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Technology scan of electric motors applications

Emerging technologies

PP Murmu, H Fielder, M McCurdy

GNS Science Consultancy Report 2024/91

PN: COMN0144

BIBLIOGRAPHIC REFERENCE

Murmu PP, Fiedler H, McCurdy M. 2024. Technology scan of electric motors applications – emerging technologies. Lower Hutt (NZ): GNS Science. 55 p. Consultancy Report 2024/91.

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EXECUTIVE SUMMARY

The goal of this report is to inform readers of systems based on electric motors and power electronics, enabling them to consider a wider range of options for meeting their motive power needs. This report is the result of an international technology scan that surveyed the technology available for electric motors in industrial and motor traction applications. Emerging technologies for electric motor applications have been identified that could contribute toward New Zealand’s energy-efficiency goals.

Electric motor drive systems, which comprise power inverters, electric motors, mechanical components and load, require a synergistic approach to improve energy efficiency. Adoption of International Electrotechnical Commission (IEC)-approved efficient electric motors is a major factor for improving the energy efficiency of motor systems. New Zealand currently uses AS/NZS 1359.5 (AS/NZS 2004) since 2002. This efficiency level is below IE2 class motors, whereas the best available motors are IE5 (ultra-premium efficiency). The energy efficiency of other motor system components benefit from emerging technologies and innovation for maximum energy saving in variable conditions. The innovation in power converters is driven by wide band-gap and ultra-wide band-gap semi-conductors, which enable high switching frequency and low switching losses. Electric motor performance is constantly improving due to new geometry design (axial and transverse flux motors) and use of soft magnetic composite (SMC) materials. The SMC materials provide alternatives for designing magnets with non-rare earth elements, thus addressing critical mineral supply chain risks. Integrated energy-management systems have been identified as an important approach to optimise the system-level design for maximum energy saving regarding motor-driven systems.

Based on our case scenario analyses, synchronous reluctance motors are found to be the most suitable for identified applications due to their relatively simple design and high efficiency as compared to brushless DC (direct current) motors, induction motors and permanent magnet synchronous motors. Permanent magnet-based synchronous reluctance motors show high power density (kW/kg), which is promising for traction or aerodynamic applications. Digitalisation and overall system design are identified as important factors to design an efficient electric motor system for overall energy savings. The upgrading of electric motors based on load profile, operation hours, correct sizing, adoption of a new class of electric motors and CDM (complete drive module) should be encouraged to synergistically improve energy efficiency toward meeting New Zealand’s zero carbon goal by 2050.

New Zealand industries use motors ranging from 0.5 to 330 kW, with a capacity of 3.2 GW operating at various load factors between 60% and 100%. Replacing IE2 motors with IE3 motors will save around 222–444 GWh of energy, equivalent to approximately $22M–$44M in cost savings and a reduction of 26.4–52.4 kt of CO_2e for motors with annual operating times of 4000–8000 hours. Energy savings of up to 38–54% could be achieved if the motors used in New Zealand industries are equipped with variable frequency/speed drive. A 38% energy saving could imply around 5.3 TWh of energy savings for IE3 motors operating for 4000 hours annually, which is equivalent to $535 million in cost savings and a reduction of 636 kt CO_2e. A broad implementation of motor-efficiency measures for motors from 0.5 to 330 kW could avoid between 2% and 40% of current motor energy usage of 13.1 TWh for 4000 hours per year for IE2 motors, saving between 261GWh and 5.2 TWh, worth between $26M and $522M per year and avoiding between 31 kt CO_2e and 621 kt CO_2e per year, assuming $100/MWh and 0.119 t$CO_2$e per MWh.

1.0 BACKGROUND AND MAIN FINDINGS

1.1 Introduction

This report provides a review of electric motors and associated powertrain technologies that are used across a broad range of applications in New Zealand. This review focuses on emerging technologies that can offer improved energy efficiency and decarbonisation opportunities. The International Energy Agency released a report in 2021 that highlighted the role of electric motors in reducing emissions in industrial and other sectors (IEA 2021). This report has a goal of all electric motors sold being best in class by 2035, as shown in Figure 1.1.

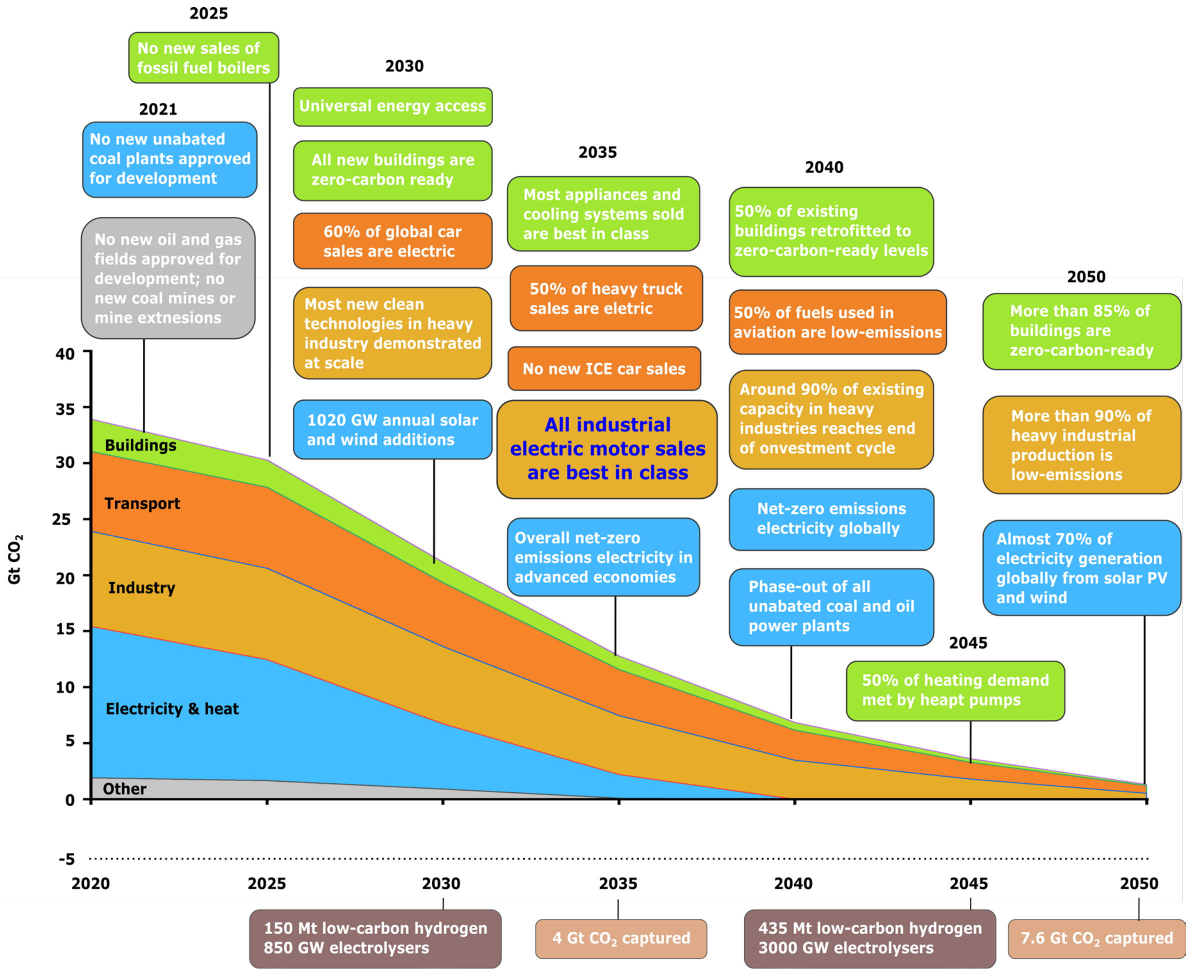


Figure 1.1 International Energy Agency net zero goal by 2050 (IEA 2021).

1.1.1 Why a Focus on Electric Motors?

Electric motors are all around us, converting electricity to motion in everything from tiny devices through to large industrial systems. Within our homes and offices, electric motors can be found in most appliances, including refrigerators, computers, ovens and heat pumps. In our industrial sector, motors drive processes such as conveying, drying, mixing and crushing. In highly automated industrial systems motors, are found in robots and actuators.

Electric motor systems are responsible for around 53% of electricity consumption globally, as highlighted in green in Figure 1.2 (Electric Motor Engineering [2024]). It is also estimated that around 65% of electricity use in industries is for electric motor systems (IEA 2016). The Paris

Agreement 2015 also states that improving the energy efficiency of electric motor systems will have significant impact on achieving the emission target (IEA 2016, 2021, 2023; Electric Motor Engineering [2024]).

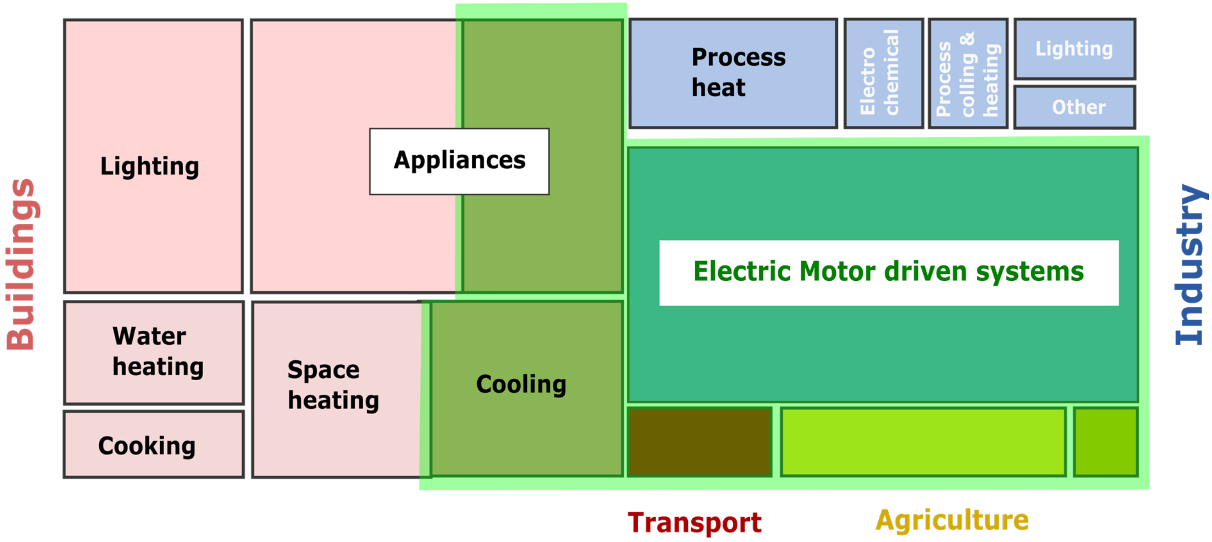


Figure 1.2 Global electricity consumption by end use and share of electric motor drive system (Waide and Brunner 2011).

Whenever a motor is run some of the electricity is converted into heat rather than motion because of loss occurring in motor components. This can be due to the copper loss, iron loss, shearing loss, and mechanical loss in the electric motor system (Waide and Brunner 2011). It is estimated that the use of efficient electric motor systems can result in around 10% overall reduction in energy consumption (IEA 2016, 2021, 2023; Electric Motor Engineering [2024]).

1.2 Scope

The scope of this study has been defined to include relevant electric motor and associated technologies that are:

- Commercially available or near-commercially available: technology readiness level 7–9.
- Likely to be available in the New Zealand market over the next 1–5 years.
- Relevant to New Zealand applications.

Technology readiness level (TRL) is a scale for assessing the stage of development of a product or technology, as shown in Figure 1.3.

Figure 1.3 Technology readiness level (Drescher et al. 2016).

The critical parameters to assess electric motors are chosen as power density (torque density), efficiency, reliability/sustainability, cost effectiveness and technology readiness level (TRL).

1.3 Approach

This international technology scan focuses on:

- Reviewing literature on advancements in motor technology and the underlying physics that define limitations of efficiency.
- Reviewing market analysis reports for electric motors, associated technologies and applications.
- Screening international studies and reports published by energy agencies or sectoral organisations, identifying those that could be of interest.

Equally important is noting that this international technology scan does not provide:

- endorsement of any technology or supplier mentioned in this report;
- new case studies;
- New Zealand case studies;
- an exhaustive review of all available technologies; or
- a technically detailed analysis of each technology's potential, generally or for specific applications.

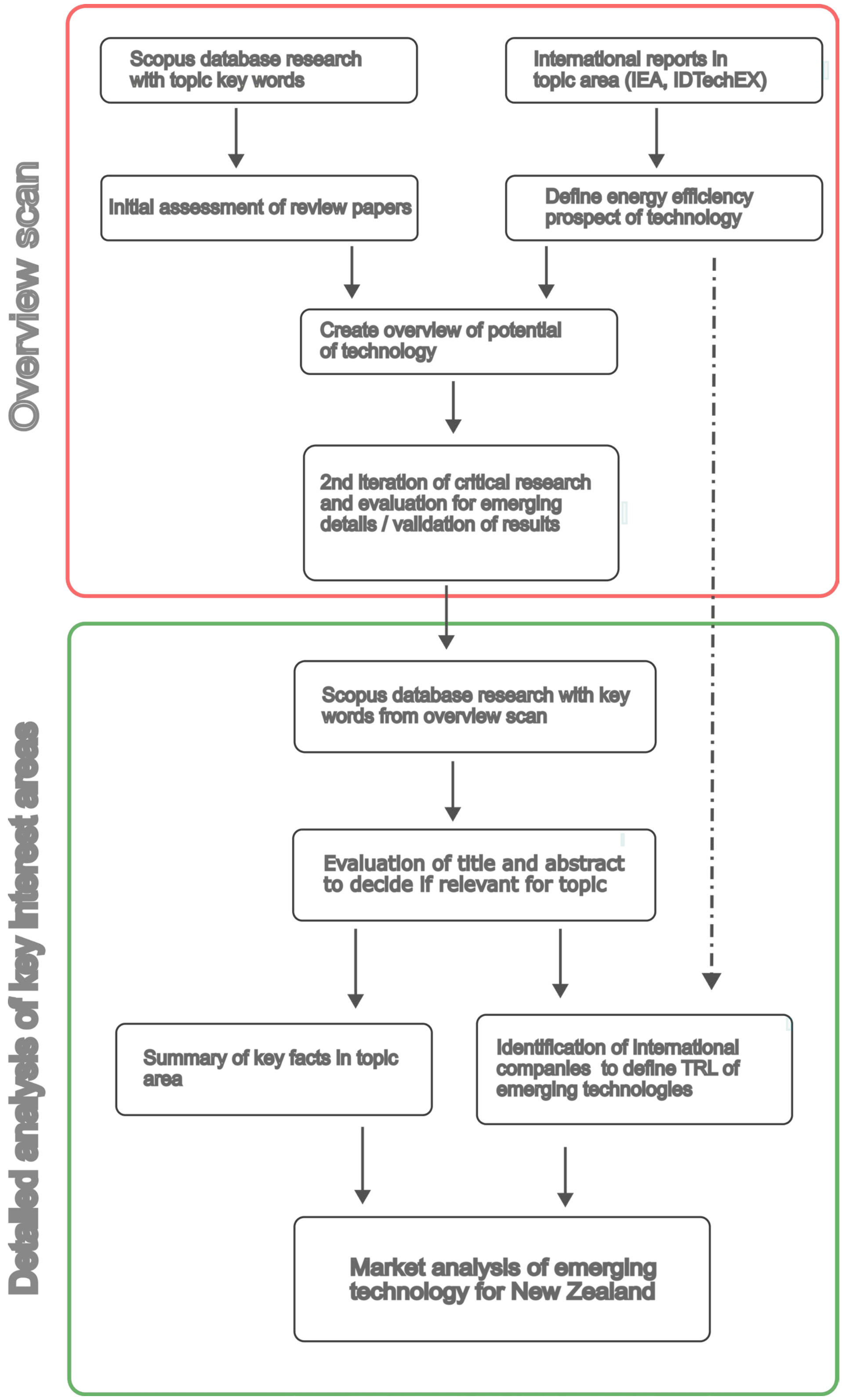


Figure 1.4 Methodology used for technology scan.

Examples of electric motor powertrains include:

- Electric vehicles and boats.
- Industrial automation.
- Commercial and domestic appliances.
- Heat pumps in refrigeration and HVAC (heating, ventilation and air conditioning) systems.

1.4 Overview of Key Findings

Based on the technological scan provided in this report, the following observations are made:

- Emerging technologies and innovation in the electric motor drive system (EMDS) are driven by the development of new materials, electronics for power converters, new motor geometry and overall system-level design.
- Individual EMDS components, as well as system-level design, all need to contribute synergistically to overall energy efficiency of the system.
- The International Electrotechnical Commission's (IEC) guidelines for electric motors (IEC 2014) and power drive systems (IEC 2023) are commonly used for standardisation and minimum energy performance standards.
- New Zealand has used AS/NZS 1359.5 (AS/NZS 2004) since 2002. This efficiency level is below IE2.
- The current highest efficiency level for electric motors is IE4 (super premium efficiency).
- The next efficiency level for electric motors is IE5 (ultra-premium efficiency), which has not been specified in standards yet – these will have a 20% proportional reduction in losses compared to IE4 motors.
- Complete drive module (CDM) constitutes an electronic power converter that, in tandem with electric motors, makes up a power drive system (PDS) in the EMDS.
- PDS guidelines (IEC 2023) suggest assessing the performance of EDMS at various load points by varying torque and speed combinations for variable load applications.
- Wide band-gap semi-conductors, such as SiC and GaN, along with ultra-wide band-gap semi-conductors, such as Ga_2O_3, AlN and diamond, are emerging technologies for high frequency switching and low switching losses.
- Thermal management is a major challenge in power electronics applications, and high thermal conductivity ultra-wide band-gap semi-conductors such as AlN are being investigated for use as a heat sink and a substrate.
- Synchronous reluctance motors (SynRM) show the best efficiency performance as compared to brushless DC motors (BLDC), induction motors and permanent magnet synchronous motors (PMSM).
- Switched reluctance motors (SRMs), axial flux motors and transverse flux motors are emerging technologies for designing robust and high-power-density electric motors.
- SMC materials provide alternatives to rare-earth-element-based permanent magnets and electric motor components, designed to address critical mineral supply chain issues.
- SynRMs are shown to have the highest efficiency as compared to BLDC, induction motors and PMSM.
- SynRM and PMSM motors are close to TRL7–8.
- System-level design, digitalisation and an integrated energy management system have been identified as important factors to system efficiency.
- Employment of CDM for variable load should be assessed on energy saving, as the payback time can vary by nearly four times when operated at low loading points and annual operation hours.
- New Zealand industries use motors ranging from 0.5 to 330 kW, with a capacity of 3.2 GW operating at various load factors between 60% and 100% for 4000 hours.

- Replacing IE2 motors with IE3 motors will save around 222–444 GWh of energy, equivalent to approximately \$22M–\$44M in cost savings and a reduction of 26.4–52.4 kt of CO_2e for motors with annual operating times of 4000–8000 hours.
- Energy savings of up to 38–54% could be achieved if the motors are equipped with variable frequency/speed drive (VFD/VSD).
- A 38% energy saving could imply around 5.3 TWh of energy savings for IE3 motors operating for 4000 hours annually, which is equivalent to \$535 million in cost savings and a reduction of 636 kt CO_2e.
- Energy saving of 2% and 40% of current motor energy usage of 13.1 TWh for 4000 hours per year for IE2 motors, saving between 261GWh and 5.2 TWh, worth between \$26M and \$522M per year, and avoiding between 31 kt CO_2e and 621 kt CO_2e per year.

Figure 1.5 provides an overview of emerging technologies and innovations in EMDS to improve efficiency. New geometry design of electric motors and use of wide band-gap and ultra-wide band-gap semi-conductors and SMC materials to make magnets and motor components are a few key emerging technologies and innovations in EMDS.

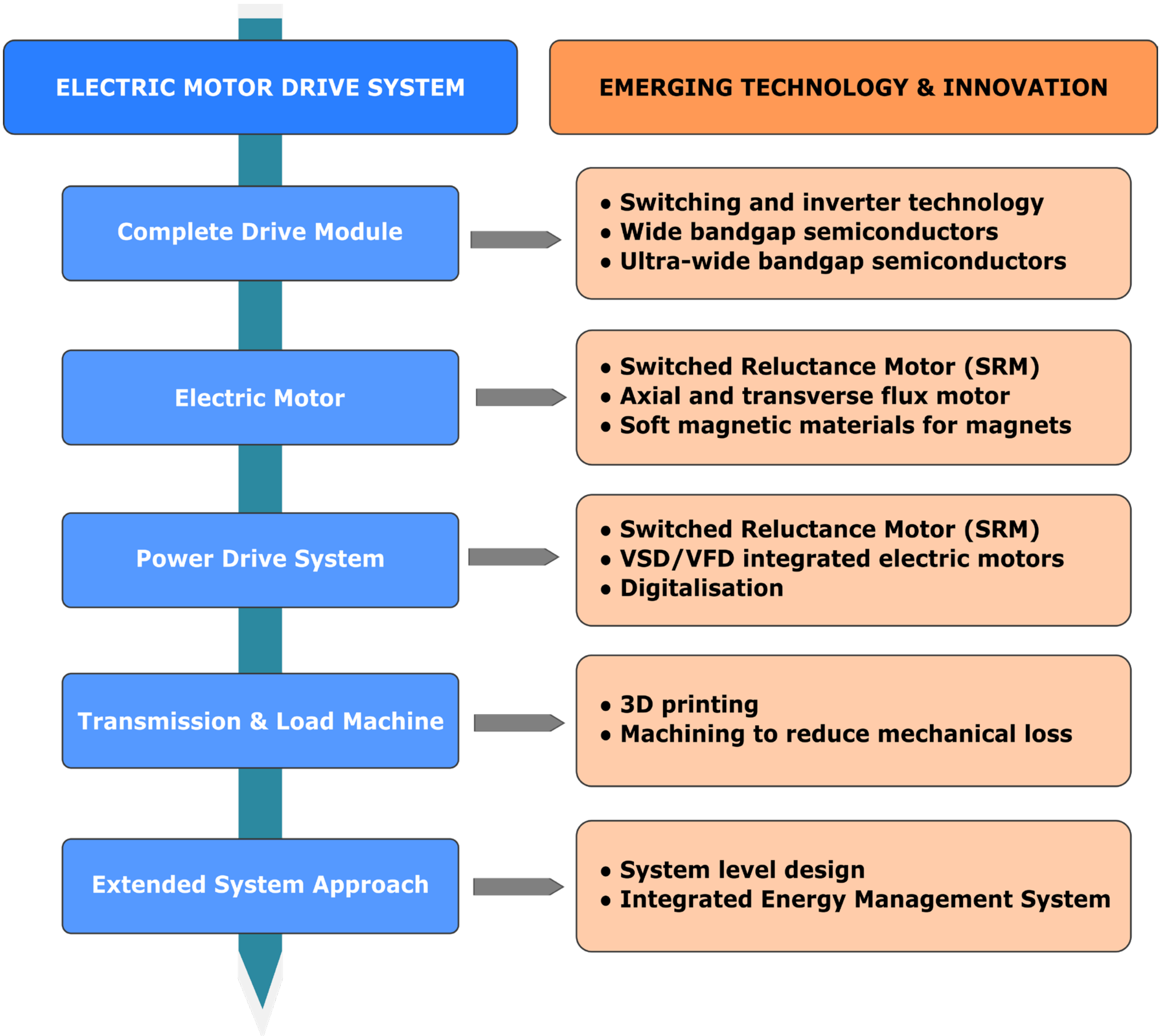


Figure 1.5 Emerging technologies and innovation in electric motor drive systems.

2.0 INTERNATIONAL SCAN: ELECTRIC MOTORS AND ASSOCIATED TECHNOLOGIES

An overview of electric motors and associated technologies is shown in Figure 2.1. This shows the logical flow from electricity generation to electricity conversion in a motor to final applications.

