Electric Machines

Narrative Report

2024

Produced by the Advanced Propulsion Centre UK on behalf of the Automotive Council UK
Information correct at time of publication

Contents

1.0 Introduction

2.0 Cross-cutting themes

3.0 Narrative to roadmap

1 Introduction

1.1 Foreword to the 2024 roadmaps

Neville Jackson
Chair, Automotive Council Strategy Group

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Chair, Automotive Council Future Technology Group
Deputy Chair, Automotive Council UK

The UK Automotive Council is well known for producing robust and detailed technology roadmaps that define potential routes for Automotive including Commercial Vehicles and Off-Road machinery and related products to achieve our UK environmental and societal goals. Roadmaps are a function of current knowledge and as new ideas and technologies emerge, must be regularly renewed. This exercise, led by the Advanced Propulsion Centre UK, has generated the fourth generation of these roadmaps.

Whilst many organisations develop roadmaps as part of their product planning process, the Automotive Council roadmaps are unique in providing a consented view from the Automotive sector including Commercial Vehicle and Off-Road Machinery, in the UK. This enables us to define common future challenges and where to focus collaborative R&D and capital resources in developing successful, sustainable, net-zero solutions.

These solutions must also meet future consumer needs and not introduce challenges in experience or limitations in operation. Often, more than one technical approach appears viable to meet future needs. It is important that all of these approaches are explored and introduced to market as the carbon reduction goal becomes more urgent. Ultimately, it is possible that one approach may dominate but we cannot afford to wait for this to emerge.

1.2 The purpose of the 2024 roadmaps

The Automotive Council UK roadmaps outline key themes, trends and drivers in the global automotive industry. This narrative report explains and provides insights to support the roadmap's themes. It helps clarify the reasons behind the roadmap's content and how it should be used.

The report aims to guide research and development (R&D), innovation, and cross-sector collaboration. A list of recommendations for how industry, academia, and government can use this information is shown opposite:

Industry

- Compare in-house R&D priorities with industry trends and drivers in the automotive sector.
- Evaluate supply chain risks and develop strategies for sustainable and circular business models in automotive products.
- Help start-ups by guiding their technology focus, investment choices, and collaboration plans.

Academia

- Address long-term research challenges that need to be solved.
- Align university research, education, and skills development with the automotive industry's needs.
- Strengthen partnerships between academia and industry to apply research to real-world solutions.

Government and policymakers

- Understand key themes and trends in automotive technologies.
- Direct policy and funding to support R&D priorities and innovation for reaching net zero.
- Promote cross-sector collaboration and trade policies that benefit the automotive industry and broader industrial sectors.

1.3 | Building a consensus

This consensus roadmap has been developed through the facilitation of the Advanced Propulsion Centre UK (APC), with contributions from 436 individuals representing 230 organisations, which include government, industry and academia.

Collating the information required for the 2024 roadmaps has only been possible due to the breadth of contribution and valuable feedback from those who have fed into the process, which began in early 2023. The APC would like to thank everyone who gave their time and input across the various webinars, workshops, and surveys conducted.

As a result of this consultation across industry and academia the 2024 roadmaps build on previous versions and demonstrate the significant change that is happening across the automotive sector and its supporting industries.

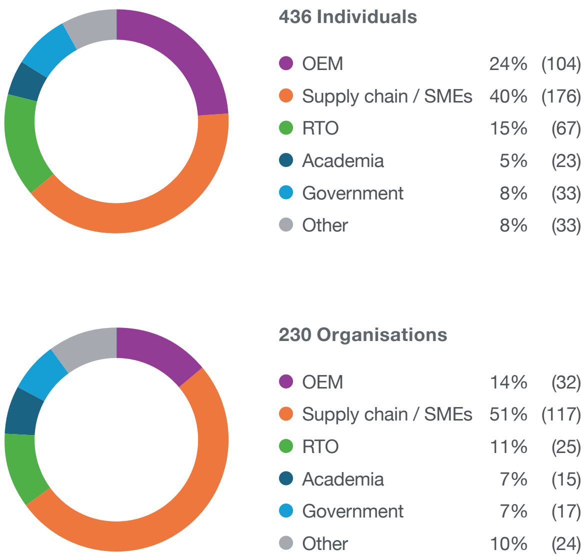
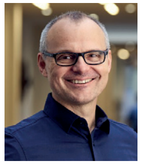


