, EtherCAT, and Modbus TCP) and often support diagnostics over OPC UA for seamless inclusion in smart factory ecosystems. They also facilitate plug-and-play installation, reducing commissioning times significantly.
- Commercial offerings such as Siemens SIMOTICS IQ, SEW-Eurodrive MOVIMOT, and ABB MotiFlex e180 illustrate this convergence of high efficiency and digital intelligence. These systems combine embedded condition monitoring, predictive diagnostics, and field-level control capabilities, enabling autonomous decision making at the equipment level without constant PLC intervention.

6.4. Strategic Role in Industry 5.0 and Human-Centric Automation

Industry 5.0 reframes the automation narrative by prioritizing human-machine collaboration, sustainability, and resilience over pure productivity. High-efficiency motor technologies align strongly with these objectives, as they can reduce environmental impact, enhance workplace safety, and enable flexible, adaptive production processes [173–175].

- From an ergonomics perspective, high-efficiency motors, particularly PMSMs and SynRMs, generate less waste heat and lower acoustic noise than their induction motor counterparts. In collaborative work environments, such as cobot-assisted assembly lines, this improves operator comfort and reduces the need for extensive cooling or noise suppression measures.
- On the sustainability front, these motors contribute to decarbonization goals by reducing energy consumption over their operational lifetime, thereby lowering associated greenhouse gas emissions. Additionally, motor manufacturers are increasingly designing products for remanufacturing and recycling, using modular construction and materials that can be recovered and reused at end-of-life. These practices align with EU Green Deal and ESG compliance frameworks, which are becoming important factors in procurement decisions.
- From a digital integration standpoint, high-efficiency motors equipped with intelligent drives can interact directly with digital twin platforms, energy management systems, and autonomous production scheduling tools. This allows production systems to self-adjust based on demand variability, equipment health, or external factors such as fluctuating renewable energy availability.

Efficiency levels beyond IE5 are addressed in this review as forward-looking performance trajectories rather than as near-term, formally defined efficiency classes. Given that existing regulatory and standardization frameworks primarily specify efficiency classes up to IE5, higher-efficiency targets should be interpreted as indicative development directions rather than imminent standardized categories. Attaining post-IE5 performance is expected to require coordinated progress in several interdependent areas, including improved loss evaluation under converter-excited operating conditions, advances in materials and manufacturing, enhanced thermal management and cooling to accommodate reduced thermal margins, and power electronics and control strategies that reduce converter losses while

limiting motor-side harmonic loading. The practical relevance of such targets also depends on the availability of robust and reproducible test procedures that enable consistent comparison across machine types, converter configurations, and operating profiles, including duty cycle-based assessment where appropriate. Beyond efficiency, next-generation motor systems are increasingly assessed in terms of dynamic capability, particularly in digitally integrated and reconfigurable production settings. Advanced IE5 and prospective post-IE5 motor–drive solutions can exhibit high torque-to-inertia ratios, enabling rapid acceleration and deceleration while maintaining accurate speed and position control. These characteristics support manufacturing contexts that require frequent setpoint changes, short cycle times, and agile changeovers, including mass customization scenarios where production systems must transition efficiently between product variants. In this sense, high-efficiency motors contribute not only to reduced energy consumption but also to the actuation performance and operational responsiveness required for resilient, human-centric Industry 5.0-oriented industrial systems.

7. Conclusions

High-efficiency electric motors are increasingly regarded as integral elements of Industry 5.0-oriented industrial systems, where energy conversion, digital integration, and lifecycle sustainability are jointly addressed. This review shows that the principal contribution of IE4–IE5 motor technologies extends beyond improvements in rated efficiency, encompassing sustained efficiency retention, operational robustness, and carbon-relevant performance when implemented within an integrated power drive system. The analyzed literature demonstrates that operational efficiency is governed by the combined effects of motor topology, power converter characteristics, control strategy, duty cycle variability, and thermal conditions. Consequently, design and technology selection benefit from a power drive system perspective that distinguishes motor-intrinsic loss reduction from efficiency improvements arising from power electronics and control. Within this context, duty cycle-aware assessment, mitigation of inverter-induced loss mechanisms under non-sinusoidal excitation, and appropriate thermal management emerge as key determinants of whether expected efficiency levels are maintained in practical operation. Within Industry 5.0 frameworks, high-efficiency motor systems also constitute essential cyber-physical components. The integration of sensing, connectivity, and data analytics enables condition monitoring and maintenance planning, while human-centered interfaces contribute to transparency, safety, and operational reliability. Such functionalities support efficiency retention and system robustness under variable operating conditions, thereby facilitating the translation of component-level efficiency gains into system-level sustainability outcomes. Several challenges continue to affect large-scale deployment, including compatibility with existing infrastructure, alignment of digital control architectures, management of converter-related harmonic losses, and sustainability considerations related to material usage and end-of-life treatment. Addressing these challenges requires coordinated development across electromagnetic design, thermal engineering, power electronics, and information-based control, supported by standardized measurement procedures and system-level benchmarking. Efficiency classes beyond IE5 are therefore best interpreted as long-term research directions rather than immediate standardization targets. Progress toward post-IE5 motor–drive systems will depend on advances in converter-excited loss characterization, materials and manufacturing processes, thermal management techniques, and integrated motor–drive co-design, together with validation methodologies that enable consistent comparison across different machine and converter configurations. This review therefore supports a transition aligned with Industry 5.0 principles, shifting emphasis from the maximization of rated motor efficiency to the optimization of power drive system performance over the operational

lifecycle, where efficiency, reliability, and sustainability are achieved through integrated hardware, control, and data-driven operation.

Future Directions

To consolidate and extend the role of high-efficiency motors in sustainable industry, future research and policy efforts should focus on

- Advancement of next-generation efficiency classes (IE6–IE9): Exploration of superconducting technologies, wide bandgap semiconductor integration, and novel electromagnetic topologies to approach near-lossless energy conversion.
- AI- and data-driven motor ecosystems: Development of advanced machine learning models for predictive maintenance, adaptive operational control, and lifecycle optimization, enhancing both efficiency and reliability.
- System-level interoperability: Establishment of standardized communication protocols and modular control architectures to ensure seamless integration with smart grids, renewable energy systems, and Industry 5.0 infrastructures.
- Circular economy integration: Implementation of sustainable manufacturing, reuse, remanufacturing, and recycling practices for motor systems, aligned with forthcoming EU directives such as the Ecodesign for Sustainable Products Regulation (ESPR).
- Policy and industrial alignment: Large-scale industrial demonstrations and techno-economic analyses that link technological advances with measurable environmental and economic outcomes, providing robust evidence for regulatory evolution and industry-wide adoption.

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