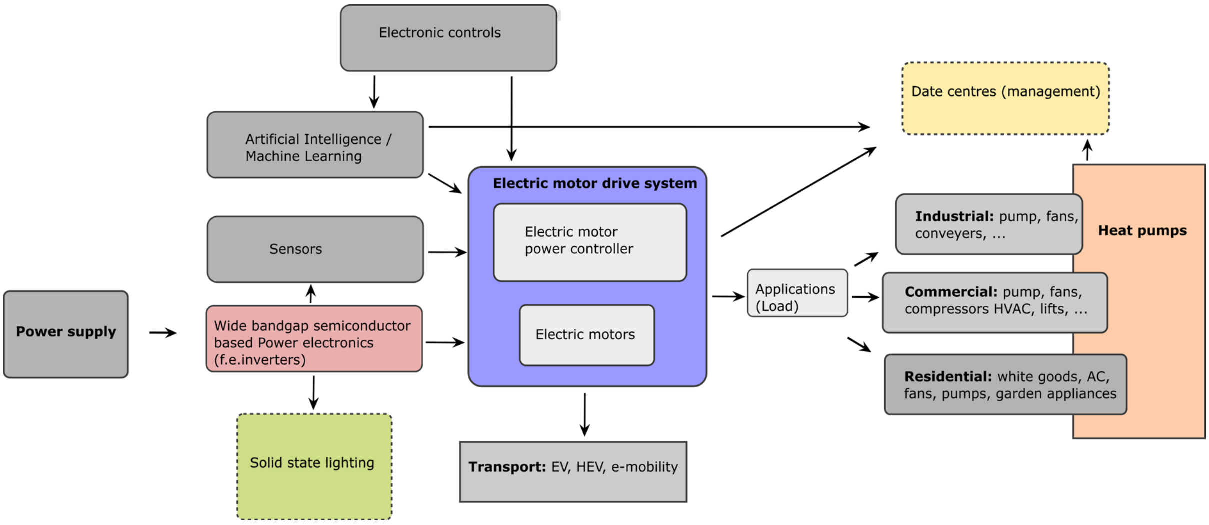


Figure 2.1 Supply chain of electricity requirements discussed in this report.

The central part of this system that is of interest is the EMDS. The highlighted technologies/ applications are discussed in this report, with the main focus on wide band-gap semi-conductors, EMDS and heat pumps that have the highest potential for energy saving in New Zealand. Indicated by dashed lines are solid-state lighting and data centres that were only initially considered, so will only be discussed briefly.

2.1 Electric Motor Drive System

An Electric Motor Drive System (EMDS) is a collection of components based around an electric motor that drives a machine, appliance or vehicle. The typical configuration for a motor system is shown in Figure 2.2. This configuration of the motor system has a power supply external to the system and groups several of the components into modules or sub-units (IEC 2017, 2024). These include:

- **CDM:** Comprises all components that connect the motor to the power supply, excluding any motor starter.
- **Motor control system:** Comprises the CDM and motor starter.
- **PDS[1]:** Comprises the CDM and motor.
- **Motor system:** Incorporates all of the above.
- **EMDS:** Also includes mechanical transmission and the machine being driven by the motor.

This EMDS comprises the electric motor along with electrical controls, mechanical coupling and the driven equipment that delivers the desired motion or flow. Outside the EMDS are power supplies and process components and controls.

1 'PDS' refers to electric motor, VSD/VFD and sensor.

It is useful to define the EMDS in this way, as all of these components are typically present for each motor. In contrast, individual power-supply equipment may supply to several EMDS or other components.

In this report, we focus on the electrical efficiency of the motor system and so will examine the drive equipment, the controls and the motor itself.

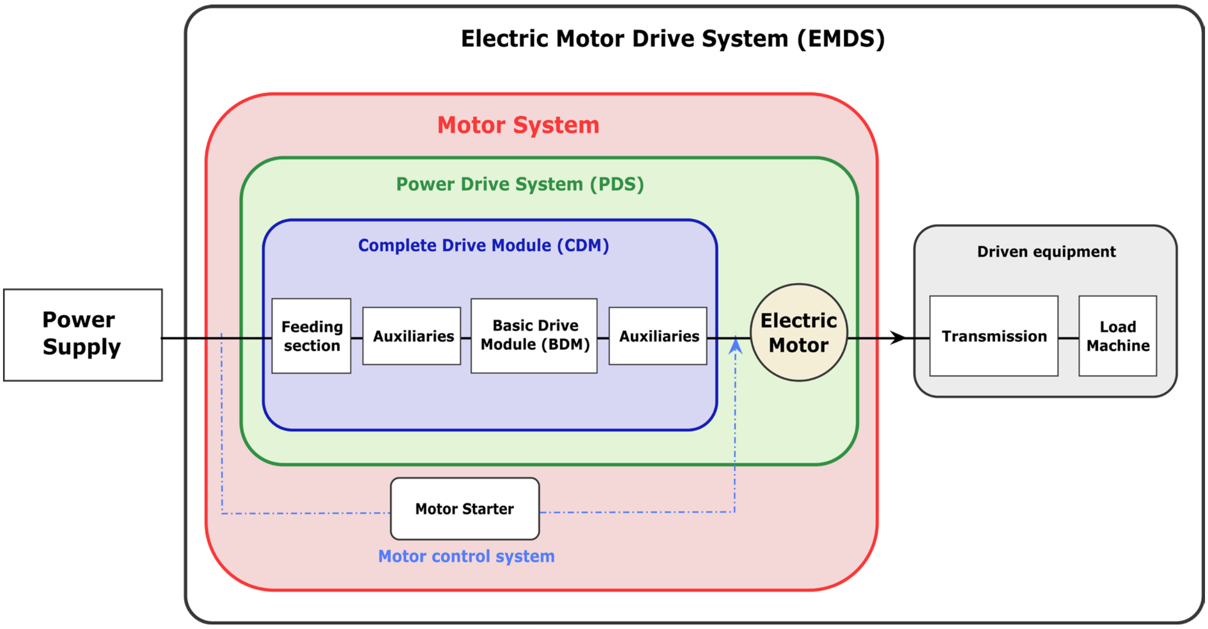


Figure 2.2 Electric motor drive system (IEC 2017, 2014).

Using multiple efficient motor-system components contributes toward efficiency gain (Figure 2.3). For example, adoption of more-efficient electric motors can gain up to 6% energy saving. If this is coupled with a PDS and efficient mechanical systems, the overall gain could be as high as 60%. In this technology scan, the focus is on the first two components, the motor and PDS (Siemens [2024]).

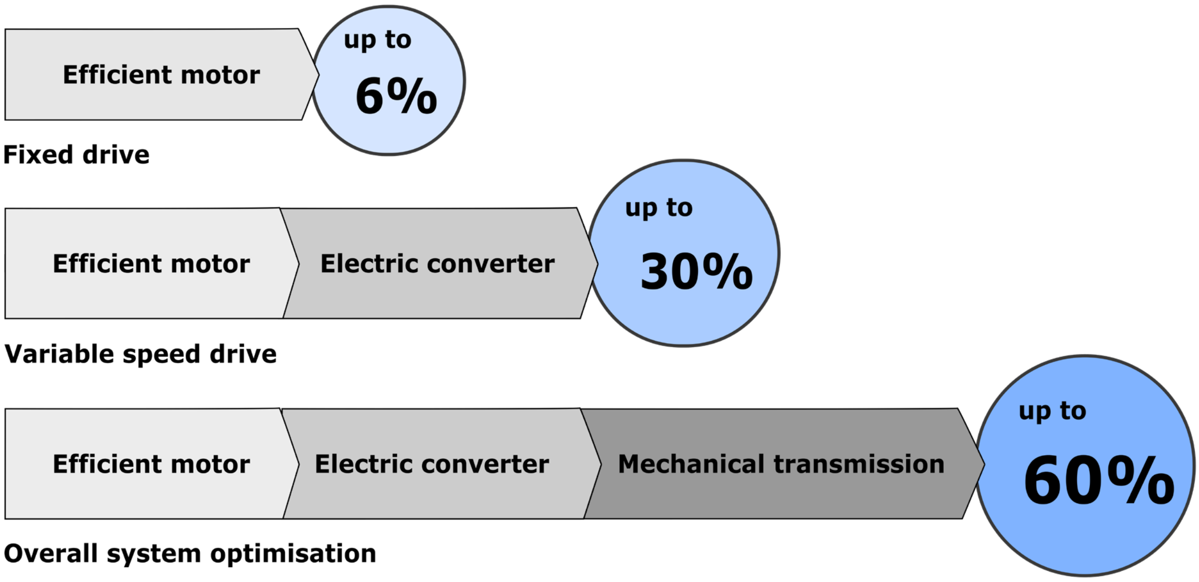


Figure 2.3 Energy saving potential in the electric motor system (Siemens [2024]).

2.2 Minimum Efficiency Performance Standards

Minimum Efficiency Performance Standards (MEPS) for electric motors is an efficiency performance guideline. The IEC specifies performance standards as shown in Figure 2.4 (De Almeida et al. 2019; Oliveira and Ukil 2019; Heidari et al. 2021). Under this standard classification scheme (IEC 2014), there are five efficiency classes:

- IE1 – standard efficiency
- IE2 – high efficiency
- IE3 – premium efficiency
- IE4 – super premium efficiency
- IE5 – ultra-premium efficiency.[2]

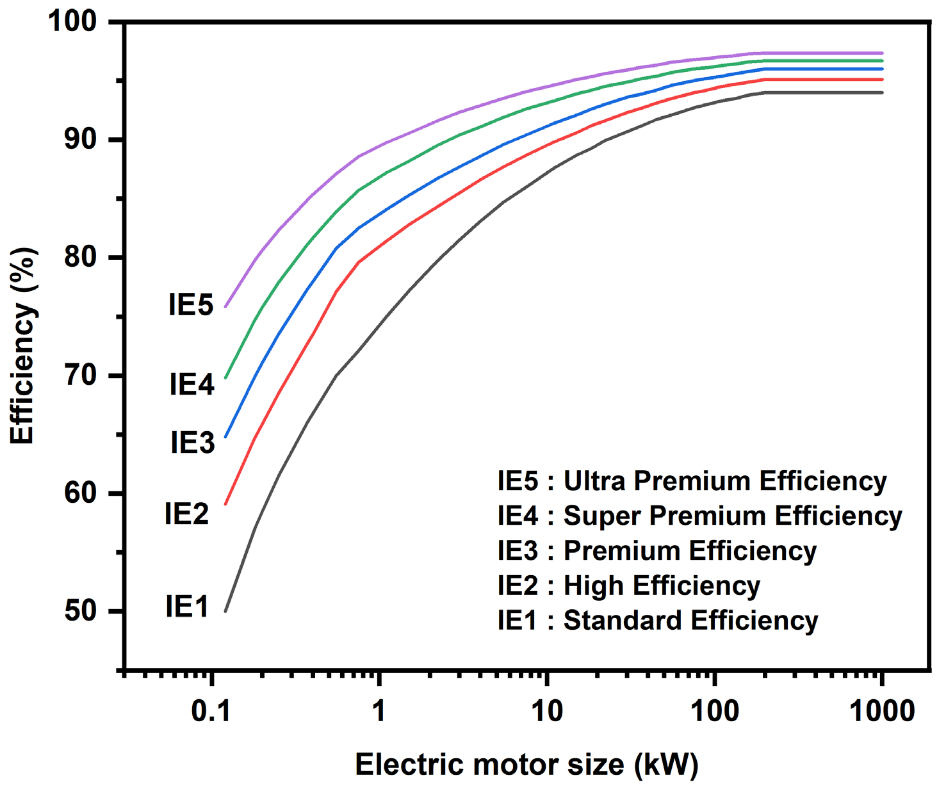


Figure 2.4 Electric motor efficiency for four poles and 50 Hz motors against electric motor size (IEC 2017, 2024).

IEC standards are being adopted globally, as shown in Figure 2.5. The European Union has adopted IE4 regulations effective from July 2023. New Zealand has set MEPS for motors in the size range 0.75–185 kW at IE2 since 2002 under AS/NZS (2004).

2 The ultra-premium efficiency class has not been specified in standards yet, but these will have a 20% proportional reduction in losses compared to IE4 motors. This implies that a ~12% loss will fall to ~9–10%.

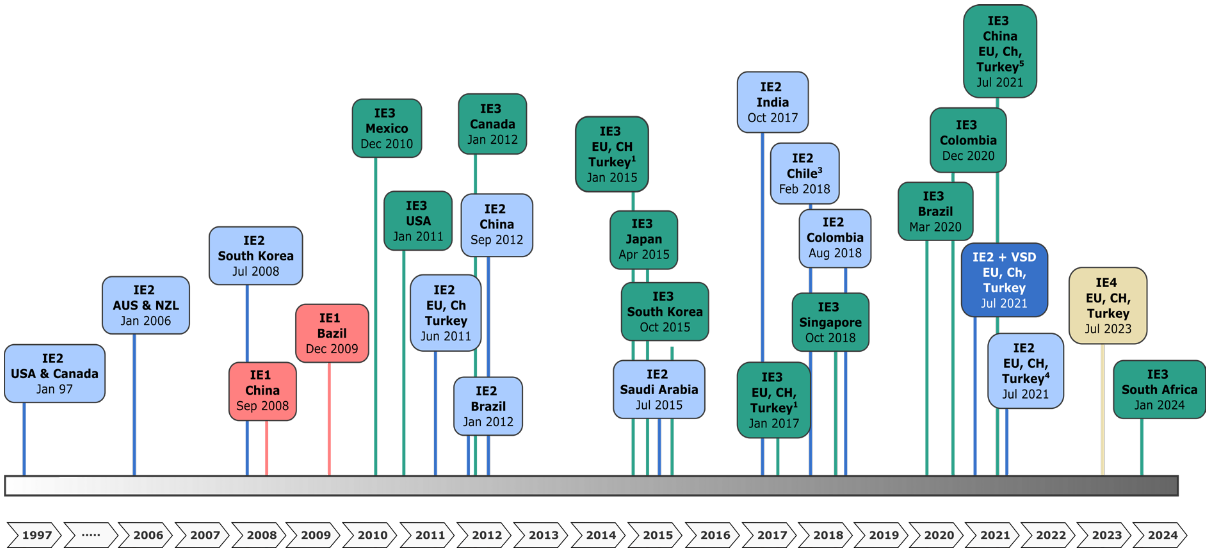


Figure 2.5 Minimum efficiency performance standards adoption for various countries ([1] 7.5–375 kW or IE2 + VSD; [2] 0.75–375 kW or IE2 + VSD; [3] 0.75–7.5 kW; [4] 0.125–0.75 kW; [5] 0.75–1000 kW; [6] 75–200 kW) (De Almeida et al. 2019).

2.3 Electric Motors

The electric motor is a device that converts electricity into mechanical energy. Typically, the mechanical energy is delivered with a rotating shaft. However, in some cases, they may deliver a linear motion, as in linear actuators. Electric motors are powered by alternating (AC) or direct (DC) current power supply, and this choice depends on the specific applications. The stator and rotor are the two main components of electric motors, and their design and operating mechanism vary across different types of motors.

2.3.1 Types of Electric Motors

Electric motors come in a range of different types, as shown in Figure 2.6 (Oliveira and Ukil 2019; Heidari et al. 2021; Du et al. 2023). The first distinction of electric motors is their power supply source. DC electric motors use a stator, which contains coil windings, and a rotor that rotates due to torque applied from the stator's magnetic field. The stator could be based on a permanent magnet or electromagnets. The DC motor usually uses a brushed commutator, which is a major source of heating and maintenance issues due to decay of the commutator. The brushless DC motor (BLDC) overcomes this issue by removing the need of a commutator with winding coils (Mohanraj et al. 2022). The DC-powered winding coils accurately measure the rotor position electronically (usually using Hall sensors) for brushless commutation of the rotor shaft. The advantages of DC electric motors include higher efficiency, precise control and faster response time. These are used in residential and commercial applications that require continuous operation for a longer period of time, as well as for traction in automotive industries. In particular, the use of BLDC electric motors is gaining more interest due to development of electronic control systems for electric vehicles and aviation applications.

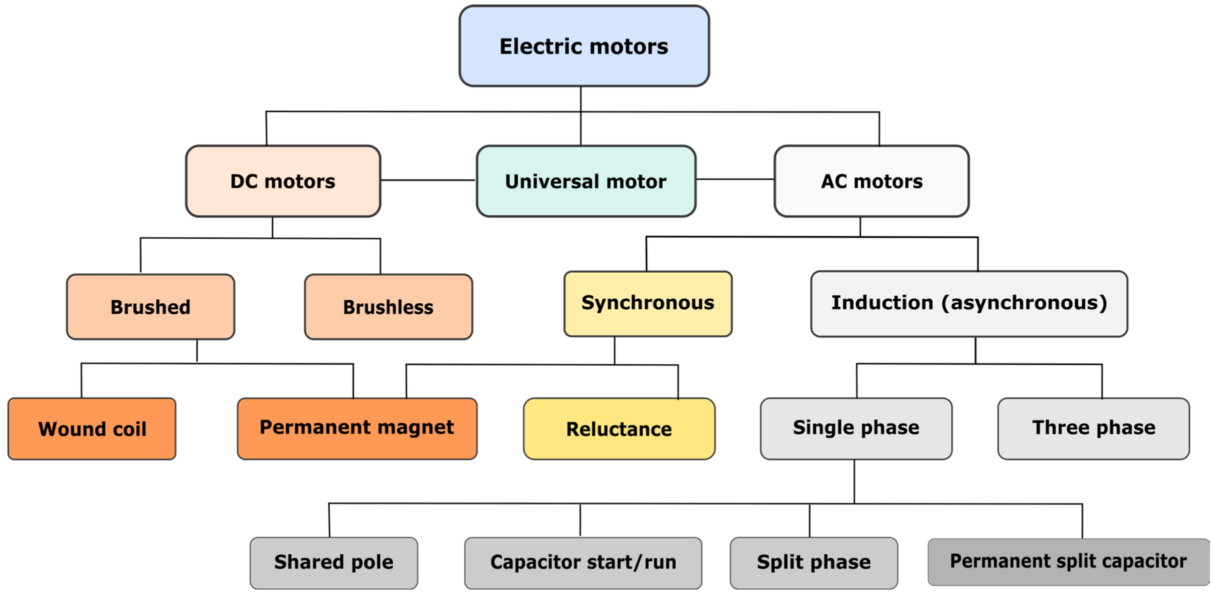


Figure 2.6 Types of electric motors.

AC-induction electric motors work on the principle of electromagnetic interaction between an electric field and magnetic field. When a single-phase induction motor is energised, the magnetic field in stator induces a current in the rotor and an opposing magnetic field, resulting in torque. The strength of the magnetic field depends on the rotor windings. Induction motors are also known as asynchronous motors due to slip between the rotation of stator and rotor magnetic fields. Three-phase induction motors use three-phase AC power supply, commonly found in commercial and industrial buildings, which have high load applications. Three-phase induction motors are highly reliable and dominate industrial applications due to cost-effective operations.

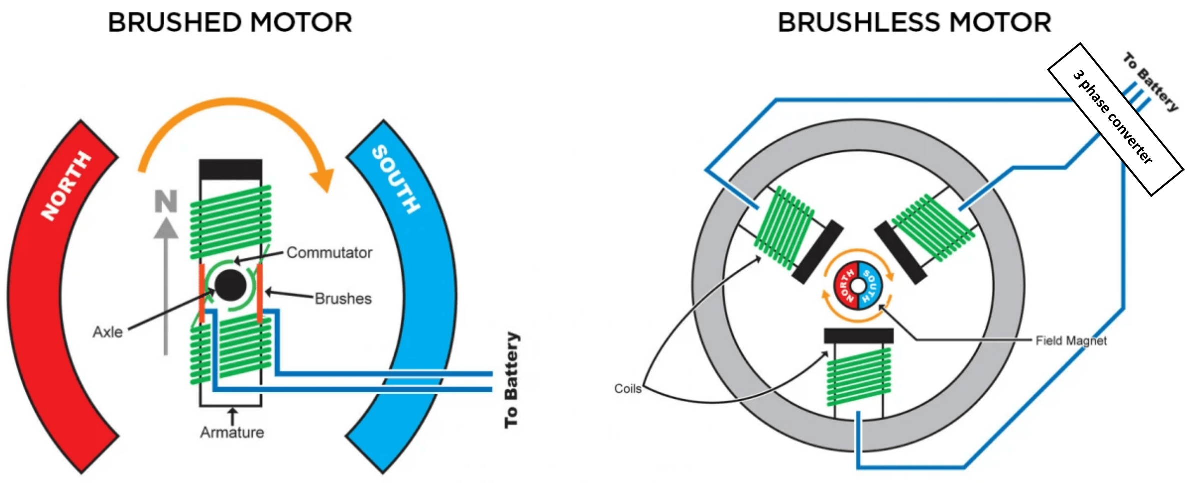


Figure 2.7 Brushed and brushless DC motor types of electric motors (Winstanley 2020).

SynRM technology exploits the synchronous rotation of a rotor with rotating magnetic field of the stator (Shen and Chen 2024). The rotor uses ferromagnetic materials, which lowers the reluctance while trying to align the magnetic fields. As there are no windings or permanent magnets in the rotor, this greatly reduces the magnetic core losses to improve the efficiency, and reliability is higher due to low maintenance. Permanent magnet synchronous reluctance motor (PMSynRM) is a synchronous reluctance motor that uses permanent magnets.

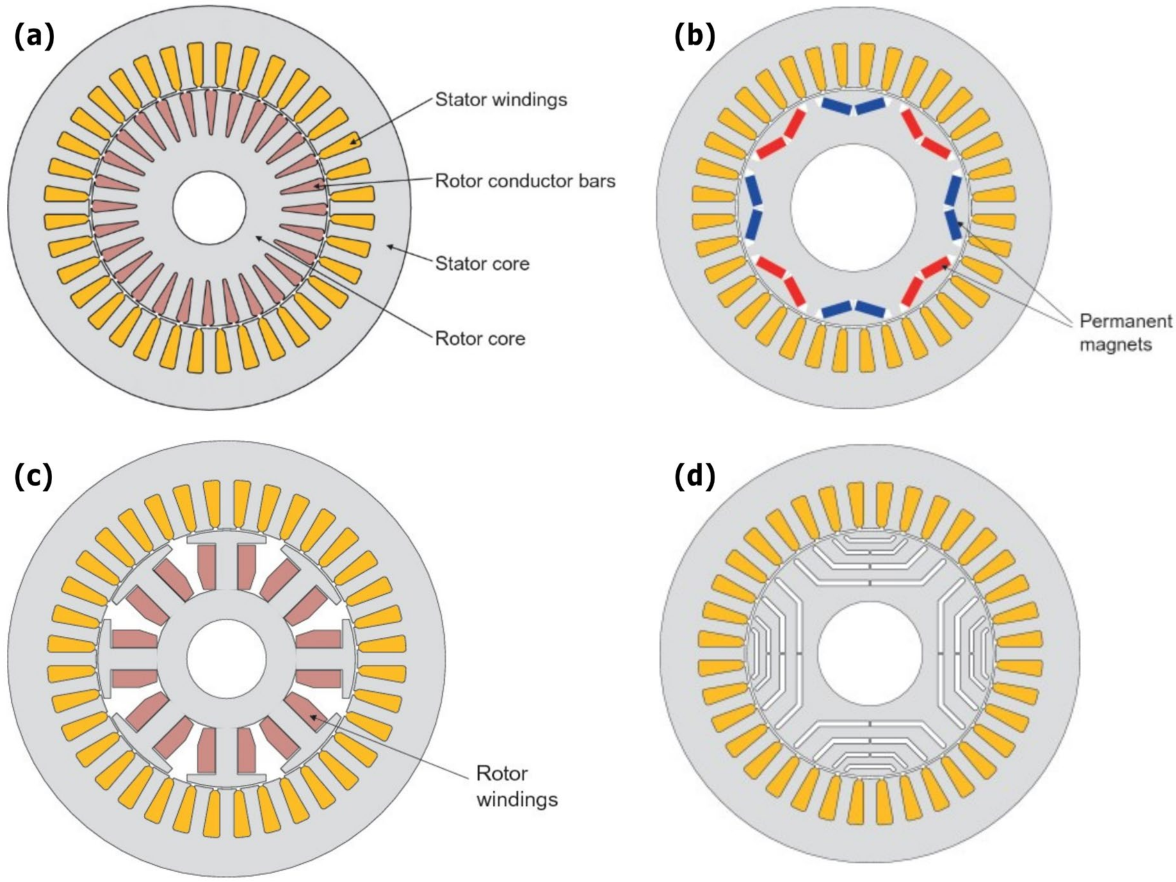


Figure 2.8 Cross-sectional views of different types of motors. (a) Squirrel cage induction motor; (b) interior permanent magnet motor; (c) wound field synchronous motor; (d) SynRM (Shen and Chen 2024).

The universal motor, also known as a series-wound commutated motor, has rotor and stator windings connected in a series. This motor can be powered by AC or DC, but commonly uses AC power supply. A brushed commutator reverses the current direction, which generates torque in the rotor. Unlike AC-induction motors, this generates much higher speed and starting torque. These motors are commonly used in vacuum cleaners, power tools, lawn mowers and food mixers; applications that require high speed and intermittent operation. Table 2.1 shows a comparison of electric vehicles and traditional industrial motors.

Table 2.1 Comparison of electric vehicles and traditional industrial motors (Cheng et al. 2015).

	Electric Vehicle Motors	Traditional Industrial Motors
Ambient Temperature	-40–140°C	20–40°C
Operation Environment	Adverse	Indoor
Coolant Temperature	75–150°C	<40°C
Winding Temperature	160–200°C	75–130 °C
Speed Range	0–15,000 rpm	<3000 rpm
Noise Level	Very low	Low
Speed Demand	Frequent changes	Keep uniform
Installation Space	Very limited	Loose
System Voltage	Independent/variable	Static grid
Efficiency	Efficient	Determined by application

2.3.2 Energy Loss in Electric Motors

Electric motor efficiency is determined by how much energy is lost, mainly in the form of heat. Figure 2.9 shows the energy losses from various components in the electric motor. The electric motor losses can be divided into two main parts – no-load losses and load losses. No-load losses are the energy loss from the motor components and are present even when there is no load applied.