Figure 1: Representation by individual and organisation



Stefan Fuchss
Chief Engineer Electric Drive
Jaguar Land Rover

The decarbonisation of fossil-based propulsion systems is a key engineering objective in order to reduce the overall effects of climate change. The increased utilisation of eMachines in hybrid configurations as well as in full electric systems with battery or fuel cell based energy storage supports the road to zero carbon emissions in two ways: firstly, by eliminating local emissions in the torque and power generation and secondly, by utilising the required energy efficiently. Particularly the drive for efficiency will determine the affordability of electric propulsion. With smaller energy storage the cost and weight will decrease and charging times to regain range will shorten. The focus on all aspects of the eMachine, from raw materials, component design to assembly and service, will create a wide array of future business opportunity and growth. That is one of the reasons why JLR has invested heavily into the inhouse design and manufacturing of their own eMachines.

Professor Markus Mueller
Chair of Electrical Generation Systems
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The automotive industry has seen rapid developments in electrical drivetrains since the last Automotive Council UK roadmap in 2020. The roadmap update identifies a number of cross-cutting enablers, such as manufacturing techniques, the lifecycle impact, and materials, in particular the supply of critical materials. There is more detail on the important aspect of noise vibration harshness (NVH), control and thermal management, which link to the power converter roadmap, highlighting the integrated aspect of electrical drivetrains. Ambitious and realistic goals are set, inspiring continued collaboration between academia and industry in R&D and skills training to secure our international leadership. The update to the 2020 roadmap ensures that the UK stays at the forefront of the power electronics, machines and drives electrical revolution across all automotive sectors.

1.4 | Electric Machines – overview

The demand for electric motors (e-motors) continues to increase as global legislation drives the adoption of low- and zero-emission vehicles requiring electrified powertrains. Global light-duty vehicle (LDV) xEV production, including battery electric vehicles (BEVs), fuel cell electric vehicles (FCEVs) and hybrids, is expected to be over 70 million by 2030[1]. Each of those vehicles requires at least one motor and, in some cases, one per wheel.

Overview: Electric machines

Technology advancements

In recent years, electric traction motors have seen advancement and change driven by the need for higher efficiency, reliability and sustainability. These motors deliver improved torque, acceleration, and overall performance, enhancing the driving experience.

As power has improved more attention is being paid to cost, efficiency, and the driving dynamics. This is seen in integration trends and in a focus on noise, vibration and harshness (NVH). Consideration of NVH in designing phase is often about providing a smooth driving experience, but for performance vehicles it can be about introducing character to the drive. Further integration with other subsystems, like power electronics, with software control systems providing new functionality enhancing safety, lifetime and performance.

Materials and lightweighting

Manufacturers are exploring lighter materials to reduce motor weight. Lightweight traction motors contribute to better vehicle efficiency, range and handling. By integrating motors into the vehicle body, space is saved, enabling more flexible design options.

While neodymium-based magnet (permanent magnet) technology dominates the market, there is innovation in alternative materials to reduce dependency on the rare earth supply chain. Materials such as iron ferrite and iron nitride show promise. There is also a growing trend of integrating magnet-free motors, particularly as a secondary drive, for example in all-wheel drive (AWD) vehicles.

While rare earth elements tend to be a primary concern when considering the EV motor supply chain, there are growing risks on copper supply. Demand for copper is increasing with the energy transition and current winding designs relying predominantly on copper. Increasing pricing and potential shortages, or gaps in supply, will see alternative materials like aluminium or innovative winding designs growing in popularity.