Iron losses are due to the energy required to overcome a change in magnetic field in the magnetic core structures (Saidur 2010; Nguyen et al. 2023). The use of better-quality steel and optimising core design to reduce magnetic flux density can decrease the iron losses. Windage and friction losses arise due to air friction and ball-bearing friction. This contribution can be reduced by improving bearings selection and cooling capability.

Load losses – stator copper losses, rotor losses and stray load losses – vary with the load applied. Stator copper losses arise from the Joule's heating in the copper windings in the stator. This is also known as I^2R losses and can be reduced by using low-loss steel and optimising geometry of the stator for maximisation of magnetic fields. The rotor losses stem from the rotor current and iron losses in the rotors. This can be reduced by lowering the rotor resistance by using conducting bars and rings. Stray load losses arise from the misalignment of stator and rotor and decay in magnetic properties in the magnetic materials. Shearing loss due to machining of rotors can also cause 9–20% iron losses (Zhu et al. 2024). This motor loss can be reduced by using an electronic control system to monitor the stator and rotor misalignment and magnetic flux leakages.

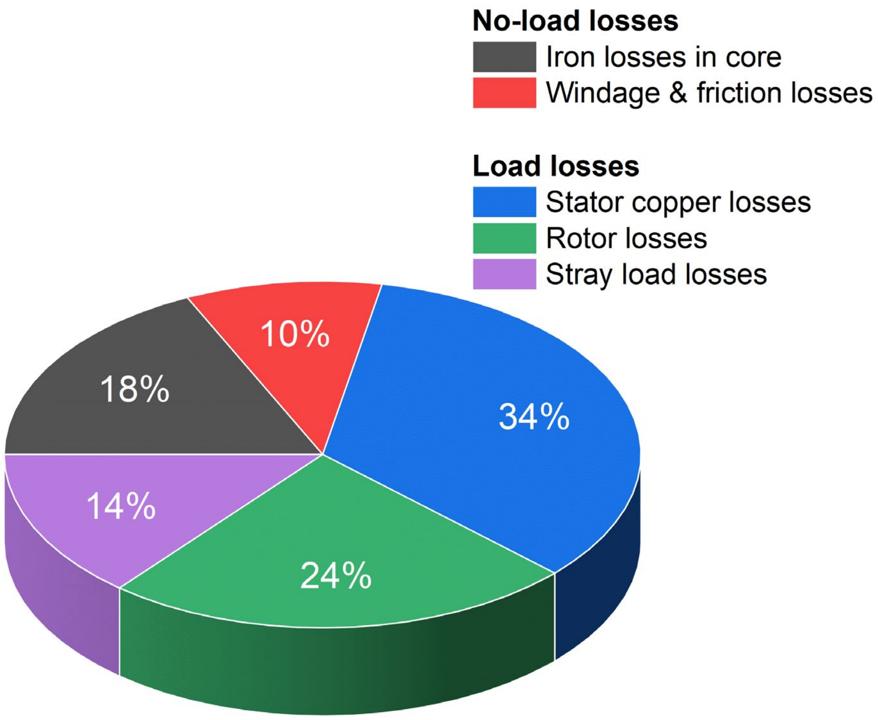


Figure 2.9 Typical fraction of losses in electric motors (Villani et al. 2022; de Almeida et al. 2023).

Table 2.2 Comparison of electric motor technology (De Almeida et al. 2019; Oliveira and Ukil 2019; Heidari et al. 2021; de Almeida et al. 2023; Du et al. 2023; Nguyen et al. 2023). BLDC = brushless DC; PMSM = permanent magnet synchronous motor; SynRM = synchronous reluctance motor; PMSynRM = permanent magnet synchronous reluctance motor.

	Types	Advantages	Disadvantages	Main Applications
BLDC Motor	Brushed, brushless	High torque, low maintenance, long life cycle	Use of rare-earth magnets	Traction applications, industrial actuators, office/household appliances, aerospace, drones, medical devices
Induction Motor	Copper rotor, aluminium rotor, wound rotor, rotor skewing	Low materials and manufacturing cost, line-start capability, minimum maintenance, high reliability and self-starting	Low power factor, bearing fault	Industrial applications (pump, fans, traction, …)
PMSM	Interior PM, surface mounted PM, line-start PM	High performance in wide speed range operation	Use of rare-earth magnets	Precise control and high speed (traction, robotics, aerospace, medical, …)
SynRM	Line-start SynRM, skewed motor, rotor with asymmetric flux	Reliable and high efficiency, high dynamic, high overload, very high-speed capability	High torque ripple, severe low power factor	Industrial applications (pump, fans, traction, …)
PMSynRM	Rotor skewing, symmetric rotor structure,	Very high performance without rare-earth magnet	Hard manufacturing and installation process	Traction applications

Figure 2.10 shows the efficiency gain achieved for various motors replaced with IE5. It should be noted that the IE5 (ultra-premium efficiency[3]) class has not been specified in standards yet but will have around 20% proportional loss reduction compared to IE4 motors.

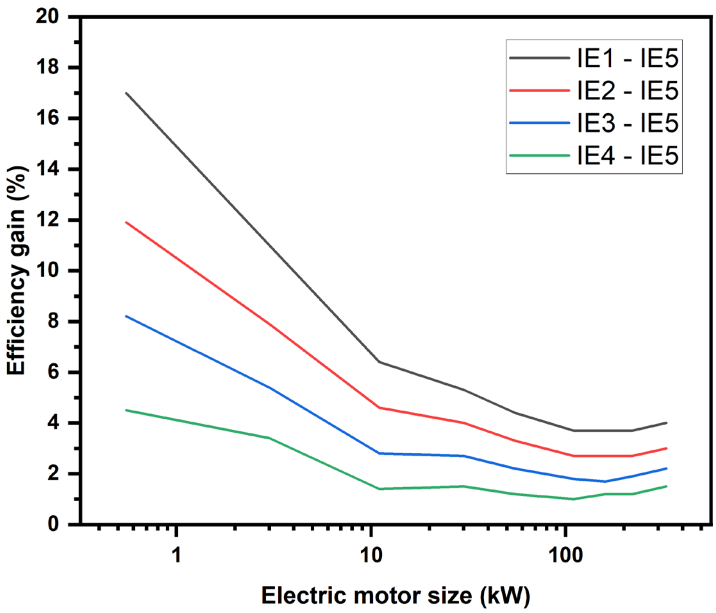


Figure 2.10 Efficiency gain against mid-point power size using IE5 efficiency motors (IEC 2017, 2024).

3 A 20% proportional reduction in losses compared to IE4 motors implies that a ~12% loss will fall to ~9–10%.

Electric motor efficiency is highly dependent on the operating conditions. Figure 2.11 shows that efficiency is highest in 50–100%-rated torque for all types of motors.

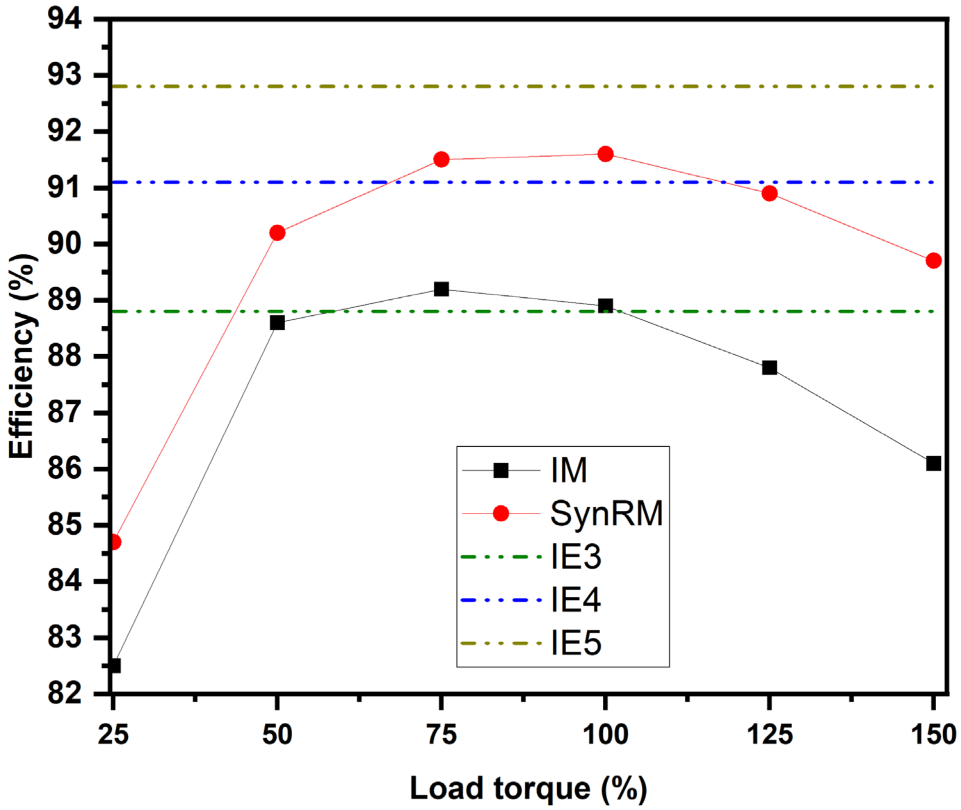


Figure 2.11 Experimental efficiency versus load torque at 400V and 50 Hz (Villani et al. 2022).

2.3.3 Electric Motor Efficiency Innovation

Innovation in electric motors is guided by requirement of high power/torque density (kW/kg), compact size, reduced vibration/sound, thermal limitation and energy security due to supply of critical elements for electric motor design. Two major directions regarding the innovation of electric motor designs are:

- Switched reluctance motor.
- New flux motors.
- New materials for magnets and components.

2.3.3.1 Switched Reluctance Motor

Switched reluctance motors (SRMs) are gaining significant interest due to their simple and robust design compared to DC motors, permanent magnet motors and induction motors (Ahn and Lukman 2018). In an SRM, power is delivered to the stator rather than the rotor, simplifying its mechanical design. Reluctance torque is used for rotation instead of electromagnetic torque, which is controlled by power-switching transistors (Ahn and Lukman 2018). SRMs are suitable for a wide range of speed applications due to their low inertia, as the rotor has no windings or permanent magnets. Table 2.3 shows that SRMs have several advantages over other electric motors, such as low cost and excellent start-up performance (Feng et al. 2024). However, these suffer from high torque ripple and noise levels compared to other electric motors. Recently, innovations with wide band-gap semi-conductor power-electronics-based motor drives have re-ignited interest in SRMs for applications in wind turbines, compressors and conveyors.

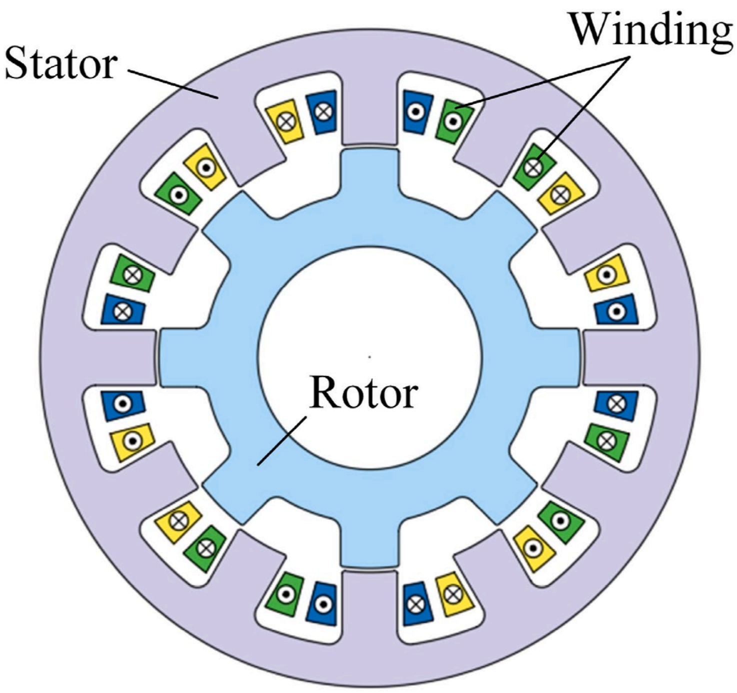


Figure 2.12 A schematic of switched reluctance motor (SRM) topology of a conventional 12/8 SRM (from Feng et al. [2024]).

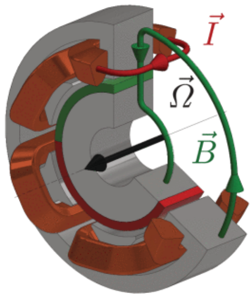
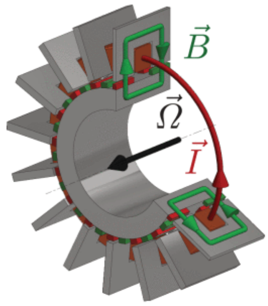
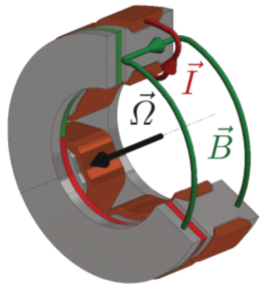
Table 2.3 Performance comparison of different types of motors (Feng et al. 2024).

Performance	Direct Current Motors	Induction Motors	Permanent Magnet Motors	Switched Reluctance Motors
Power Output	Low	Medium	High	High
Efficiency	Low	Medium	High	Medium
Speed Range	Medium	Medium	Medium	Wide
Speed Driver Requirement	Necessary for variable speed applications	Necessary for variable speed applications	Necessary for variable speed applications	Always necessary
Mass	Heavy	Medium	Light	Medium
Overall Cost	Low	Low	High	Low
Start-Up Performance	Excellent	Poor	Medium	Excellent
Torque Ripple	Low	Low	Low	High
Overload Ability	Excellent	Medium	Medium	Excellent

2.3.3.2 New Flux Motors

Electric motors generate rotation by converting electrical energy into mechanical energy, which are influenced by the current and magnetic flux direction. There are three types of electric motors – radial flux motors, axial flux motors and transverse motors based on current ($\vec{I}$), magnetic flux ($\vec{B}$) and axis of rotation ($\vec{\Omega}$). Table 2.4 provides an overview of these motors.

Table 2.4 Overview of radial flux, axial flux and transverse motors (Ballestín-Bernad et al. 2021; Kaiser and Parspour 2022; Nishanth et al. 2023).

Parameters	Radial Flux Motor	Axial Flux Motor	Transverse Flux Motor
Schematic of Current ($\vec{I}$), Magnetic Flux ($\vec{B}$) and Axis of Rotation ($\vec{\Omega}$)			
Magnetic Flux Direction	Perpendicular to the axis of rotation	Parallel to the axis of rotation	Combination of radial and axial flux motors
Torque Density	Moderate	Usually high	High
Heat Dissipation	High	Low	Medium
Motor Design	Thick and cylindrical	Thin and flat	Complex
Size and Weight	Bulkier and heavier	Compact and lightweight	Variable
Durability and Robustness	High	Medium	Medium
Cost-Effectiveness	High	Medium	Medium
Common Applications	Industrial and traction motors	Electric vehicles, aircrafts, robotics	Direct-drive systems, e.g. wind turbines

Radial Flux Motors

Radial flux motors (RFM) are the most common electric motors due to their versatility, durability and cost-effectiveness for industrial and commercial applications. In n RFM, such as BLDC, the permanent magnets acting as rotors are placed inside the copper coil wound stator, where magnetic flux is perpendicular to the axis of rotation. These are suitable for applications that require low torque and high speed of rotation. The simpler design and low manufacturing cost of RFM make them preferred electric motors due to low installation cost, low maintenance and reliable performance.

Axial Flux Motors

The axial flux motor (AFM) has magnetic flux parallel to the rotation axis. Due to its compact and flat geometry, large rotors can be designed to produce higher torque due to a cubic increase in the diameter as compared to square increase in a radial flux motor. Moreover, its unique geometry means that high-magnetisation materials can be used instead of steel, while still generating high magnetic flux interaction. An AFM can have 30–40% more power density as compared to a similar size radial flux motor, due to higher torque and effective magnetic flux interactions (Figure 2.13) (Husain et al. 2020; Kaiser and Parspour 2022). AFM are in demand where power-to-weight ratio is critical, such as in electric vehicles and aircraft due to their high power density (kW/kg). However, relatively complex design, strong magnetic interaction between rotor and stator and a small air gap pose significant challenges to adoption of these motors.

Transverse Flux Motors

Transverse flux motors (TFM) utilise a special geometry where the magnetic flux crosses axially through the stator, circumferentially through the rotor and radially through the gap between these (Husain et al. 2020; Kaiser and Parspour 2022). TFM are more suitable for motors requiring low speed and torque applications, as their unique geometry allows compact design for high power density, suitable for applications such as electric vehicles and robotics. However, their complex geometry is a drawback that increases cost and thermal management.

Figure 2.13 illustrates the comparison of PMSMs as RFM, AFM and TFM based on finite-element analysis calculation (Kaiser and Parspour 2022). The highlighted area presents the broad operating conditions for efficiency η >96%. The figure shows that the RFM has the smallest operating regions to achieve η >96%, which requires moderate speed and torque. AFM require high torque over a wide speed range for high efficiency. TFM can achieve high efficiency even with low speed range over a wide range of torque. The AFM is in the highest and widest area of high efficiency, which shows its suitability to high-power-density motor applications.

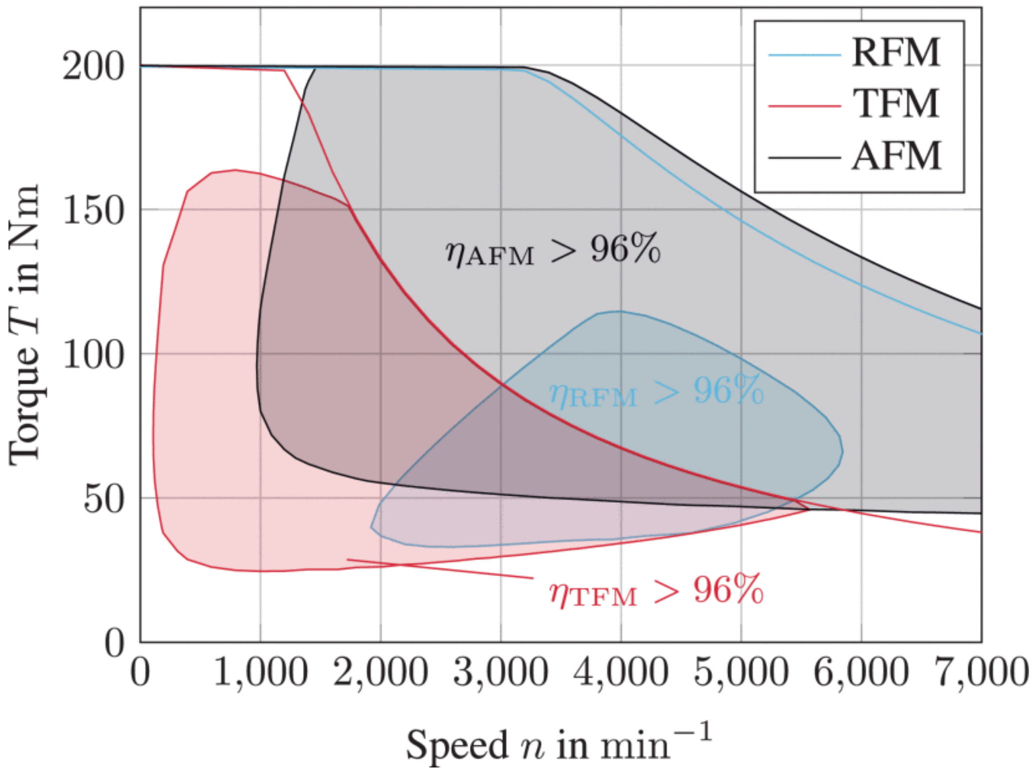


Figure 2.13 Comparison of efficiency in dependence of operation point of permanent magnet synchronous motors as radial flux motors (RFM), axial flux motors (AFM) and transverse flux motors (TFM) (Kaiser and Porspour 2022).

Power Loss in Radial Flux and Axial Flux Motors

Power loss effects the efficiency of electric motors. This could be from copper loss, iron loss or eddy current loss from the stator, rotor or permanent magnet components. Recently, Tsunata et al. (2023) compared a radial-flux permanent magnet machine (RFPM) and axial-flux permanent magnet machine (AFPM) using 3D finite-element analysis and experimental results. Figure 2.14 illustrates the power loss from RFPM and AFPM. There is a larger eddy current loss in the RFPM, which causes higher copper loss.

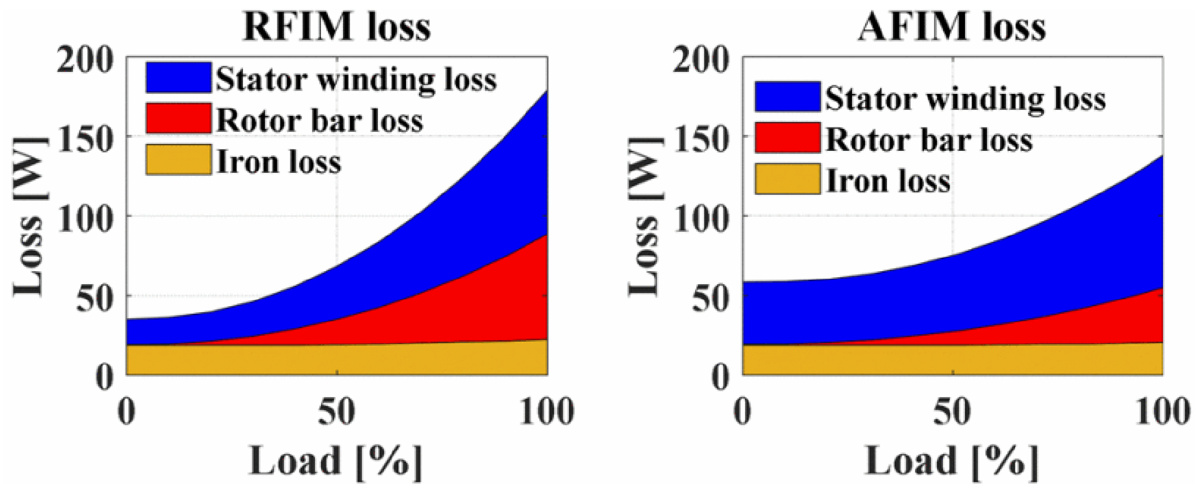


Figure 2.14 Efficiency and loss in radial-flux permanent magnet machine and axial-flux permanent magnet (Tsunata et al. 2023).

2.3.3.3 New Magnetic Materials

Electric motor components such as rotor, stator, case and magnets are made of silicon, aluminium, transition metals and rare earth elements. Table 2.5 shows the common elements used in various types of electric motors.

Table 2.5 Summary of minerals used in electric motors.

Electric Motor	Minerals Used	Risk
Brushless DC (BLDC)	Rare earth elements, electrical steel.	High
Induction motor	Significant copper or aluminium use, electrical steel. No rare earth elements.	Low
Permanent magnet synchronous motor (PMSM)	Neodymium, dysprosium, dysprosium, terbium.	High
Synchronous reluctance motor (SynRM)	No rare earth elements or copper.	Medium
Permanent magnet synchronous reluctance motor (PMSM)	Neodymium, dysprosium, dysprosium, terbium.	High

Rare earth elements are key minerals used in magnets, which are critical minerals with strategic and supply-chain risks. Recently, ‘soft magnetic materials’ are being increasingly used for designing electric motors, partly due to the energy security and supply-chain issues. These are magnetic materials that can rapidly respond to changes in external magnetic fields and achieve high-saturation magnetic flux density that have low losses due to small coercive fields (Shokrollahi and Janghorban 2007; Wang et al. 2016; Silveyra et al. 2018; Tahanian et al. 2020; Nematov et al. 2022; Theisen 2022). These possess low coercive field (H_C) to achieve saturation magnetisation termed as permeability (μ_{max}) (He et al. 2023). Coercive field is the magnetic field that is required to completely de-magnetise magnetic materials. Figure 2.15 shows a characteristic magnetic field and magnetisation curve commonly used for assessing the magnetic material’s response to the applied magnetic field.

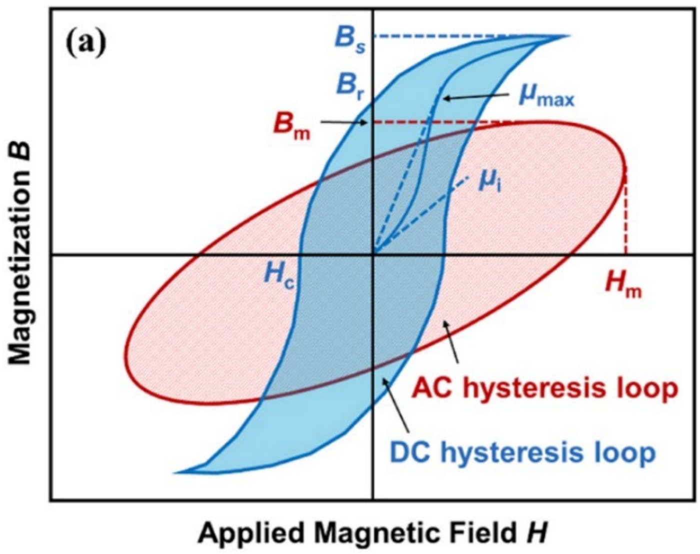


Figure 2.15 Schematic of hysteresis loops of soft magnetic materials obtained by direct and alternating current conditions (He et al. 2023).

SMC-based, iron-containing ferrite materials are a potential alternative for rare-earth-element-based magnets and are being used in other technologies such as switched reluctance motors. The magnets made from soft magnetic materials do not have as high power/torque density as the rare-earth-element magnets. However, they have several advantages over rare-earth-element-based materials, as shown in Table 2.6.

Table 2.6 Comparison of iron and rare-earth-element-based electric motors (Wang et al. 2016; Tahanian et al. 2020; IEA 2022).

	Iron-Based Electric Motors	**Rare-Earth-Elements-Based Electric Motors**
Advantages	• High efficiency at high speed • Low cost • Low losses in permanent magnets • Environment-friendly	• High torque density • High efficiency • High power factor • Compact size • Good dynamic performance
Disadvantages	• Low torque density • Large size • High de-magnetisation rate • Heating limitation • Low power factor	• High cost • Considerable power losses • De-magnetisation at high temperatures

Ideally, soft magnetic materials should have high-saturation magnetisation, high relative permeability, high electrical resistivity and low coercivity. Coercivity and permeability are sensitive to microstructure and grain size of magnetic materials. Figure 2.16 shows the typical soft magnetic materials and their saturation magnetic flux (B_S) and effective permeability (μ_e) at 1 kHz (Wang et al. 2016). Silicon steel is a commonly used soft magnetic material due to high saturation flux density (B_S), but these show high loss due to low permeability (μ_e). Amorphous materials offer high permeability and low coercivity and core loss, which are considered for replacing silicon steel. However, the amorphous materials show relatively high coercive fields that cause low-frequency loss. Nanocrystalline alloys were developed to improve the soft magnetic performance due to high magnetic induction, high permeability and low coercivity.

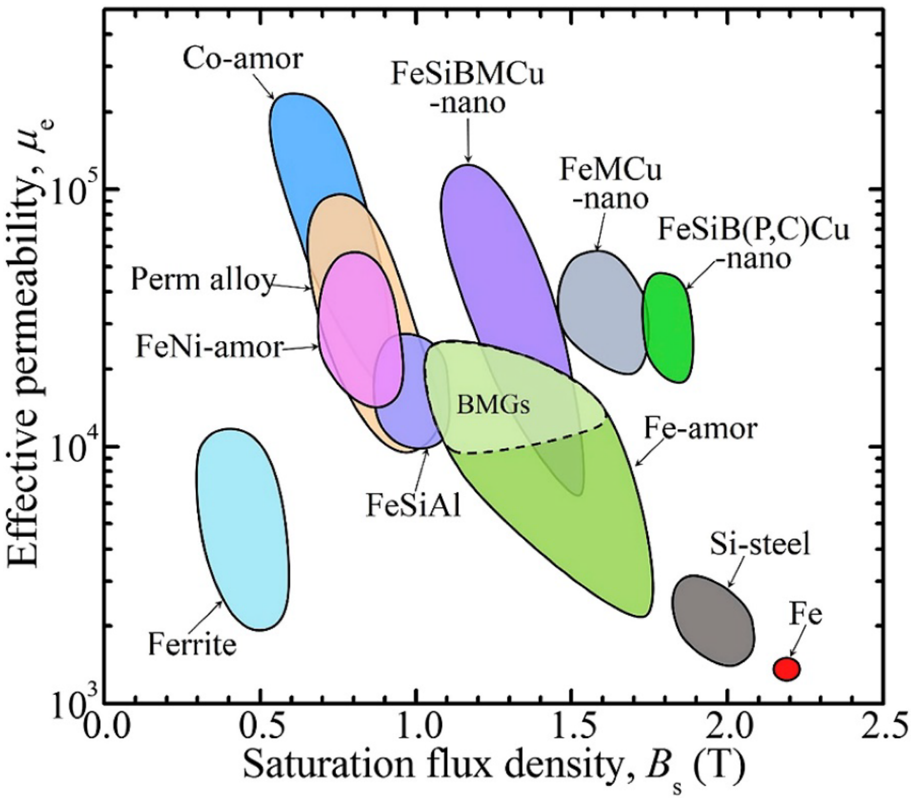


Figure 2.16 Relationship between permeability (μ_e) at 1 kHz and saturation flux density (B_s) for soft magnetic materials (Tahanian et al. 2020).

Table 2.7 Merits and demerits of amorphous versus nano-crystalline alloys.

Material	Merits	Demerits
Nanocrystalline magnetic materials	• Higher saturation flux density, lower coercivity and higher permeability at high frequencies. • Ideal for high-power-density and high-frequency applications. • Nanocrystalline materials can have higher electrical resistivity to allow for lower core losses.	• High-frequency application, resulting in high eddy current loss. • Fragile. • Relatively higher cost of manufacturing nanocrystalline materials. • Magnetic loss in the high temperature-magnetic annealing is larger at high frequencies.
Amorphous magnetic materials	• Higher magnetic permeability at low or medium frequencies, suitable for low-frequency applications. • Amorphous alloys are strong, hard and ductile. • Relatively low coercivity and core loss. • Compared to nanocrystalline magnetic materials, amorphous materials offer cost-effectiveness.	• At low frequencies, core loss is mainly due to the hysteresis loss. • Substantially reduced magnetic permeability makes these not ideal for applications that require high magnetic performance.

Power loss is influenced by the coercive fields of the magnetic materials. Figure 2.17 shows the power loss for common soft magnetic materials (Theisen 2022). Ferrites show a wide power loss range but possess low power density. Rare-earth-element-based magnetic materials show high (Trinh et al. 2021) power density but have very high power loss compared to the soft magnetic materials. Current research on soft magnetic materials is driven by increasing the power density while lowering the coercive fields by reducing the power loss. The power loss, also referred as core loss or iron loss in the magnetic materials, is due to three mechanisms as follows (Wang et al. 2016):

1. **Hysteresis loss:** This is due to the pinning of magnetic wall domains, which leads to high loss stemming from high energy required to change the magnetisation of the materials. This is due to the extra energy required to de-magnetise magnetic materials and switch direction of their magnetisation. The extra energy is needed to completely switch magnetic moments that are pinned in magnetic wall domains. Hysteresis loss is the main mechanism for power loss in the low-frequency range. Heat treatment is often employed to reduce domain wall-pinning sites to minimise this loss.
2. **Eddy current loss:** Eddy current loss is due to electrical resistance loss and causes a skin effect, i.e. incomplete magnetisation of the magnetic materials, and increase in core loss from high magnetic flux density. This loss is minimised by developing a composite structure which lowers the electrical conductivity or using thin laminates parallel to the magnetic field to inhibit eddy currents being generated perpendicular to the magnetic field.
3. **Residual loss:** Residual loss is mainly observed in very low induction and high-frequency applications. This loss is relatively overlooked due to main losses arising from hysteresis and eddy current losses in power transfer devices.

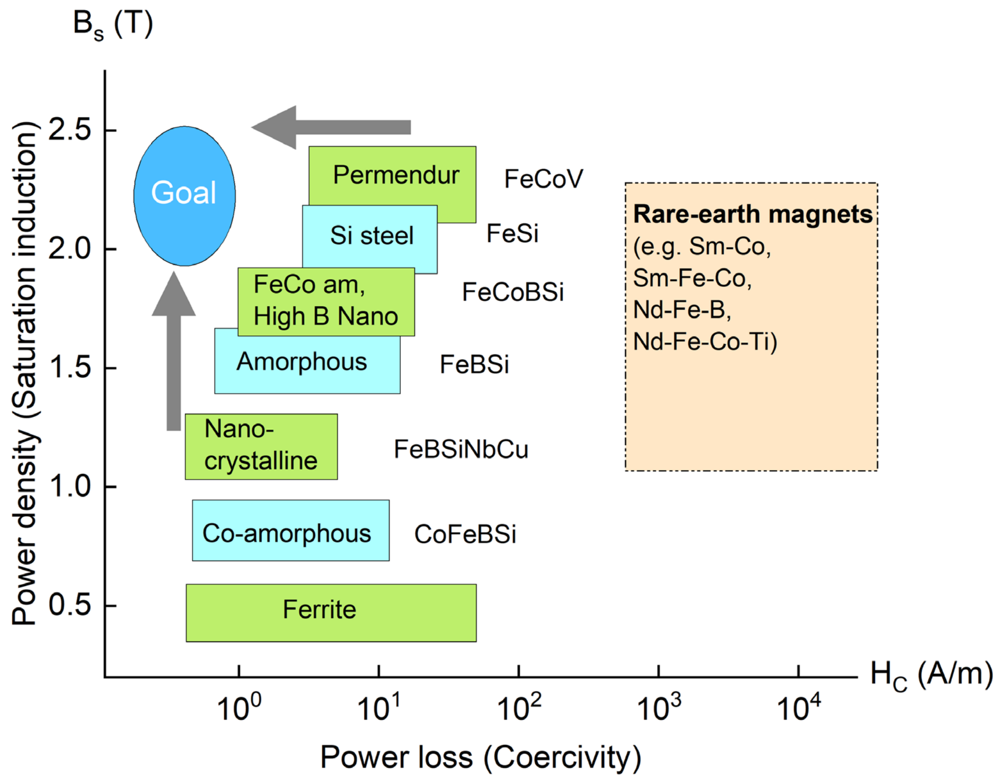


Figure 2.17 Soft magnetic materials (Theisen 2022) and rare-earth-element-based magnets (Trinh et al. 2021) categorised by power density versus power loss.

Iron-based and cobalt-based soft magnetic materials are being actively researched for power transfer applications. Figure 2.18 shows the power loss in motor stator made from silicon steel and cobalt-based amorphous magnetic materials (US Department of Energy [2024]). It is evident that the motor components manufactured from cobalt-based magnetic materials have low power losses, which are promising for designing high-efficiency electric motors. However, manufacture of these materials has been challenging due to heat-treatment responses and high mechanical hardness. Table 2.8 compares the effect of heat treatments on iron-based nanocrystalline and cobalt-based amorphous soft magnetic materials.

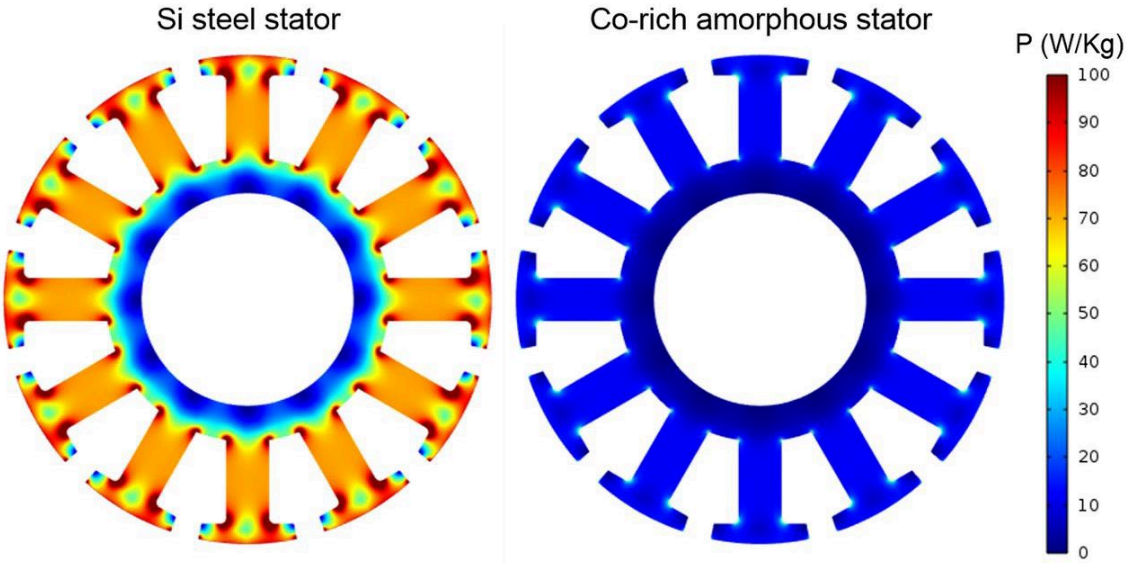


Figure 2.18 Motor stator power loss distribution in stator made of (left) silicon steel and (right) cobalt-rich amorphous alloy (Silveyra et al. 2018).

Table 2.8 Iron- and cobalt-based nanocrystalline soft magnetic materials.

	Iron-Based Nanocrystalline Magnetic Materials	**Cobalt-Based Amorphous Magnetic Materials**
References	Tahanian et al. (2020); Li et al. (2021)	Nematov et al. (2022)
Heat Treatment	Isothermal annealing at 227–427°C	Annealing at 430–560°C
Annealing Effect	• Enhancement of permeability, mainly attributed to the formation of α–Fe(Si) phase. • Structure anisotropy affects the permeability. • High-temperature annealing for a shorter time improves permeability.	• Forms a negative magnetostriction. • Enhances the circumferential anisotropy. • A change in magnetostriction sign leads to temperature-stable soft magnetic properties.

Soft magnetic materials are increasingly being researched for addressing requirement of magnetic materials with higher permeability, higher-saturation magnetisation, low coercivity, higher electrical resistivity and low loss at high frequency (He et al. 2023).

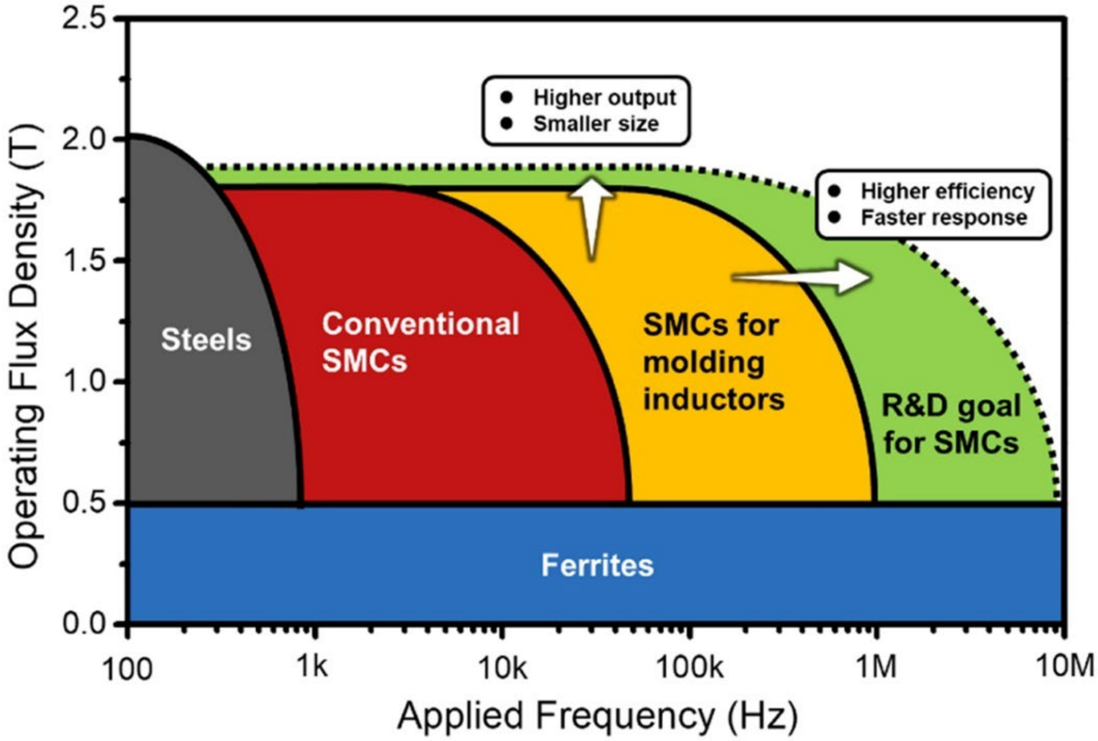


Figure 2.19 Comparison of magnetic materials and the research direction for soft magnetic materials used in alternating current magnetic fields (He et al. 2023).

Rare earth elements such as neodymium and dysprosium are required for permanent magnets used in electric motors and generators. NdFeB permanent magnets are used in electric vehicles due to a high power to weight ratio. It is estimated that electric vehicle motor traction motors will consume around 23% of permanent magnets, whereas a small portion of magnets are also used in sensors, speakers and micro-motors. Energy storage (primarily batteries) requires critical elements such as nickel, cobalt, lithium and graphite. Recently, the IEA (2024), the European Union (Bobba et al. 2023) and US Department of Energy [2024] published reports on critical minerals. The latter report on critical minerals (Figure 2.20) shows the importance and risk factors associated with the minerals used in energy applications (US Department of Energy [2024]). Rare earth elements (used for magnets) and crucial transition elements (used in storage systems) are identified to be critical minerals (Gielen and Lyons 2022; Bobba et al. 2023; Geng et al. 2023; The global… 2023; US Department of Energy [2024]). IEA's report 'Global Critical Minerals Outlook 2024' highlights the regionally concentrated suppliers and risks associated with price volatility in last decade (IEA 2024). Rare-earth-element prices seem to have fallen significantly over the course of 2023. For example, neodymium prices are estimated to have fallen by 45%. However, significant risks remain with rare-earth-element supply due to geopolitical situations.

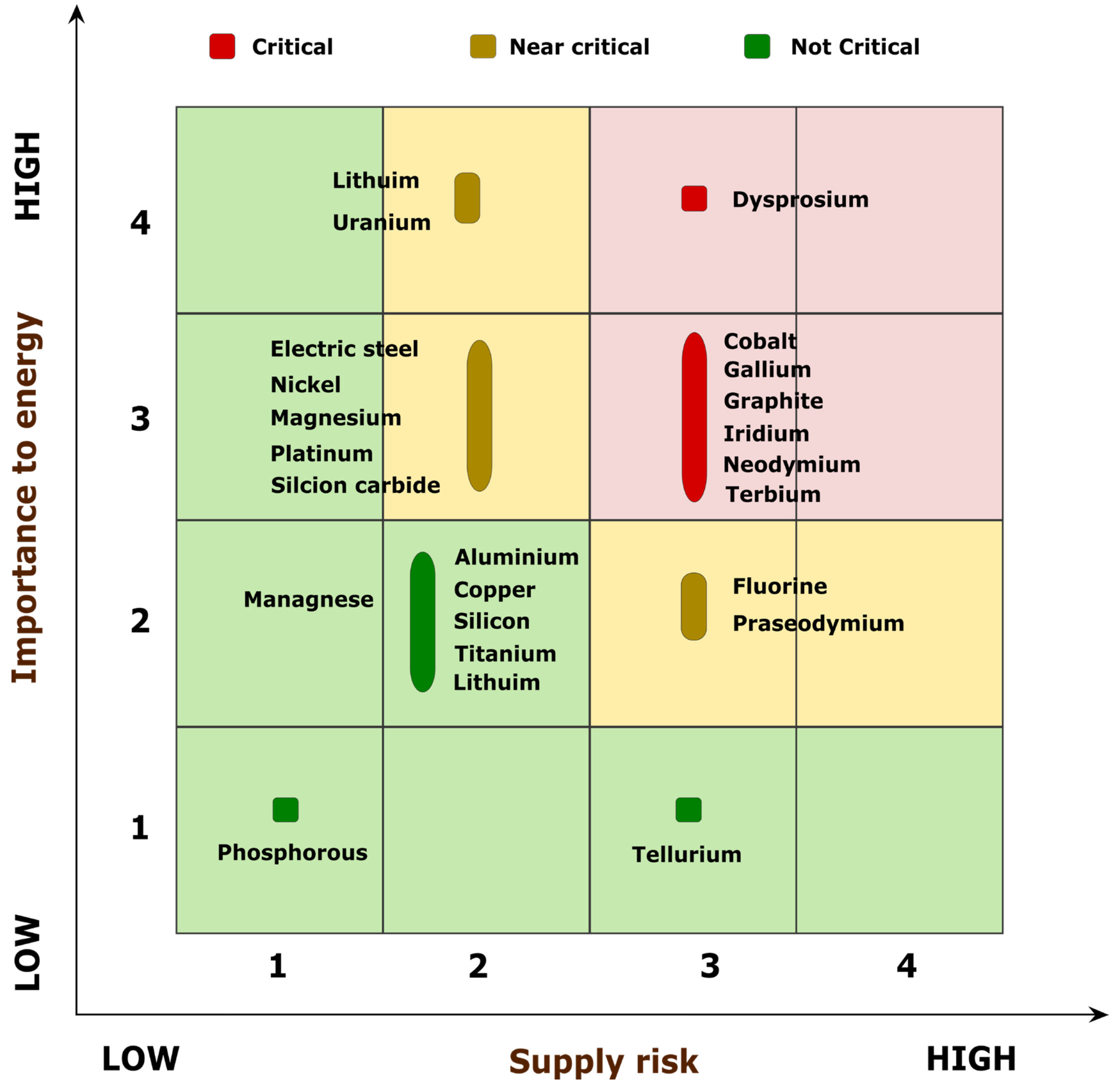


Figure 2.20 Critical minerals supply risk (US Department of Energy [2024]).

Extraction of these materials occur in countries such as the Democratic Republic of Congo, Indonesia, Australia, China, Chile, Argentina and the United States of America (Geng et al. 2024). However, China still dominates the processing of these critical elements and has a significant control on the supply chain. Recently, mixtures of induction motor and permanent magnets are being explored to reduce the dependency on rare earth elements.

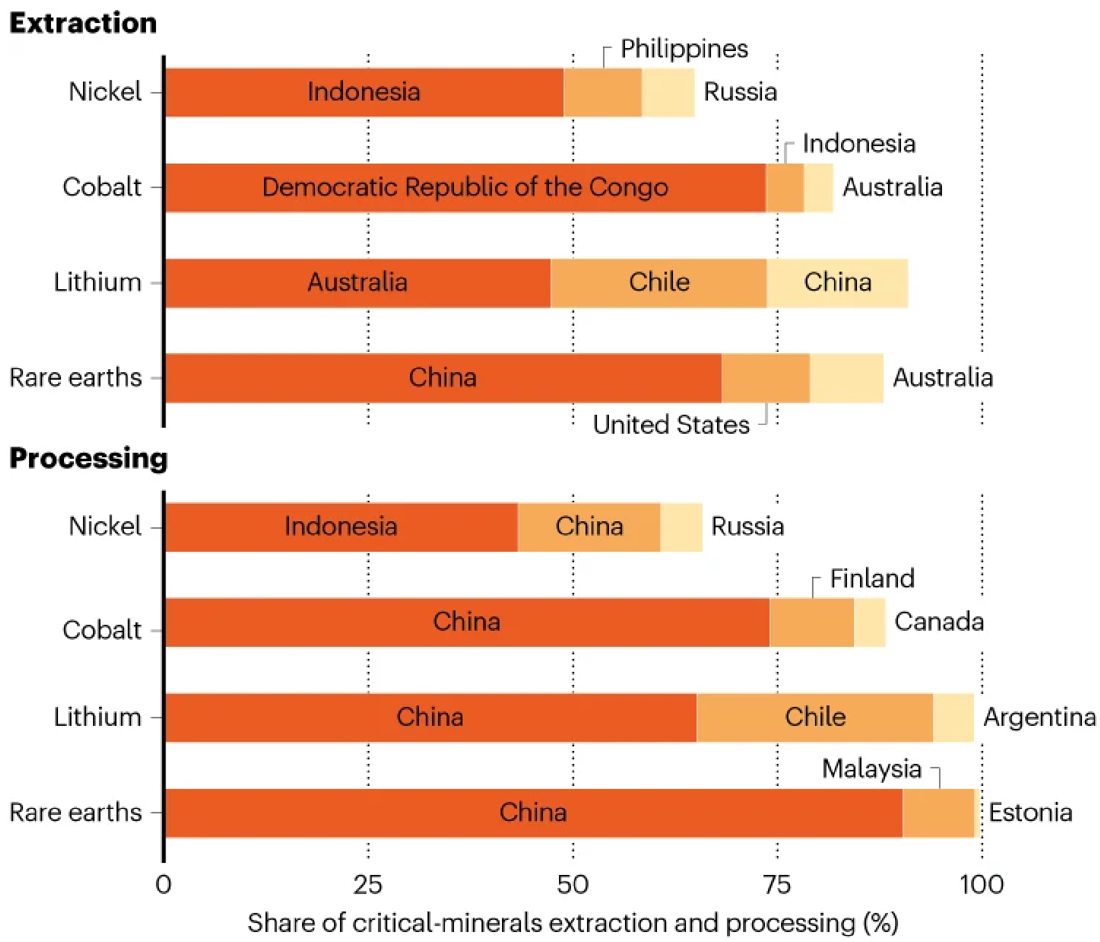


Figure 2.21 Share of critical minerals extraction and processing (Geng et al. 2023).