Rise of digital technologies

Digital technologies feature prominently in the Electric Machines Roadmap from design through to manufacturing and control. It is clear artificial intelligence (AI) and data will play a key role.

Improving sustainability is challenging as differing design and levels of integration makes disassembly and recycling difficult. New methods for extracting materials are needed, particularly as volumes increase and the value of the embedded materials increases.

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[1] APC analysis from S&P global data

This is a new section for the 2024 roadmaps and aims to provide a comprehensive context for issues and drivers that extend beyond vehicular systems and technologies.

Four overarching themes or micro-level drivers that influence all aspects of the technology roadmaps have been pinpointed. The drivers identified are multifaceted, ranging from global to local scales. Global drivers encompass changes and challenges that transcend national boundaries, often beyond the direct influence of UK suppliers. National drivers are those that are unique to the UK's socio-economic and regulatory environment, while local drivers affect specific regions or communities within the UK. The interplay between these cross-cutting themes and drivers impacts the evolution and development of forecasted technology solutions. These drivers interact with each other and with the technology roadmaps – expediting the advancement of certain technologies, while simultaneously necessitating change in others. In this section, we delve into four pivotal drivers that are reshaping the landscape of technology and innovation:

1. Policy and regulations: examining the influence of legislative frameworks on technological progress.
2. Energy and infrastructure: assessing the role of energy availability and infrastructural support in driving innovation.
3. Materials and manufacturing: understanding the impact of manufacturing capabilities and constraints on technology development.
4. Digitalisation: exploring the transformative power of digital technologies across the automotive sector.

2 Cross-cutting themes

2.1 Policy and regulations

There are key regulations and mandates being implemented globally that could impact extraction, usage and recycling of materials, including magnets, copper and e-steel.

EU's Critical Raw Materials Act[2]

The European Union's (EU) Critical Raw Materials Act will seek to build a resilient supply chain in Europe for critical raw materials used in energy transition technologies. The EU Critical Raw Materials Act has listed 34 critical materials as of 2023 and more than 10 in the list are associated within the EV supply chain. The act sets the listed benchmarks to be hit by 2030 for strategic raw materials:

- at least 10% of EU's annual consumption for extraction within the EU
- at least 40% of the EU's annual consumption for processing within the EU
- at least 15% of the EU's annual consumption for recycling
- not more than 65% of the annual consumption of strategic raw materials of processing from a single third country.

The Critical Raw Materials Act, which lists 34 materials in total, can be seen as both a threat and an opportunity for European original equipment manufacturers (OEM) suppliers. It is a threat from the incoming regulations and barriers to sourcing key strategic materials from a single third country and the opportunity lies in the investment and improvement of the electrification supply chain within the continent.

UK Critical Minerals Strategy

The UK released its Critical Minerals Strategy in July 2022 to bolster energy security and improve domestic industry resilience on strategically important materials. The strategy is working towards improving the growth of the UK's domestic capabilities on critical minerals. It potentially incentivises new mining and will refine capability establishment within the UK.

The critical material developments detailed above, especially in relation to magnets, would have implications for the automotive industry in the form of designing and producing magnet-free motors to reduce volatility and uncertainty in the supply chain.

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[2] https://single-market-economy.ec.europa.eu/sectors/raw-materials/areas-specific-interest/critical-raw-materials_en

Global emissions reduction targets

Global mandates (see Figure 2) to accelerate EVs and progress a potential ban on internal combustion engine (ICE) vehicles will result in direct higher demand for e-motors. The Advanced Propulsion Centre UK (APC) Q1 2024 Demand Report[3] predicts there will be 23 million electric motors needed in Europe and these would require 25 kt of magnets for the use and application of motors. It states that by 2035 there will be nearly 2 million electric motors needed in the UK, resulting in an overall demand of 2.4 kt of magnets.