2.4 Complete Drive Module and Power Drive System

The CDM encompasses all of the electrical components between the power supply and electric motor. When combined with the electric motor, it forms the power drive system (PDS). The CDM includes variable speed drive (VSD) and variable frequency drive (VFD). VSD and VFD are often used interchangeably to describe the drive controllers that constitute PDS.

2.4.1 Complete Drive Module and Power Drive System Efficiency

The efficiency of CDM and PDS are covered in IEC (2014) and IEC (2023), which mentions that CDM and PDS should be evaluated at different operating conditions (see Figure 2.22). These operating points are given in terms of speed and torque, and denoted as (speed;torque), which represents the proportional share of maximum-rated torque and speed of the motors. For example, CDM should be normalised with respect to 90% frequency and 100% torque, whereas PDS should be evaluated at 100% motor speed and 100% torque. For CDM, 90% motor frequency is recommended to avoid any issues arising from over-modulation of the voltage-source inverter. $P_{L,CDM}$ and $P_{L,RCDM}$ are losses of the CDM and reference CDM (RCDM), and $P_{L,PDS}$ and $P_{L,RPDS}$ are losses of the PDS and reference PDS (RPDS), respectively (Fong et al. 2020).

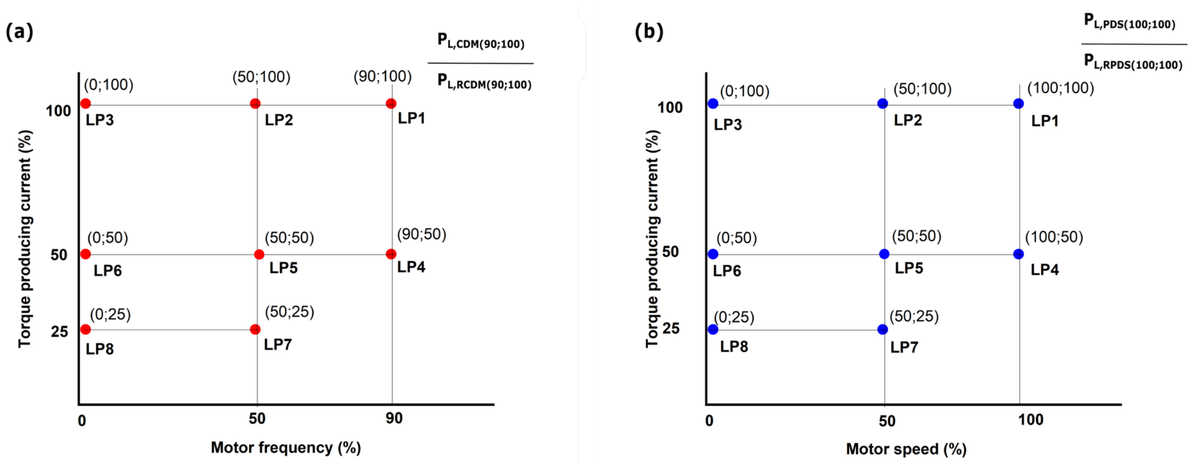


Figure 2.22 Illustration of the operating points for relative loss estimation for (a) complete drive module and (b) power drive system as set in IEC 61800-9 (IEC 2023).

IEC recommends calculating the energy loss rather than the efficiency of CDM (IEC 2017, 2024). The energy losses in CDM and PDS are determined by estimating losses from a single component and input-output measurements. Additionally, calorimetric testing is performed to determine the losses in CDM. Based on the guidelines, this can be divided into three categories: IE0 class, IE1 class and IE2 class. The IE1 class provides baseline performance, while the IE0 and IE2 classes represent 20% higher and lower power losses, respectively.

- **IE0 class:** $P_{L,RCDM}$ are at least 20% higher than $P_{L,RCDM}$.
- **IE1 class:** $P_{L,CDM}$ are within ±20% of $P_{L,RCDM}$.
- **IE2 class:** $P_{L,RCDM}$ are at least 20% lower than $P_{L,RCDM}$.

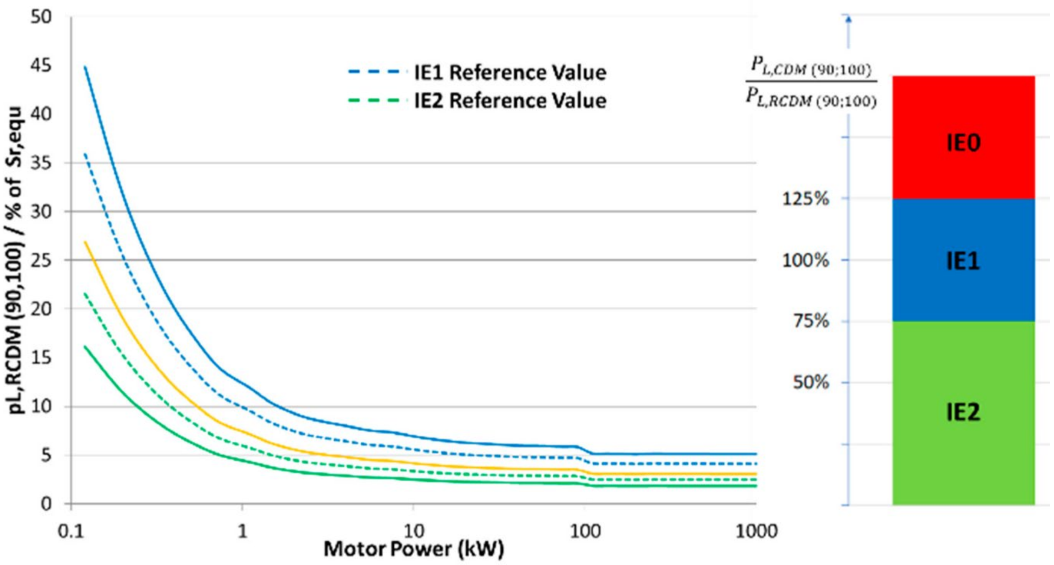


Figure 2.23 Efficiency levels and IE-classes for complete drive modules (IEC 2017, 2024; Fong et al. 2020).

The selection of load points to estimate energy losses depends on the electric motor applications. For example, in centrifugal pumps and applications, the losses are proportional to the quadratic-square of torque. The load points (100;100), (100;50) and (50;25) can be used to estimate the losses for such applications. For motor applications that require constant torque, such as conveyer belts and hoisting machines, load points (100;100), (50;100) and (0;100) can be used to estimate losses. For motor applications such as mixers and drivers that require constant power motors, the load points (0;100), (50;50) and (100;50) can be used for energy loss determination.

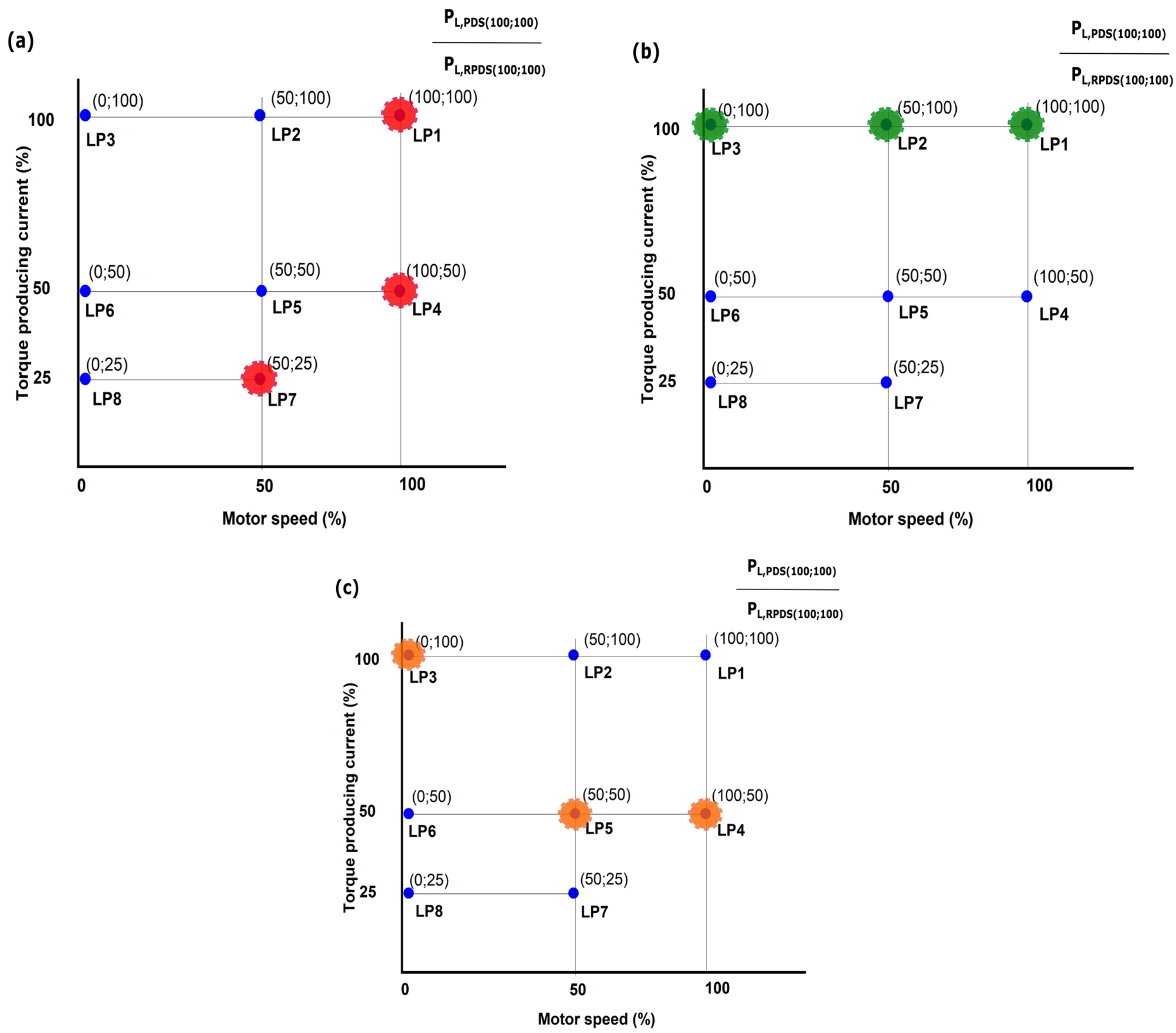


Figure 2.24 Load points for loss estimation for (a) variable load (red circles), (b) constant torque (green circles) and (c) constant power (orange circles) motor applications.

An example of PDS energy losses for SCIM (squirrel-cage induction motor) IE3 and SynRM IE5 electric motors is shown in Figure 2.25, reported by Fong et al. (2020). PDS efficiency (or losses) depends on electric motor efficiency and duty cycles (speed and torque profiles). There are significant differences in the PDS efficiency for speeds lower than 60%, whereas, above this threshold speed, the PDS efficiency does not vary substantially up to the maximum rated speed. The motor efficiency plays an important role on PDS efficiency, as evident in Figure 2.26, which shows PMSM-IE5 better across the whole range.

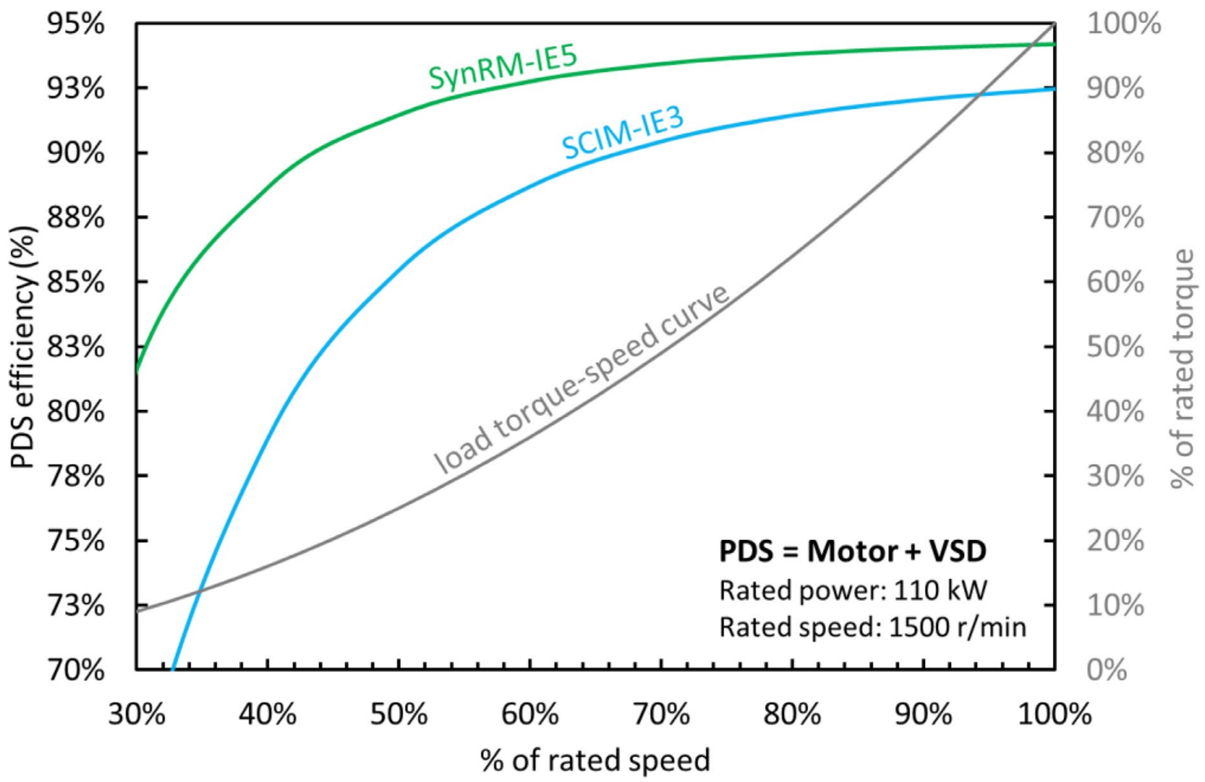


Figure 2.25 Comparison of variable speed drive (VSD)-controlled IE3 and IE5 SynRM motors efficiency (Fong et al. 2020).

The PDS energy losses for SCIM IE3, SCIM IE4, SynRM IE5 and PMSM IE5 motors are estimated for various load points for PDS loss comparison. PDS loss for three-phase 7.5 kW motor data is taken from Fong et al. (2020), shown in Table 2.9 and plotted in Figure 2.26. The PDS losses are below 6% for duty cycles up to (75;50) for IE3 motors. However, at the maximum rated (speed;torque), the PDS losses are up to around 14%. Similar trends are observed for SCIM IE4, SynRM IE5 and PMSM IE5 motors, where higher loads show high PDS loss.

Table 2.9 Comparison of power drive system energy losses for IE3, IE4 and IE5 motors (Fong et al. 2020).

(Speed;Torque)	IE3	IE4	SynRM IE5	PMSM IE5
(25;12.5)	2.2%	2.2%	1.1%	1.4%
(50;25)	3.8%	3.6%	2.4%	2.1%
(75;50)	5.9%	5.4%	4.8%	3.6%
(100;100)	13.8%	11.2%	10.9%	7.3%

Across all the load points, PMSM IE5 shows the lowest PDS losses compared to SCIM IE3, SCIM IE4 and SynRM IE5 motors, suggesting its suitability for applications requiring variable loads. PMSM motors generally show higher efficiency compared to SynRM (Artetxe et al. 2021).

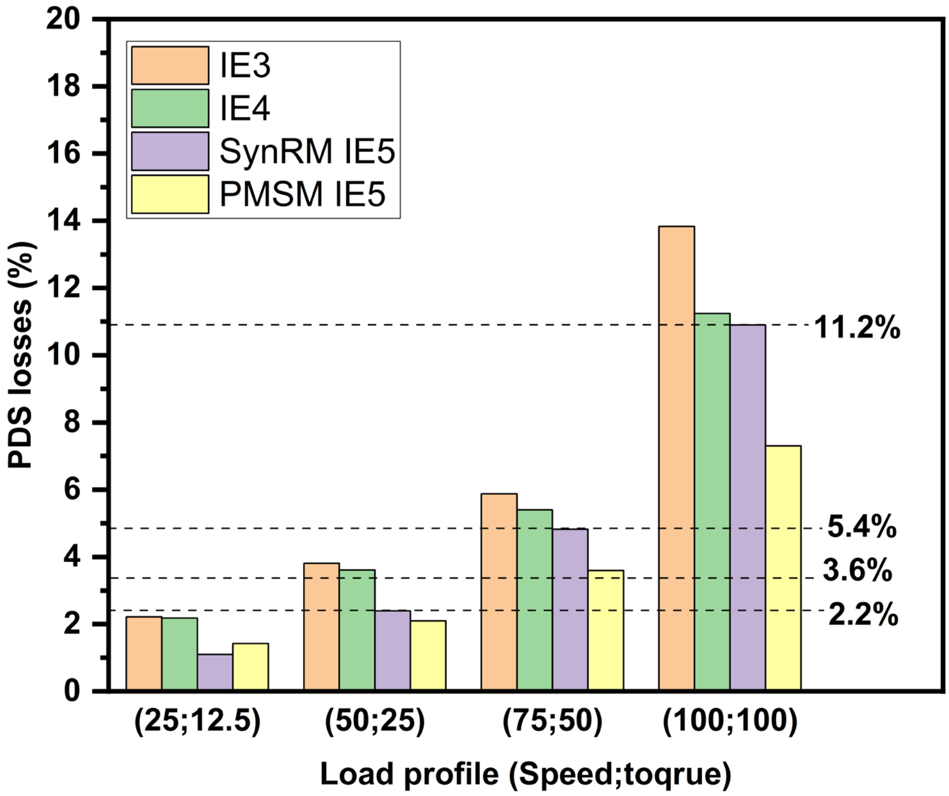


Figure 2.26 Comparison of power drive system losses in electric motors (Fong et al. 2020).

The implementation of VFDs depends on motor applications and payback time. For example, Kapp et al. (2024) reported an industrial energy audit for VFD-controlled motors. They presented case studies on the performance of VFDs in hydraulic motors, process-cooling water pumps and blower operations and found that energy savings using VFDs for variable and constant loads varied across different applications, as shown in Figure 2.27. The adoption of VFDs depends on the initial cost, which affects the payback time. Figure 2.28 shows that motor VFDs have a much higher cost and longer payback time compared to compressed air VFDs.

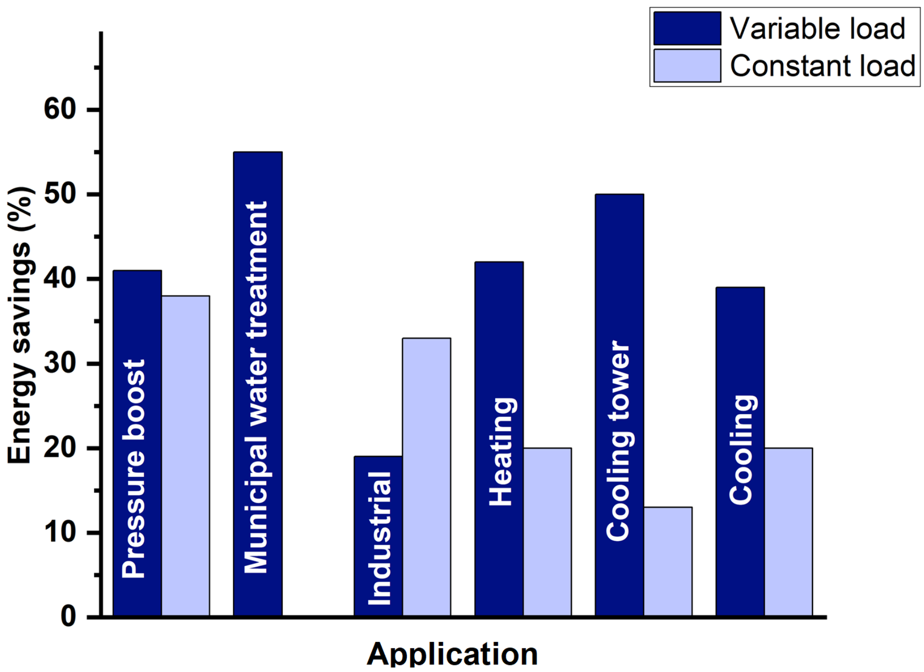


Figure 2.27 Energy savings for various applications at variable and constant load (adapted from Cadeo Group [2020]).

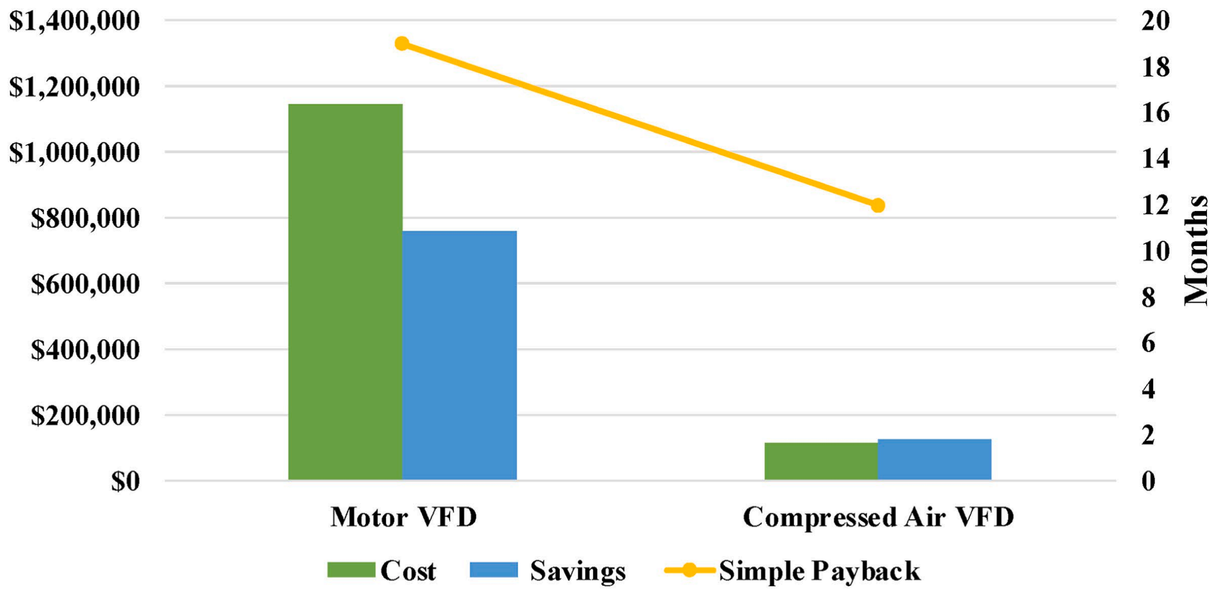


Figure 2.28 Energy savings and payback time for motor and compressed air using VFDs (Kapp et al. 2024).

2.4.2 Power Controller between Inverter and Motor – Wide Band-Gap Semi-Conductors

The inverter or power controller is responsible for converting the electricity input into a suitable electronic signal for the motor. These should deliver frequency, voltage and current with minor losses, as well as minor ripples for high stability. For lowest losses during the conversion from electrical to mechanical energy, an inverter should be used to match the load for optimal efficiency. A delay in the electrical signal could cause a delay in motor operation. The optimal operation condition is determined by a suitable mechanical structure. Sensors are employed to monitor vibrations that can be used to optimise energy efficiency during the system lifetime. The advantages and disadvantages of feedback-cycle technologies are discussed in Section 2.4.3.

The basis of power conversion electronics are semi-conductors and transistors. The technologies can be classified into designs of MOSFET (metal-oxide-semiconductor field effect transistor) and IGBT (insulated gate bipolar transistors) (Zhang et al. 2022; Mariani 2023). The operating envelopes of thyristor, IGBT, vertically diffused MOSFET and laterally diffused MOSFET are shown in Figure 2.30. The second separation is based on materials, specifically the employed wide band-gap semi-conductors, summarised in Table 2.10.

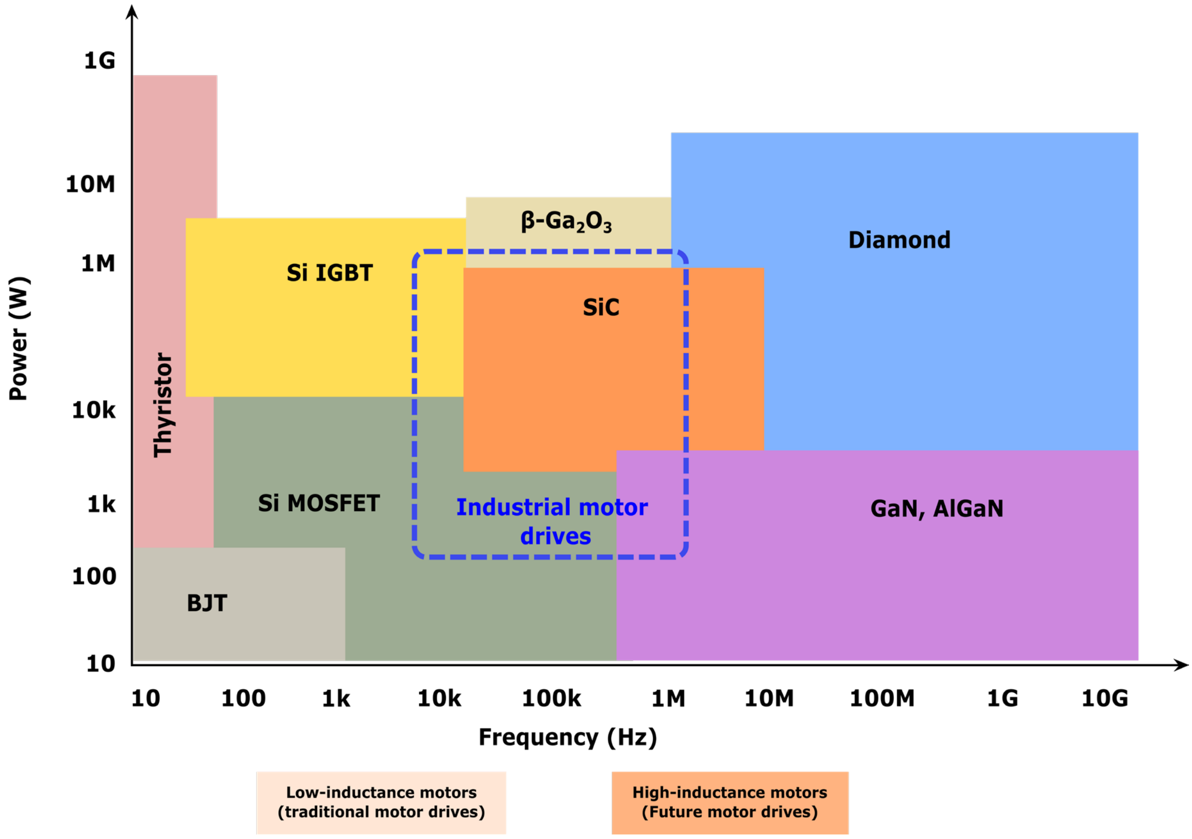


Figure 2.29 Motor drives' switching technologies positioning (Zhang et al. 2022).

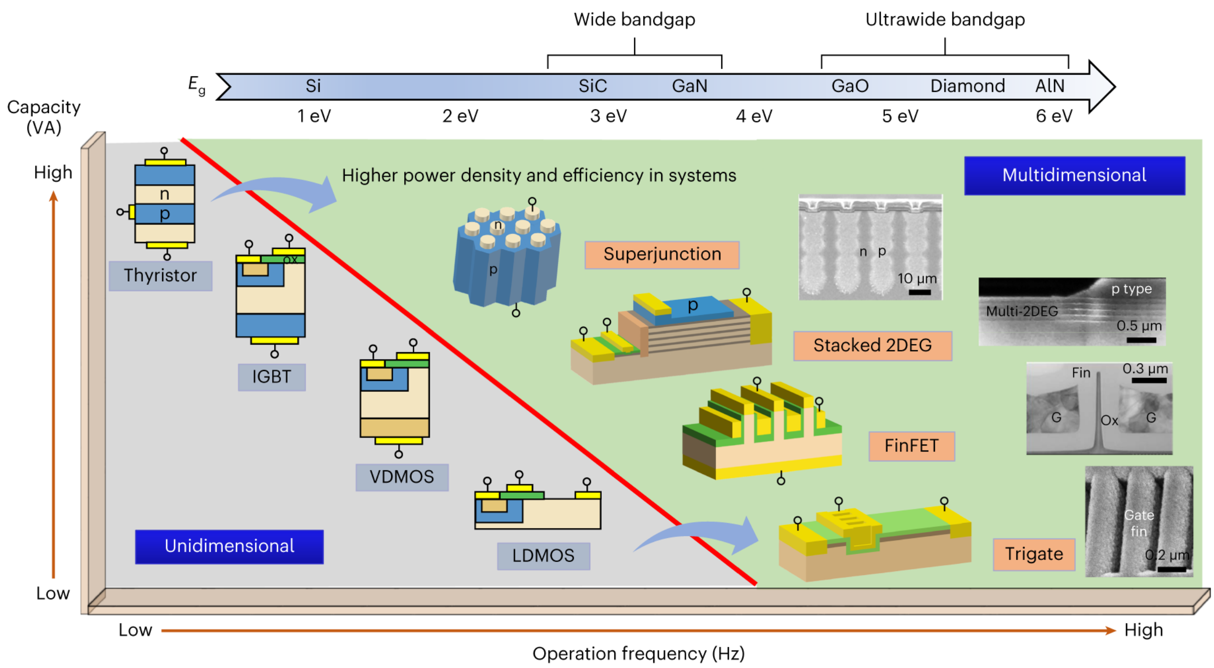


Figure 2.30 Schematic of thyristor, IGBT, vertically diffused MOSFET (VDMOS) and laterally diffused MOSFET (LDMOS) (Zhang et al. 2022). The red line illustrates the approximate limit of 1D power devices (Geng et al. 2023)

Performance of wide band-gap and ultra-wide band-gap semi-conductors is based on their band gap, electron mobility, thermal conductivity, on-resistance and maximum operating frequency (Armstrong et al. 2016; Ballestín-Fuertes et al. 2021; Meneghini et al. 2021; Gupta and Pasayat 2022; Zhang et al. 2022; Mariani 2023). Various figures of merit are commonly used to compare the performance of wide band-gap and ultra-wide band-gap semi-conductors, as follows (Ballestín-Fuertes et al. 2021):

- **Baliga's Figure of Merit (BFOM):** This parameter determines conduction loss, which is based upon the assumption that power losses are dominated by dissipation due to current flow through the on-resistance of the power device.
- **Johnson's Figure of Merit (JFOM):** This parameter defines the power-frequency product. It is commonly used to determine the frequency capability for a transistor.
- **Huang's Material Figure of Merit (HMFOM):** This parameter determines the best material for high-frequency applications.
- **Keyes' Figure of Merit (KFOM):** This parameter provides a thermal limitation of the transistors used in semi-conductor devices.
- **Huang's Thermal Figure of Merit (HTFOM):** This parameter determines maximum working temperature and breakdown voltage. This is particulary usfeul to design smaller devices and therefore small packages for a lower heat dissipation.

Table 2.10 Material properties for Si, 4H-SiC, GaN, β-Ga_2O_3, diamond and AlN (Armstrong et al. 2016; Ballestín-Fuertes et al. 2021; Meneghini et al. 2021; Gupta and Pasayat 2022; Zhang et al. 2022; Mariani 2023).

Material Property	Symbol (Unit)	Si	4H-SiC	GaN	β-Ga_2O_3	Diamond	AlN
Band gap	E_g (eV)	1.12	3.23	3.4	4.9	5.5	6.2
Relative dielectric permittivity	ε_r	11.7	9.66	8.9	10	5.7	8.5
Critical electric field	E_{crit} (MV/cm)	0.3	2.5	3.3	8	10	15
Electron mobility	μ (cm^2/Vs)	1440	950	1400	250	4500	450
Electron saturation velocity	v_s (10^7 cm/s)	1	2	2.4	1.1	2.3	1.4
Thermal conductivity	κ_{th} (W/mK)	130	370	250	10-30	2300	285
Maximum operation temperature	T_{max} (°C)	175	600	400	600	700	250
Switching frequency in high-power applications	JFOM	1	10.1	6.5	23.2	29.6	22.3
Keyes' Figure of Merit	KFOM	1	3.3	0.8	0.2	1.9	21.0
Baliga's Figure of Merit	BFOM	2	13.8	18.9	9.7	25.0	82.0
Huang's Material Figure of Merit	HMFOM	1	8.7	9.0	9.8	18.0	26.1
Huang's Chip Area Figure of Merit	HCAFOM	1	76.6	69.3	223.4	523.3	241.9
Huang's Thermal Figure of Merit	HTFOM	1	0.35	0.11	0.01	0.07	1.46
Feasibility of these products on the market, availability of raw material and manufacture of high-quality wafers	Availability	5	4	2	2	2	1
Estimated device-production (doping, packaging, etc.) costs	Manufacturing	5	4	3	2	1	1

Figure 2.31 shows the performance factors of the key parameters wide band-gap and ultra-wide band-gap semi-conductors, normalised with GaN. Wide band-gap semi-conductors, i.e. GaN and SiC, are devices that are commercially available and used in high-performance electronics applications.

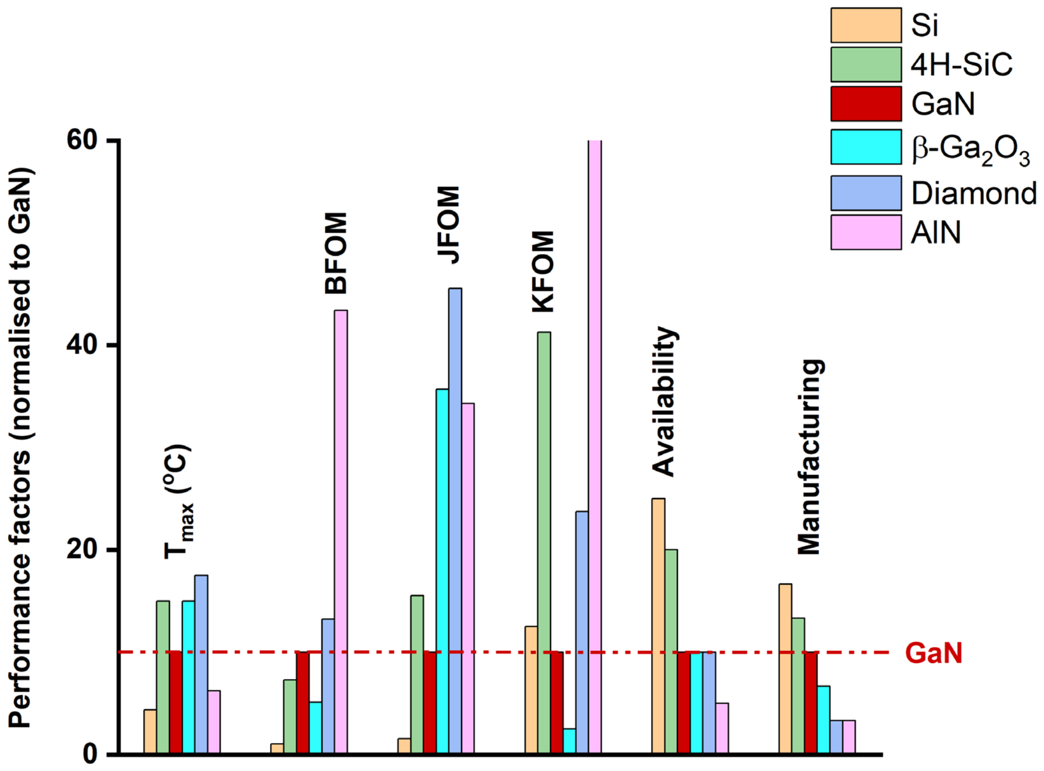


Figure 2.31 Comparision of material's key performance factors. All values are normalised to GaN (Armstrong et al. 2016; Ballestín-Fuertes et al. 2021; Meneghini et al. 2021; Gupta and Pasayat 2022).

Energy efficiency of devices depends on the choice of wide band-gap or ultra-wide band-gap semi-conductors and system-level design (Armstrong et al. 2016). Figure 2.32 shows how materials' inherent properties impact the performance of electronic devices.

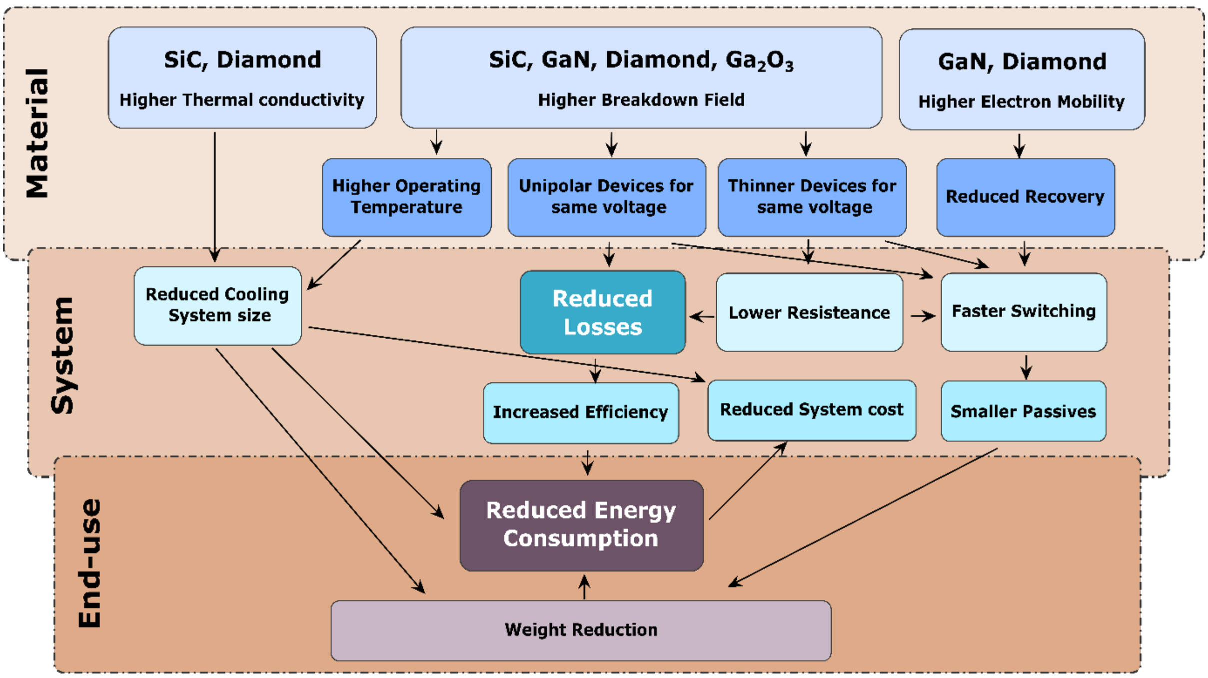


Figure 2.32 Impact of materials' properties on device, system and application performance (Armstrong et al. 2016).

Figures 2.32 and 2.33 show the key parameters and availability of common wide band-gap and ultra-wide band-gap semi-conductors. Wide band-gap semi-conductors, i.e. GaN and SiC, are commercially available devices that are used in high-performance electronics applications. However, ultra-wide band-gap semi-conductors (β-Ga_2O_3, diamond, AlN) are still at research and development levels due to challenges associated with ambipolar doping, lack of suitable substrate and growth of high-quality materials (Seppänen et al. 2019; Perez et al. 2020; Tetzner et al. 2020; Ballestín-Fuertes et al. 2021; Qin et al. 2023).

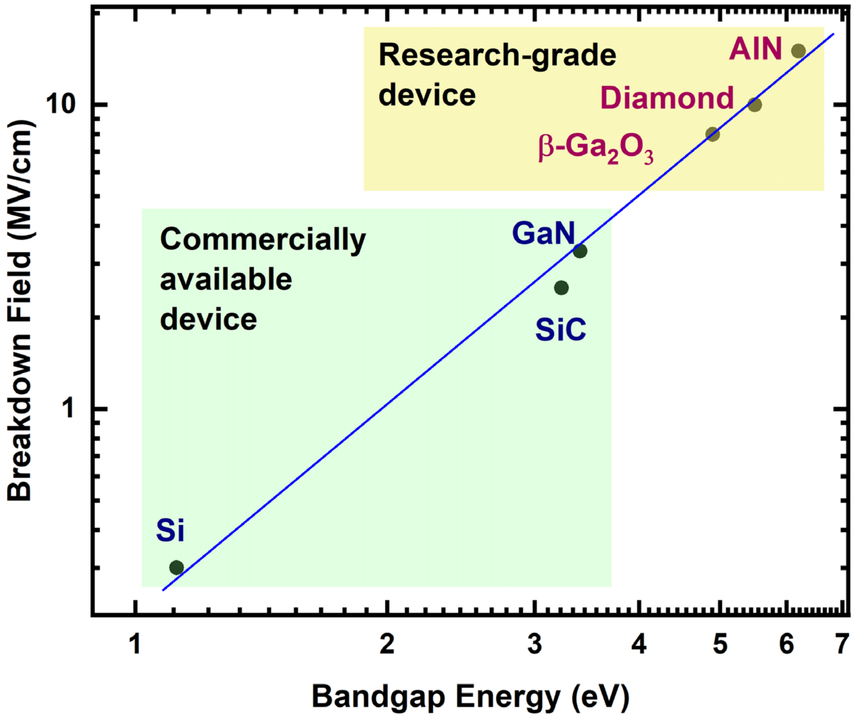


Figure 2.33 Band-gap energy and breakdown field of semi-conductors (Cadeo Group 2020; Zhang et al. 2022; Mariani 2023; Kapp et al. 2024).

Figures 2.34 and 2.35 show the overall losses for a specific motor. While the mechanical impact of motor losses generally reduces with switch frequency as it enhances motor stability, the losses of the inverter increase with switching frequency, which results in an optimum of the motor efficiency from balancing these two parameters.

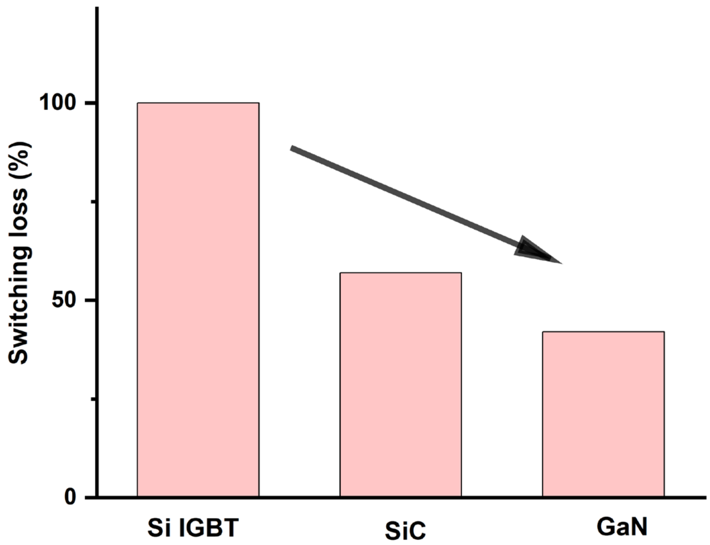


Figure 2.34 Switching loss comparison of Si-IGBT-, SiC- and GaN-based switches (Mariani 2023).

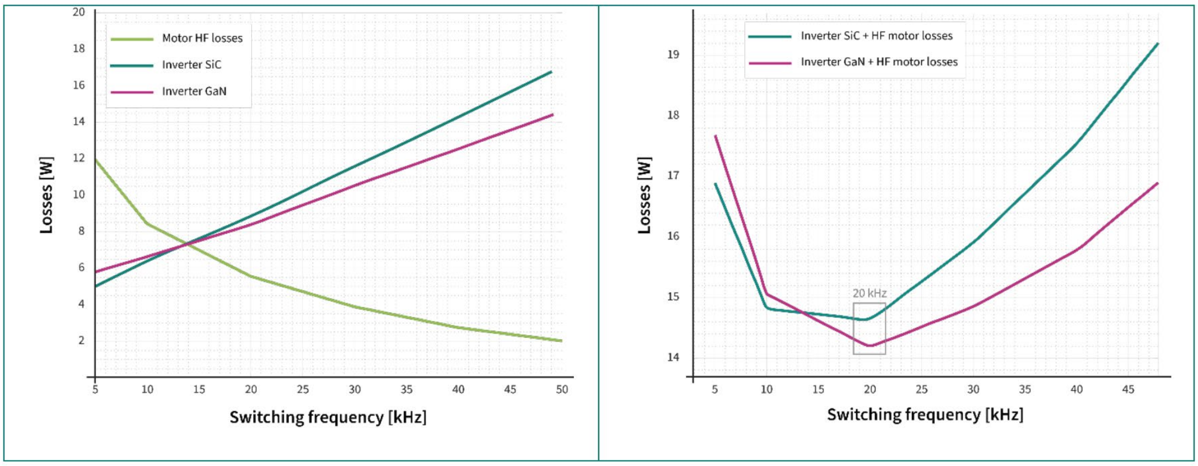


Figure 2.35 Example for motor efficiency with switching speed (Mariani 2023).

Thermal management has been a key challenge, with demand for more efficient and shrinking electronic devices (Qin et al. 2023). This provides opportunities for device-level, package-level and thermal management designs. Table 2.11 shows the problems, solutions and research opportunities for wide band-gap and ultra-wide band-gap devices.

Table 2.11 Thermal management in wide band-gap and ultra-wide band-gap devices (Qin et al. 2023).

	Problems	**Solutions**	**Research Opportunities**
Device Level	Heat generation at the device junction	• New device structure/ layout design • Heterojunction design using high thermal conductivity substrate	• Device-package co-design • Electro-thermal co-design • Thermal boundary optimisation
Package Level	Heat dissipitation	• Bottom-side or junction-side package • Double-side package	• Develop high-temperature package using new composite materials • Improve thermal and mechanical robustness
Heat Sink	Heat transfer	• High thermal conductivity substrate	• Develop high thermal conducitivity substrate, e.g. AlN

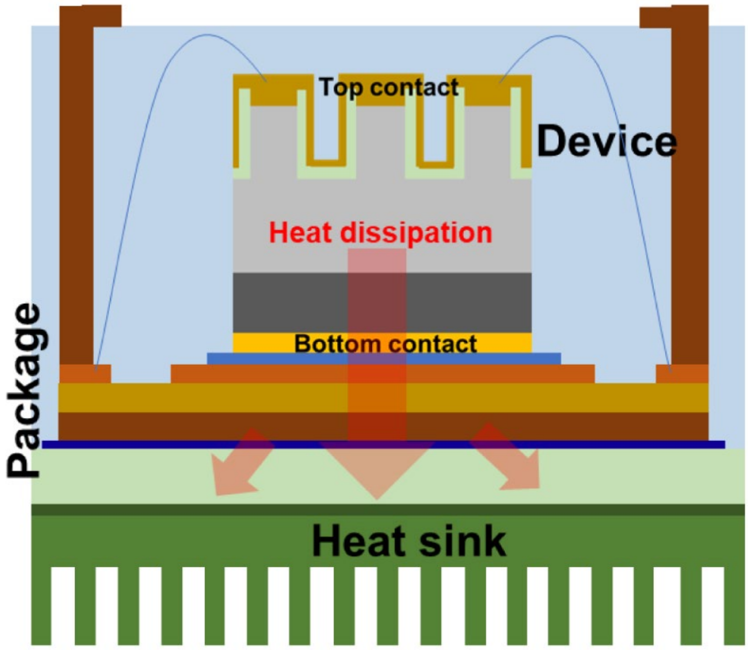


Figure 2.36 Scheamtic of thermal management and packaging of wide band-gap and ultra-wide band-gap devices (Qin et al. 2023).

Figure 2.37 gives a 'roadmap' of likely technology developments for different applications. For low-powered motors with <10 kW power and a comparable low switching speed, the cost savings of established silicon technology is paramount, with an excellent efficiency. However, at high switching speed and high power densities, switching and conduction losses start to dominate due to the limited electron-mobility and heat dissipation, respectively. The two commercialised technologies with wide-bandgap semi-conductors are GaN-based HEMT (high electron mobility transistors), which minimise switching losses between the load. Thus, for frequencies >200 kHz, GaN is the current material of choice. For example, Infinion's CoolGaN™ transistor series is specified for powers up to 54 kW with a low switching capacitance down to 1.2 nC for the IGLR60R340D1 transistor, which only causes half (43%) of the switching losses of comparable silicon technology and gives an efficiency of 98.8% at the optimal switching frequency. That technology already incorporates AlGaN, which has a higher electron mobility than GaN and represents a step in the transition to AlN with an even further enhanced electron mobility (Geng et al. 2023). However, to the best of our knowledge, AlN-based HEMT technology is not commercialised yet and is currently at TRL5.

Other technologies that are not mature yet but with promising research progress are Ga_2O_3 (TRL5) (Tetzner et al. 2020) and diamond-based technology (TRL4) for high temperature applications (Seppänen et al. 2019).

The main drawback of GaN technology is the similarly low thermal conductivity as silicon. Thus, at high power densities and high frequencies, thermal dissipation causes significant efficiency losses. Thus, for these applications, SiC MOSFETs that are more efficient at higher powers, such as IMW120R045M1/IMZ120R045M1 were developed, which operate at 1200 V. These extend the operational power at optimal efficiency to motors that require higher loads.