Figure 2:
Zero-emission vehicle sales commitments

	2025	2030	2035	2040
EU	• 15% CO_2 reduction across car fleet • 15% CO_2 reduction across HDV fleet	• 55% CO_2 reduction across car fleet (50% for LCV) • 45% CO_2 reduction across HDV fleet	• All new cars zero CO_2 emissions • HDV 65% fleet CO_2 reduction	• HDV 90% fleet CO_2 reduction
UK	• ZEV sales targets 22% cars and 10% vans	• ZEV sales targets 80% cars and 70% vans	• All sales ZEV for cars and vans • All HDV <26 tonnes ZEV	• All HDV ZEV
Rest of the world	• **Canada** 20% ZEV for light and heavy-duty sales (2026)	• **USA** 50% of vehicle sales to be electric • **China** NEV 60% of sales • **Japan** 20% BEV and PHEV passenger car sales • **India** 30% car sales ZEV, 70% commercial vehicles ad 80% two / three-wheelers • **Australia** 30% LDV sales to be ZEV	• **Canada** 100% ZEV for light- and heavy-duty sales • **Japan** 100% EV passenger car sales • **Australia** 100% LDV sales to be ZEV	• **China** 100% NEV for light- and heavy-duty sales

Dates correct at time of publication

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[3] https://www.apcuk.co.uk/wp-content/uploads/2024/07/APC_xEV_Demand_Q12024_FINAL.pdf

2.2 | Energy and infrastructure

A high inflationary environment and heightened geopolitical risks have disrupted emerging technology value chains, including BEVs. The disruption has meant the focus for the e-motor industry has shifted from performance-driven technologies to cost-centric innovation.

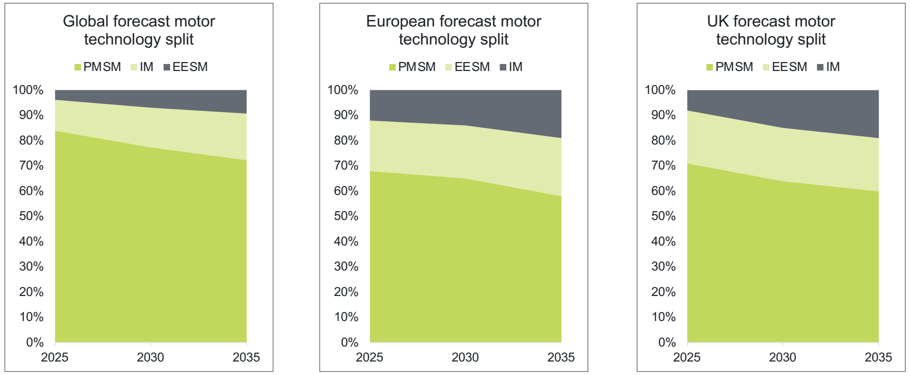
To improve cost and increase efficiency of the vehicles, powertrain efficiency is regarded as a key enabler for the overall system. E-motors have a direct implication on the energy consumption within the powertrain, and evolution to 800 V system architecture will enable increased efficiency with less material usage.

The current generation of electric motors are predominantly permanent magnet synchronous motors (PMSM) and they use magnets made from rare earth elements (REE). Candidates like iron nitride are explored as a substitution for rare-earth-powered permanent magnets. The APC's 2024 E-motors Value Chain Report[4] suggests that the cost of magnets covers a substantial portion of the overall manufacturing cost of electric motors.

As predicted by the APC's quarterly demand analysis (see Figure 3), we are seeing an increased effort on alternative approaches to magnetic technologies. This includes EESM and induction motors. However, there are reliability and performance concerns on the magnet-free motors compared to the permanent-magnet motors.

Other material sensitivities relate to aluminium, copper and e-steel pricing. By migrating away from magnets, the pricing of e-steel, copper and aluminium becomes prominent. Therefore, there is an urgency among major countries and governments to improve the overall infrastructure and supply chain to mine and distribute these critical raw materials.