An overview of the technology readiness for several wide band-gap technologies and their application and emerging market share was published by the International Energy Agency in 2020 (Fong et al. 2020). Indeed, the reports of companies from 2023 confirm that the significant penetration of these technologies in 2023 has occurred as envisioned.

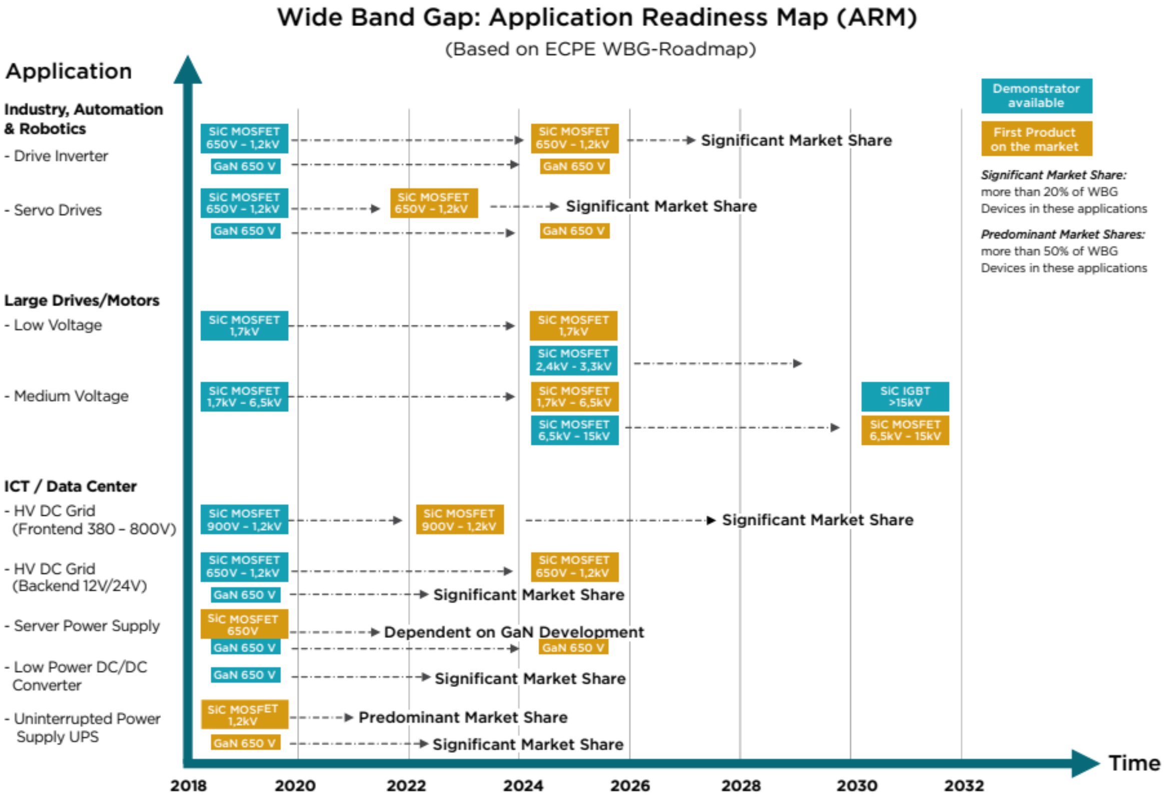


Figure 2.37 Market penetration of wide band-gap high-power electronics conversion systems into applications (PECTA 2020).

2.4.3 Software Optimisation through Microcontrollers

A microcontroller is used to power-match the actual uses of the motor with an integrated energy management system. The aim of this process is to immediately adjust the varying power requirements of the application to the power delivery of the electronics and the motor. A high-level overview of this principle is shown in Figure 2.38a.

Optimisation of the operational efficiency is based on integrated energy management strategy, with the applied logic being rule-based, optimisation-based and learning-based, as shown in Figure 2.38b (Tran et al. 2020).

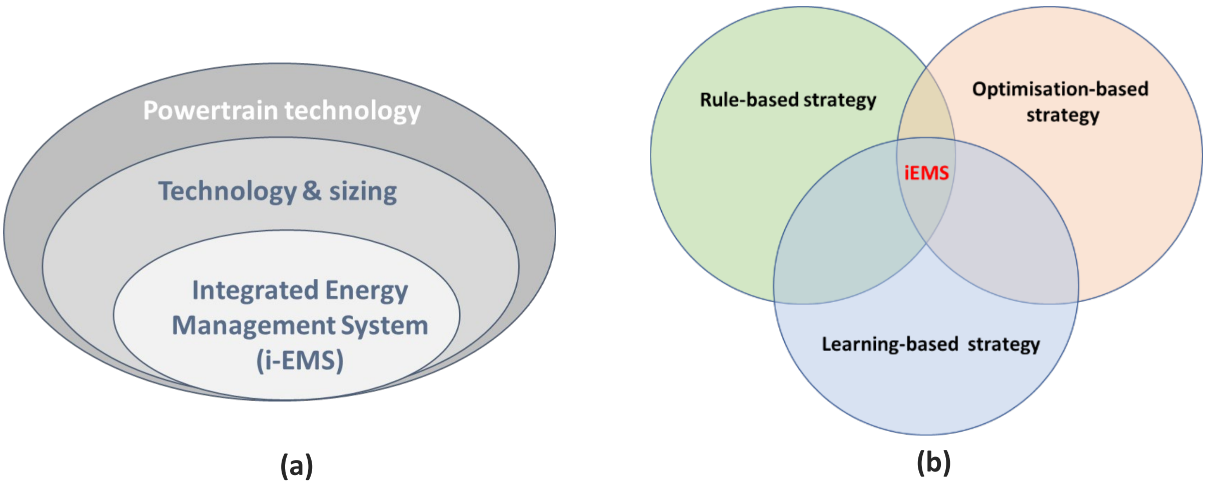


Figure 2.38 (a) System-level design and (b) classification of energy management strategies (Tran et al. 2020).

Rule-based logic is simple and easy to implement but will likely not find the optimum efficiency. In contrast, learning-based approaches (such as digital twins) (Bhatti et al. 2021) can yield high optimisations but are computationally expensive. Optimisation attempts to find a trade-off between complexity and efficiency opportunities (EMSA [2024]).

These intelligent control systems and their subsequent analysis (EMSA [2024]) relies on accurate reliable sensors that have an electricity saving potential of 5–10% in motor-driven systems (EMSA [2024]; IEA 2024). Such control sensors measure the speed, temperature and vibrations of motor-driven equipment and the energy consumption of the power supply or dedicated process parameters such as pressure, moisture and gases, which are used as a proxy for the system's energy efficiency and health. Slight deviations in operation conditions can thus be rectified by performing predictive maintenance (reduced maintenance costs), improving operation by selectively tuning the speed, power and performance of a motor for optimal production and energy efficiency (EMSA [2024]). However, barriers to uptake include cost and difficulties with collecting clean data in industrial environments.

2.5 Energy Efficiency Index

The Energy Efficiency Index (EEI) is useful in determining efficiency in an extended product approach (Figure 2.39) (Fong et al. 2020; IEA 2017, 2024). In this, the EEI is calculated by considering the time taken at different operating points, as highlighted in Sections 2.1 and 2.5. EEI is given as:

$$EEI\ (\%) = \frac{\sum_i \left(P_{L,i} . T_i\right)}{P_{L,ref}}$$

where $P_{L,i}$ is the load profile at i^{th} operating condition and T_i is operation time (%).

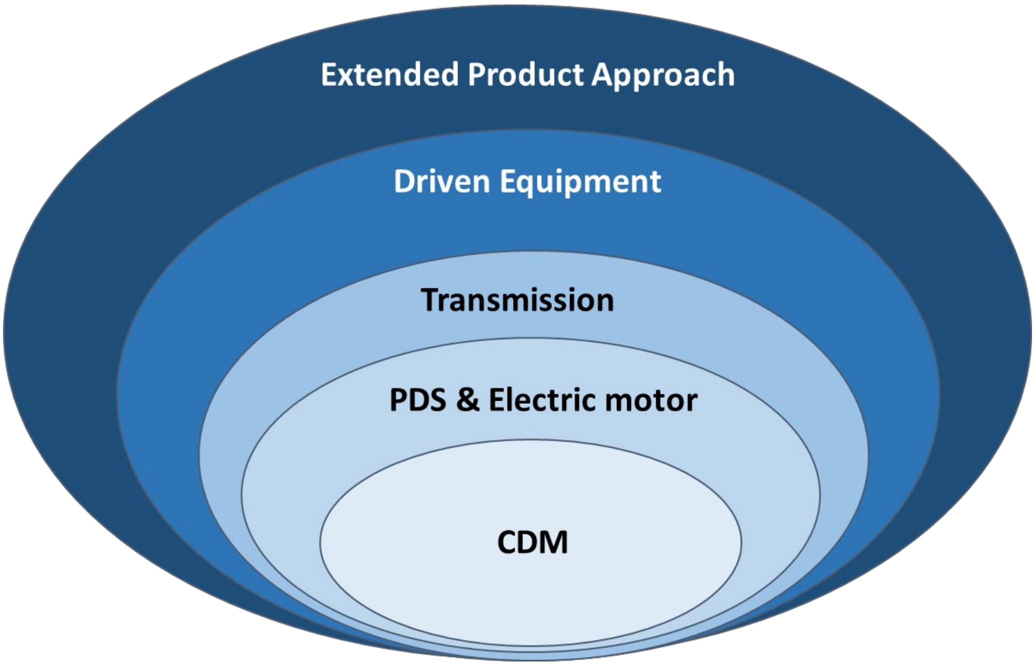


Figure 2.39 Extended product approach to which the Energy Efficiency Index is applied (Fong et al. 2020).

3.0 ELECTRIC MOTORS IN NEW ZEALAND AND SCENARIO / COST-BENEFIT ANALYSIS

This section explores several scenarios for improving the energy efficiency of electric motor-driven systems in New Zealand. Electric motors in New Zealand commercial and industrial sectors are found in pumps, fan units, compressors, conveyors and various other applications. The total stock in New Zealand is around 469,000 electric motors, with a capacity of around 4.0 GW. Among them, 97% are less than 30 kW in size, occupying around 80% share of industrial motors. The 60–330 kW electric motors are mainly found in industry, with capacity of around 1.6 GW. It has been reported that the life cycle of low-power motors is 10 years, mid-power motors is 15 years and high-power motors 20 years (Rao et al. 2022).

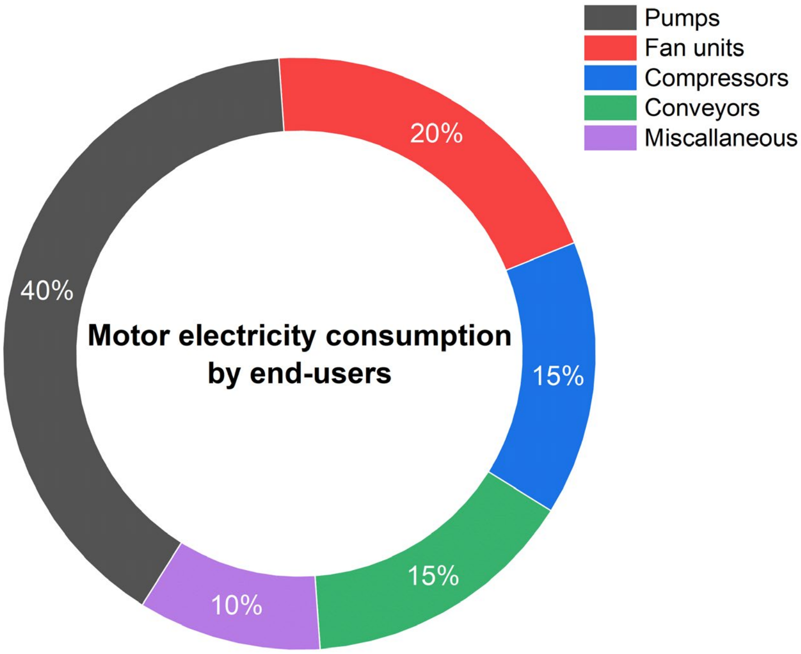


Figure 3.1 Electricity consumption of electric motors by end users (EECA c2024).

3.1 Comparison of Electric Motors

The previous sections have shown that electric motors are a part of larger electric motor system, and each component of this system must be optimised for maximum efficiency gain. Table 3.1 provides a comparison of the key factors affecting energy efficiency for the electric motors selected in this report. The key factors cover the availability of latest electric motor technology, cost and sustainability of the materials used in designing various components of electric motor systems.

Induction motors still make up the biggest share of industrial applications owing to their simplicity, easy maintenance and durable performance. Increasing demand for energy savings and rapidly developing electronic devices make efficient electric motors such as SynRM increasingly appealing.

It is envisaged with that, with emerging electric motor technology, innovation in tandem with regulatory initiatives will propel the use of highly efficient electric motor systems to contribute toward achieving emissions goals.

Table 3.1 Comparison of electric motor technology. BLDC = brushless DC; PMSM = permanent magnet synchronous motor; SynRM = synchronous reluctance motor; PMSynRM = permanent magnet synchronous reluctance motor; CDM = complete drive module.

Electric Motor	BLDC Motor	Induction Motor	PMSM	SynRM	PMSynRM
Typical motor efficiency	IE4	IE1–IE4	IE3–IE4	IE3–IE4	IE4–IE5
CDM required	Yes	Yes	Yes	Yes	Yes
Power density (kW/kg)	High	Low	High	Medium	Medium
Motor cost	High	Low	High	Low	Medium
CDM cost	-	Low	Low	Medium	Low
Rated power factor	High	Medium	High	Low	Medium
Efficiency reduction at partial torque/speed	High	Medium	High	High	High
Motor reliability and robustness	Medium	High	Medium	Medium	Medium
Rare-earth-element permanent magnet	Yes	No	Yes	No	No
Life-cyle time	Medium	High	Medium	High	Medium
Technology readiness level (TRL)	8–9	9	8	7	6–7

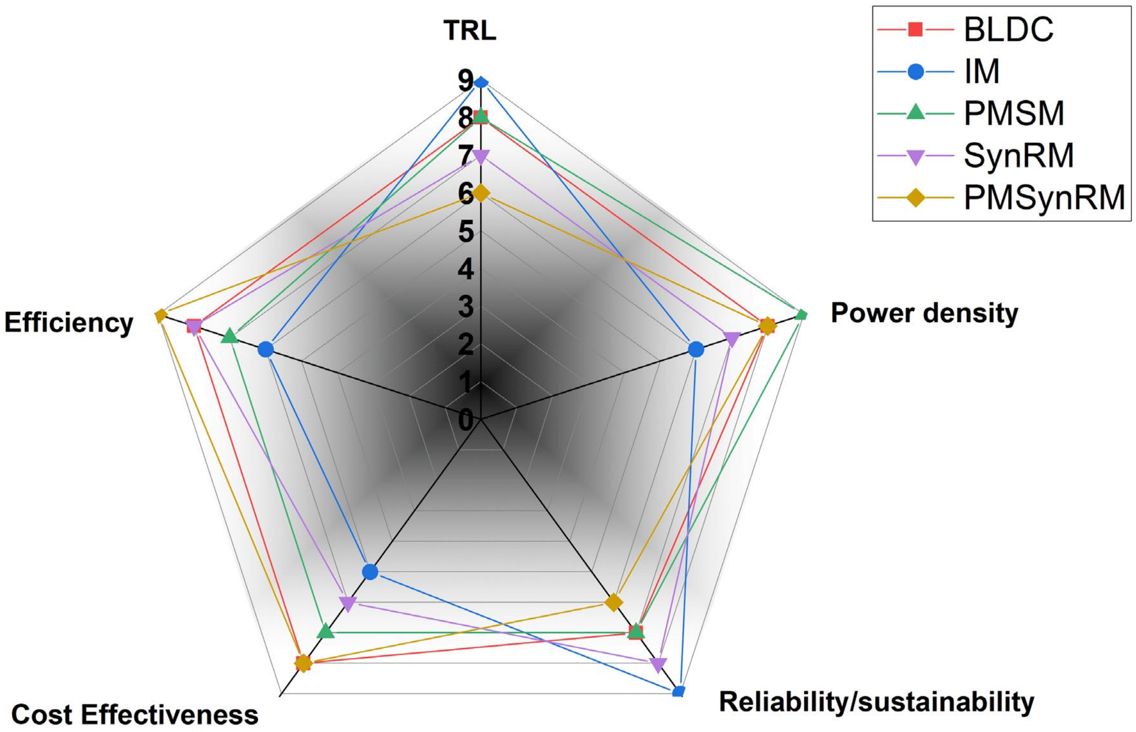


Figure 3.2 Comparison of electric motor performance. BLDC = brushless DC; IM = induction motor; PMSM = permanent magnet synchronous motor; SynRM = synchronous reluctance motor; PMSynRM = permanent magnet synchronous reluctance motor; TRL = technology readiness level.

3.2 Scenario Analysis Assumptions

This section examines the cost-benefit analysis of using emerging electric motors and power electronics for electric motor applications. The important factors for improving efficiency of electric motor systems are that these should be operated in correct load, use PDS[4], be the correct size, reduce idle time and have a proper energy audit so that correct selection of motor systems equipment can be undertaken to achieve full energy efficiency potential for economic and emission benefits. These could lead to:

- Reduced maintenance.
- Reduced down-time.
- Improved reliability.
- Higher flexibility.
- Reduced production time.
- Reduced production loss.
- Increased productivity.
- Increased quality control.

Energy saving, ΔE, is estimated for electric motors using IE2, IE3, IE4 and IE5 electric motors. Three scenarios are considered for estimating the energy savings:

1. Relacing IE2–IE5 class electric motors.
2. Using PDS-based IE2 and IE3 motors.
3. Replacing IE2 with IE3 motors in New Zealand industries.

3.2.1 Scenario Analysis and Cost Benefits for IE2, IE3, IE4 and IE5 Motors

New Zealand currently roughly follows the IE2 MEPS guidelines (MBIE 2024). There could be significant energy savings upon adoption of higher-efficiency electric motors. Figure 3.3 shows the energy-saving (ΔE) potentials when higher-efficiency motors are adopted.

The IE3 motor is estimated to save around 2% energy as compared to the IE2 motor. If a failed 11 kW IE2 motor (cost ~$2000) is replaced with an IE3 version (10% additional cost) and operated at 75% load factor annually, the payback time is less than a year (~7.5 months). Use of IE4 and IE5 motors results in an extra ~1.5% energy savings for each step. If an 11 kW IE2 motor is replaced with IE5 motor, the total energy savings could be nearly 5%.

The energy-saving potential for a larger-size motor (e.g. 170 kW) is bit lower and only results in around 2.7% of energy savings by moving from IE2 to IE5 class motors (Figure 3.4). If the cost of an IE5 motor is ~30% more than the IE2 motor, the payback time is less than half a year (~5.8 months) in high-load-factor applications. The annual energy saving is ΔE ~61 MWh, which is equivalent to ~5t CO_2e emissions.[5]

4 PDS refers to electric motor, variable speed drive (VDS) or variable frequency drive (VFD), and sensor.

5 https://ecotricity.co.nz/carbon-calculator

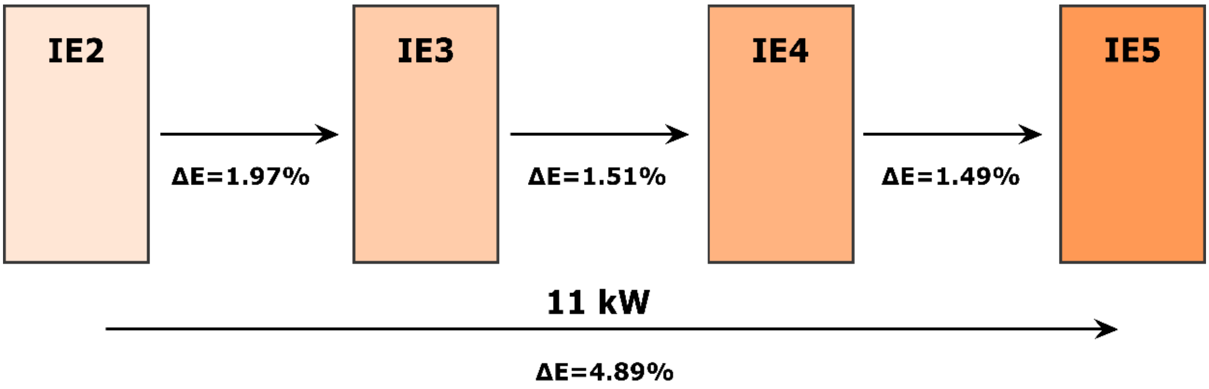


Figure 3.3 Energy savings using IE2, IE3, IE4 and IE5 class 11 kW motors.

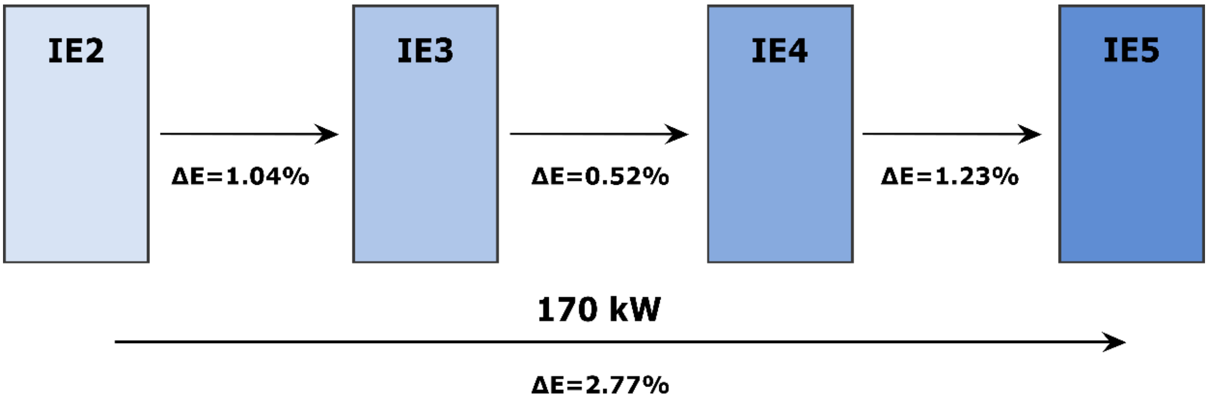


Figure 3.4 Energy savings using IE2, IE3, IE4 and IE5 class 170 kW motors.

3.2.2 Scenario Analysis and Cost Benefits for Power Drive System

This section analyses two scenarios where the motors are used in a variable load and constant load. Electric motors are used in a range of applications that require constant torque, variable torque or constant power. PDS energy losses provide a more realistic scenario of energy losses in the combined CDM and electric motor system. These losses are dependent on the CDM and electric motors and are usually estimated by carrying out testing of the CDM and electric motors based on IEC and manufacturer guidelines.

The goal of our scenario is to estimate energy savings using PDS based on IE2 and IE3 class motors. Energy consumption was evaluated for two different scenarios:

- **Case 1** – Fan
- **Case 2** – Pump

where PDS is used to control the flow rate for a realistic assessment. Energy consumption, energy savings, cost savings and CO_2 reduction were directly estimated using the online ABB energy calculator.[6] Energy consumption for 11 kW and 170 kW motors was considered to simulate low-power and high-power motors. Figures 3.5 and 3.6 show the energy consumption for damper outlet and drive-controlled centrifugal fans using 11 kW and 170 kW motors with 4000 hours of annual operation time. For IE2-based PDS, the annual energy consumption is 26.6 MWh, and, if a drive is used, this can save up to 10.1 MWh of energy. Energy savings using the drive are estimated to be 38%. IE3 motors with and without a drive showed around 9.9 MWh in energy savings.

6 https://energysave.abb-drives.com/

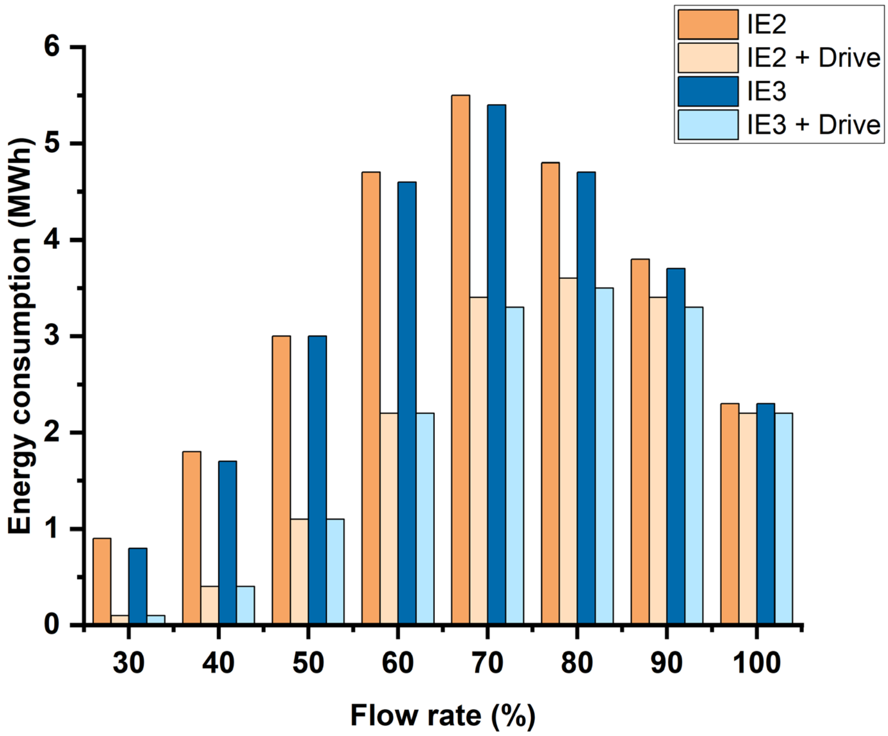


Figure 3.5 Energy consumption for a fan using 11 kW motor with and without a power drive system.

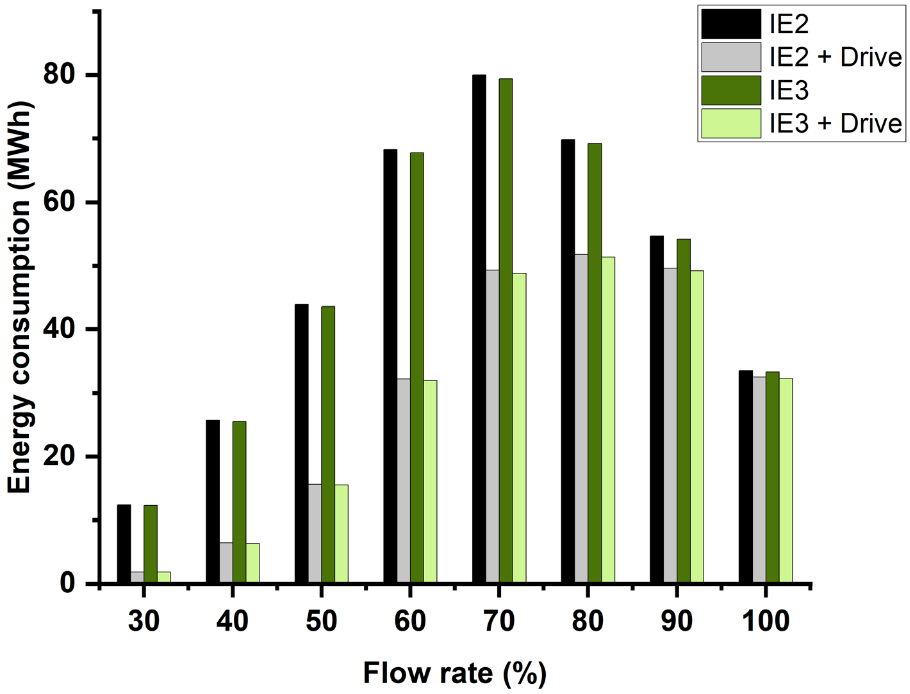


Figure 3.6 Energy consumption for a fan using 170 kW motor with and without a power drive system.

Annual energy savings for IE2–IE3-based PDS systems, along with cost savings and CO_2 reduction for this centrifugal fan, are plotted in Figure 3.7. Energy savings are proportional to the operation duration. If IE3-based PDS is used, the energy savings could be around 19.8 MWh for an annual operating time of 8000 hours, which corresponds to approximately $1,982 in cost savings and a 5.9t CO_2e reduction as per the ABB energy savings calculator.[6] However, taking account of recent emission factors, a conservative estimation for 19.8 MWh energy savings is equivalent to ~1.5t CO_2e reduction.

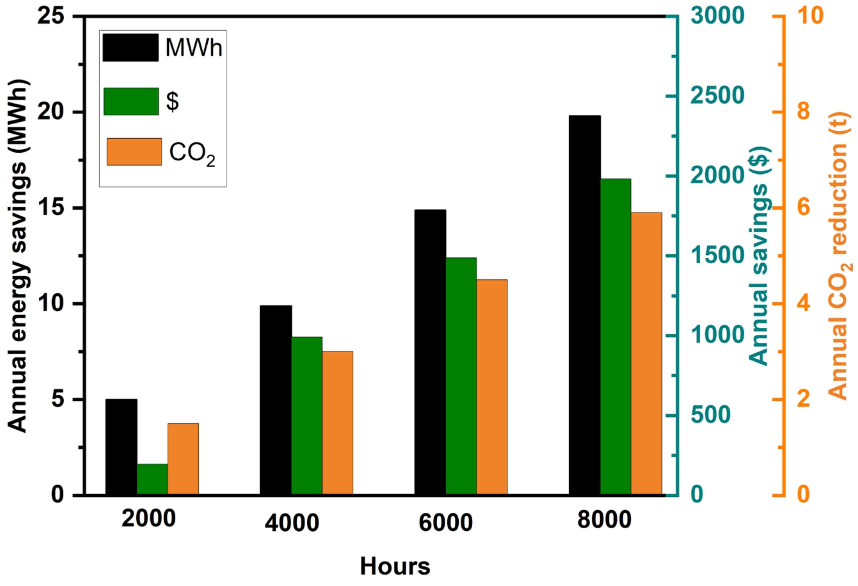


Figure 3.7 Energy and cost savings, as well as CO_2 reduction, for a fan using an 11 kW motor with a power drive system.

Case 2 considers a pump using throttling/valve control and a drive controller. Figures 3.8 and 3.9 show the energy consumption for 11 kW and 170 kW motors with IE2- and IE3-based PDS operating for 4000 hours annually. An 11 kW IE2-based PDS system uses around 16.9 MWh of energy compared to conventional flow control, which uses around 36.7 MWh of energy. A 170 kW IE2-based PDS uses around 533.9 MWh of energy, which decreases to 245.3 MWh when using a drive controller. An IE3-based PDS system with an 11 kW motor uses around 36.5 MWh of energy, which reduces to around 16.5 MWh when using the drive controller. This is equivalent to around 54% energy savings, highlighting the importance of drive control for variable load applications.

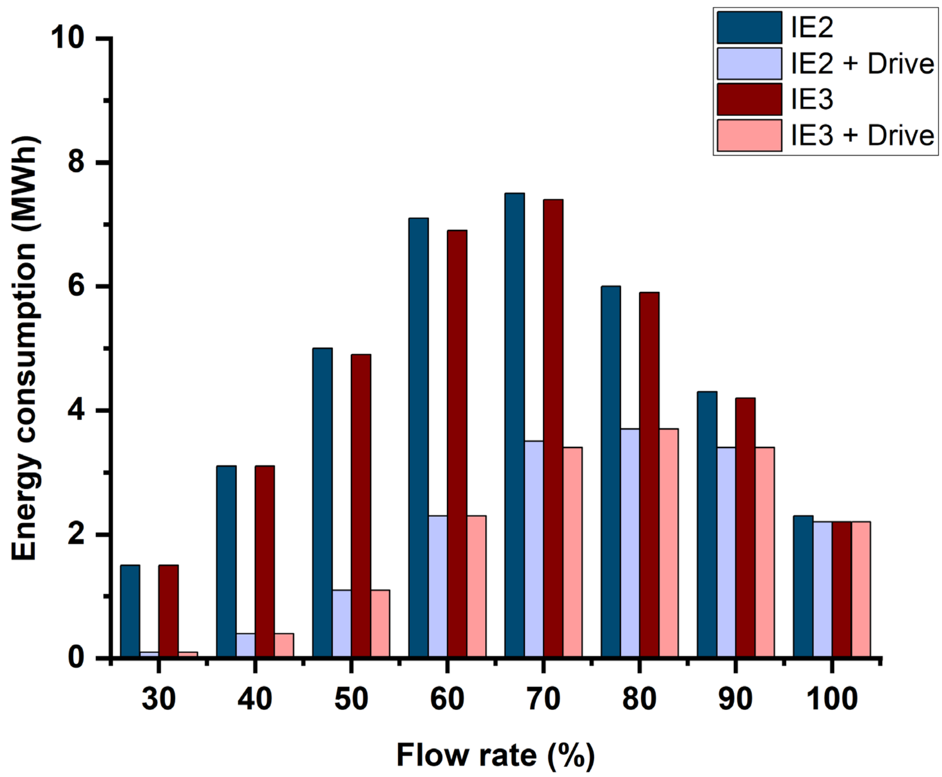


Figure 3.8 Energy consumption for a pump using 11 kW motor with and without a power drive system.

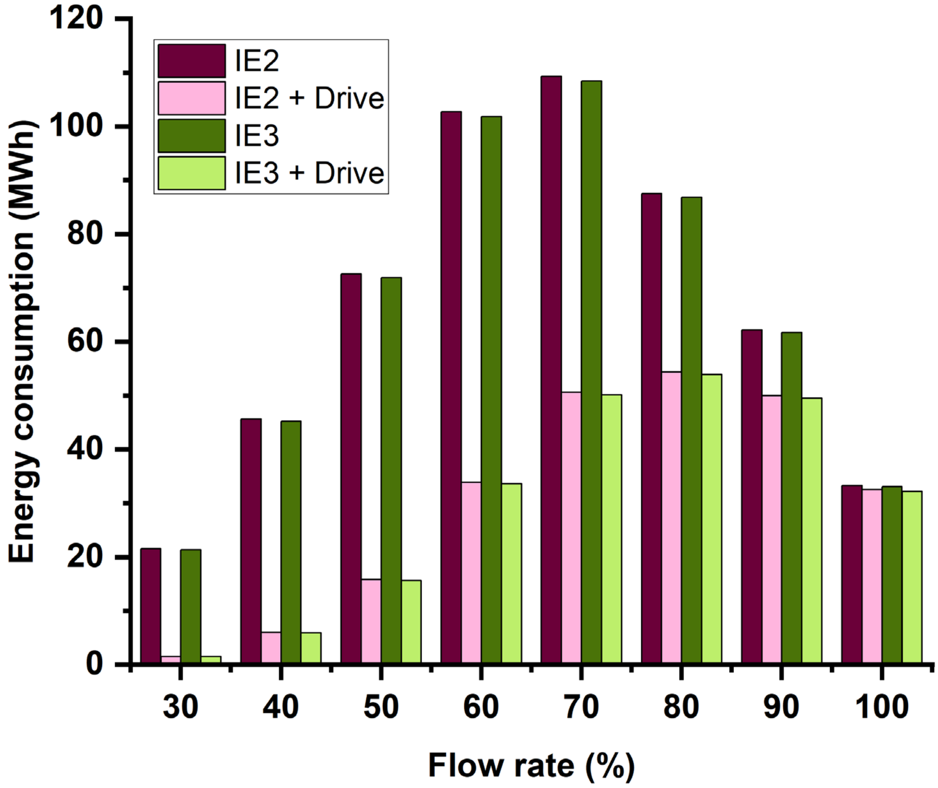


Figure 3.9 Energy consumption for a pump using 170 kW motor with and without a power drive system.

Energy savings are proportional to the operation duration. For 8000 hours of annual operating time, the energy savings could be around 38.9 MWh, which corresponds to approximately \$3,800 in cost savings and an 11.7t CO_2e reduction as per the ABB energy savings calculator[6] (Figure 3.10). However, taking account of recent emission factors, a conservative estimation for 38.9 MWh energy savings is equivalent to ~3t CO_2e reduction.

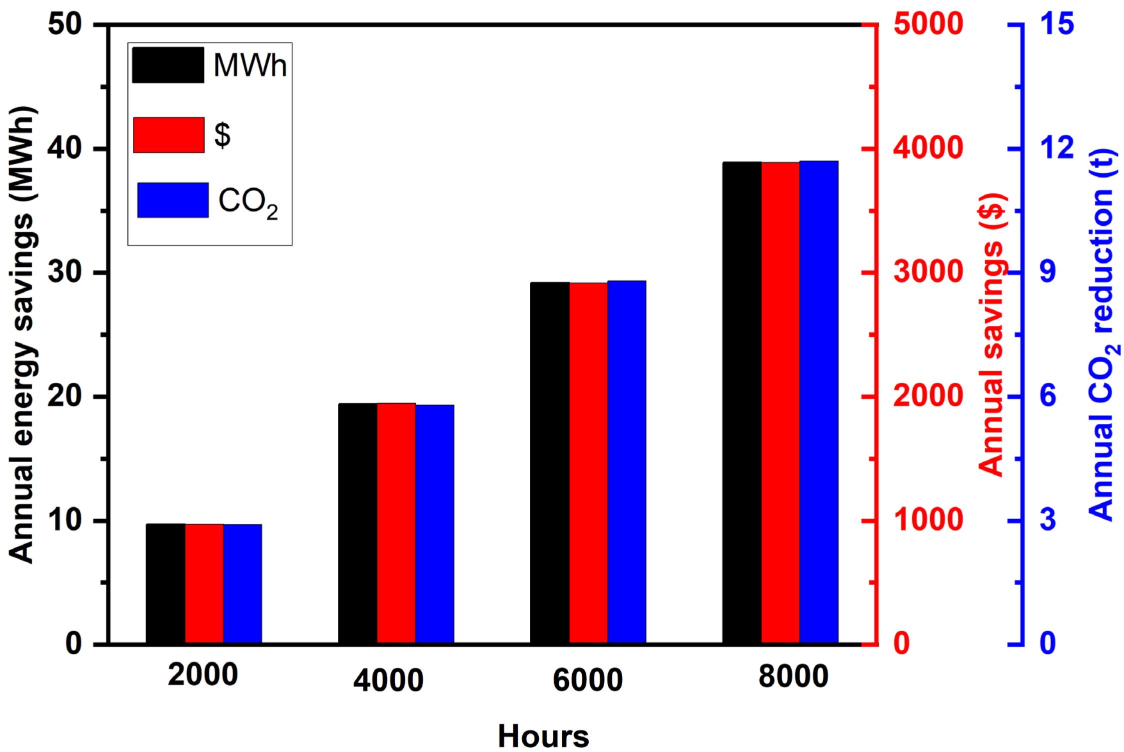


Figure 3.10 Energy and cost savings, as well as CO_2 reduction, for a pump using an 11 kW motor with a power drive system.

3.2.3 Scenario Analysis and Cost Benefits for Efficient Motors in New Zealand Industries

Table 3.2 shows industrial electric motors ranging in size from 0.5 kW to 330 kW. The majority of electric motors fall in the size ≤30 kW category and constitute up to 80% of the market share. Larger motors (≥60 kW) are mainly used for industrial applications. Payback periods vary and tend to be longer for larger motors, as the cost penalty is higher and efficiency gain smaller.

Electric motors in New Zealand have a capacity of around 3.2 GW across the motor size range of 0.5–330 kW. Tables 3.2 and 3.3 show that the cost savings for these motors operated at a 60–100% load factor for 4000 hours annually. Replacing IE2 motors with IE3 motors will save around 222.1 GWh of energy, equivalent to approximately $22.1 million in cost savings and a reduction of around 26.4 kt of CO_2e. The energy savings are even higher if the operating hours are increased, as the savings are proportional to the use of more efficient electric motors. For example, if replaced with IE3 motors operating for 8000 hours annually, these will save around 444.1 GWh of energy, $44.2 million in cost savings and 52.4 kt of CO_2e reduction.

Table 3.2 Electric motors (0.5–330 kW) in New Zealand.

Category	Mid-Point Size (kW)	Price ($)	Cost per kW ($)	Motor Stock	Industrial Share	IE2 → IE3 Savings (~$M)	IE2 → IE4 Savings (~$M)	IE2 → IE5 Savings (~$M)
1	0.5	140.3	280.6	210,000	80%	2.1	4.1	6.2
2	3	356.5	118.8	125,000	60%	3.0	5.3	9.1
3	11	801.5	72.9	85,000	70%	5.7	10.1	14.3
4	30	2,129.8	71.0	35,000	80%	5.1	9.6	15.2
5	60	4,072.1	67.9	6000	85%	1.5	2.9	4.5
6	120	7,435.9	62.0	4500	90%	1.9	3.6	5.7
7	170	12,351	72.7	2000	100%	1.5	2.2	3.9
8	220	14,492.3	65.9	750	100%	0.6	1.1	1.9
9	330	23,302.4	70.6	500	100%	0.6	1.1	2.1

Table 3.3 summarises the energy savings from replacing IE2 motors with IE4 and IE5 motors. Although this presents a very simplified picture of energy savings, it highlights the significant energy savings achievable when high-efficiency motors are used for various applications.

Table 3.3 Energy saving for electric motors (0.5–330 kW) in New Zealand.

	IE2 → IE3 Savings	IE2 → IE4 Savings	IE2 → IE5 Savings
Energy Saving (GWh)	222.1	402.1	631.5
Energy Saving ($M)	$22.20	$40.21	$63.10
Equivalent CO_2e Reduction (kt)	~26.4	~47.9	~75.2

Moreover, if IE3 motors are further used with VFD/VSD, additional energy savings of 38–54% could be achieved based on load profiles, as discussed in Section 3.2.2. Energy consumption for IE3 motors in New Zealand is estimated to be around 14.1 TWh for 4000 hours of operation annually. A 38% energy saving could imply around 5.3 TWh of energy savings, which is equivalent to $535 million in cost savings and a reduction of 636 kt CO_2e.

3.3 Barriers

There are barriers for adoption of higher-efficiency electric motor systems, which depend on many factors. These factors can be grouped into two categories – internal factors and external factors. These groupings are based on recent literature that identified important factors for barriers affecting decision-making abilities for technology adoption (Cagno et al. 2019; ABB Ltd 2021; Patterson et al. 2022; Siddique et al. 2022).

The internal factors affecting technology adoption include lack of organisational and management support, high capital investment cost, technical risks, poor information on energy efficiency and lack of synergy between various departments in the organisation, as well as other organisational priorities. A lack of information on energy savings capability plays an important role on internal factors. Often a fragmented approach is taken to energy efficiency in an organisation, where each department applies different strategies. High capital cost is aften a major barrier on adopting new technology. However, cost-benefit analysis and investment recover time estimation helps to address this challenge. A co-ordinated approach with organisational support and technical expertise can be used to overcome internal factors.

The external factors for technology adoption barriers include lack of regulatory and compliance requirement, lack of support from government, no incentive, availability of old motors, supply-chain issues and lack of shareholder and public pressure to employ energy-saving measures. Availability of old motor stocks and slow delivery of replacement motors arising from supply-chain issues often means that users continue to use inefficient motor systems. Moreover, market penetration of new technology hindered by cost may require incentives for utilisation. An external factor, such as zero emission targets as per the Paris Agreement, can influence government and regulatory agencies to incentivise the adoption of new technology to assist in achieving targets.

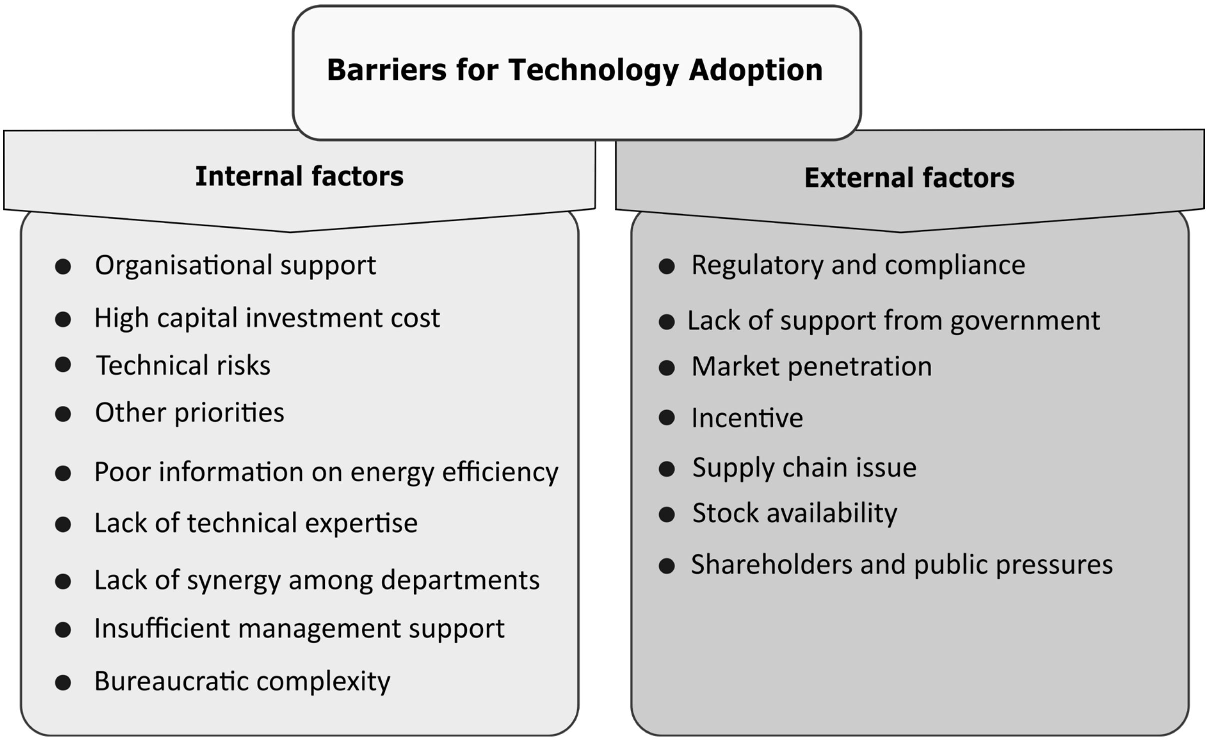


Figure 3.11 Barriers for technology adoption.

3.4 Recommendations

Electric motor systems require a holistic approach to deliver energy savings using efficient electric motors, electronics, mechanical, transmissions and loads. Based on a technology scan and electric motor application requirements, we suggest the following recommendations:

- Use of high-efficiency motors, such as replacing IE2 with IE3 efficiency motors.
- Retro-fit electric motors correctly sized for targeted applications.
- Design electric motors to operate at 75% load factor.
- Install CDM (VSD/VFD) for variable load operation.
- Use PDS-level analysis to assess the combined CDM and electric motor energy loss across multiple load points for variable applications.
- Incorporate digitalisation and sensors for monitoring motor operation.
- Consider how to limit use of old electric motors as replacements for non-functioning motors.
- Apply an extended product approach for maximum benefit of system-level design for specific electric motor applications.

4.0 SUMMARY

This report provides an overview of emerging technologies in electric motor systems. Emerging electric motors and electric motor system controllers were discussed. Barriers and possible solutions are suggested for adoption of electric motor technologies toward meeting emissions targets. The electric motors covered in this study show that each motor technology has advantages and disadvantages based on target applications.

Synchronous reluctance motors (SRMs) are found to be the most suitable for common applications due to their relatively simple design and high efficiency, suitable for industrial applications. Brushless DC (BLDC) motor and permanent magnet synchronous reluctance (PMSynRM) motors show high reliability and high power density (kW/kg).

New Zealand industries use motors ranging from 0.5 to 330 kW, with a capacity of 3.2 GW operating at various load factors between 60% and 100%. Replacing IE2 motors with IE3 motors will save around 222–444 GWh of energy, equivalent to approximately $22M–$44M in cost savings and a reduction of 26.4–52.4 kt of CO_2e for motors with annual operating times of 4000–8000 hours.

Energy savings of up to 38–54% could be achieved if the motors are equipped with VFD/VSD. For example, a 38% energy saving could imply around 5.3 TWh of energy savings for IE3 motors, which is equivalent to $535 million in cost savings and a reduction of 636 kt CO_2e.

The study finds that electric motor and complete drive module selection should consider end-use applications for variable speed operations. Payback of investment in new technology significantly depends on conditions such as number of running hours, load factor and variable speed operation. A broad implementation of motor efficiency measures could avoid between 2% and 40% of current motor energy usage of 13.1 TWh for 4000 hours per year for IE2 motors. This implies energy saving between 261GWh and 5.2 TWh, worth between $26M and $522M per year and avoiding between 31 kt CO_2e and 621 kt CO_2e per year. The design and use of electric motor-driven systems based on load profile, operation hours, correct sizing, adoption of a new class of electric motors and CDM should be encouraged to synergistically improve energy efficiency toward meeting New Zealand's zero carbon goal by 2050.

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www.gns.cri.nz

Principal Location

1 Fairway Drive, Avalon
Lower Hutt 5011
PO Box 30368
Lower Hutt 5040
New Zealand
T +64-4-570 1444
F +64-4-570 4600

Other Locations

Dunedin Research Centre
764 Cumberland Street
DX Box YP80001
Dunedin 9016
New Zealand
T +64-3-477 4050
F +64-3-477 5232

Wairakei Research Centre
114 Karetoto Road
Private Bag 2000
Taupo 3352
New Zealand
T +64-7-374 8211
F +64-7-374 8199

National Isotope Centre
30 Gracefield Road
PO Box 30368
Lower Hutt 5040
New Zealand
T +64-4-570 1444
F +64-4-570 4657