Figure 3: E-motor technology split across automotive applications (APC analysis)



Source: https://www.apcuk.co.uk/knowledge-base/resource/e-motors-value-chain/

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[4] https://www.apcuk.co.uk/knowledge-base/resource/e-motors-value-chain/

2.3 | Materials and manufacturing

Cost drivers

The focus on improved costs and reduced time to market for e-motors will require innovation and novel manufacturing methods.

Traditional e-motor configurations are being challenged from radial to axial and transverse flux motors, which require specialised component processing like windings and lamination of key materials in stators. Manufacturing costs can attribute to one-fifth of the overall production cost for e-motors and this is due to the labour-intensive nature of the process. Automation and robotics have a key role in managing and improving the efficiency of e-motor production lines.

New regulations and new materials

Due to the incoming regulations on recycling and sustainability initiatives, extraction and reuse of key materials will become important in the manufacturing of e-motors.

There will be renewed focus on designing the motor and its components for assembly, disassembly and reusability (life cycle impact). Integrating recycled magnets from various existing energy transition technologies, like wind turbines and current EVs, will gain traction in the near future.

REE are a key focus, with China dominating both the supply chain and processing of materials. To diversify the risk of supply, other countries globally are starting to establish their respective critical material supply chains. Whilst REE dominate the bill of materials in a motor, copper is not far behind. The price of copper has trebled in the last 12 years and continues to increase, with demand growing for the usage in energy transition technologies. The pace of new supply coming online is unlikely to keep up with demand, which will see some applications move to alternative materials such as aluminium.

Globally, the incoming regulations on rules of origin (currently in the UK and EU) will expand the scope of the current material-passport tracking systems. Material origin tracking can enable circular passporting methods that can further enhance the drive towards sustainability and net-zero manufacturing. Digital innovations and architecture can be developed to improve the overall functionality of the passporting systems.

2.4 Digitalisation

Digitalisation is a key enabler for the e-motor development within the automotive industry and within the value chain. It consists of three major pillars:

- design and optimisation
- manufacturing
- measurement and monitoring

The design of e-motors is increasingly enabled by emerging technologies in the form of AI and advanced simulation techniques. A combination of superfast computing power and the emergence of large language models (LLMs) have resulted in rapid simulation and iteration of various possible designs to achieve customer and operational requirements.

Noise, vibration and harshness

Noise vibration and harshness (NVH) is a segment that could benefit from advanced digital technologies. NVH is key for improving driver experience and increasing the reliability of vehicles. A combination of AI-enabled design, simulation and modelling can aid in providing the optimal pathways for best NVH performance.

Future of manufacturing

Future manufacturing assembly lines could benefit from technologies like digital twins, robotics and automation.

Digital twins will provide efficient representation of the physical assembly units and provide an opportunity for elimination of wastage, improving the safety of operations. They could help in the real-time monitoring of the operations and potentially intervene before a faulty operation becomes a catastrophic failure.

Additive manufacturing, commonly called 3D printing, can reduce cost and improve innovative design in the production of e-motors. Additive manufacturing is enabled by producing a physical object, such as an e-motor, from a computer-aided design file. Additive manufacturing has the potential to enable weight reduction and improve overall performance.

Real-time monitoring and proactive fault detection can improve operational resilience of the electric drive units (EDUs). Embedment of sensors and proliferation of internet-of-things (IoT) technology can enable predictive and preventive maintenance for fleet managers of EVs. Better reliability will result in an improved offer to customers on resale value and insurance premiums.

IoT monitoring, coupled with cloud-based analytics, can provide real-time thermal management of e-motors. It can also enable energy-saving mechanisms through intelligent software control methods.

3 | Narrative to roadmap

3.1 | Electric Machines – technology indicators

The technology indicators demonstrate increasing power density whilst decreasing cost. This is expected to be achieved through the realisation of new technologies on the roadmap and with manufacturing cost reduction gained through digitalisation.

Mass-volume

Achieving economies of scale at a low cost is paramount for these products. Applications include high-volume passenger cars and delivery vans.

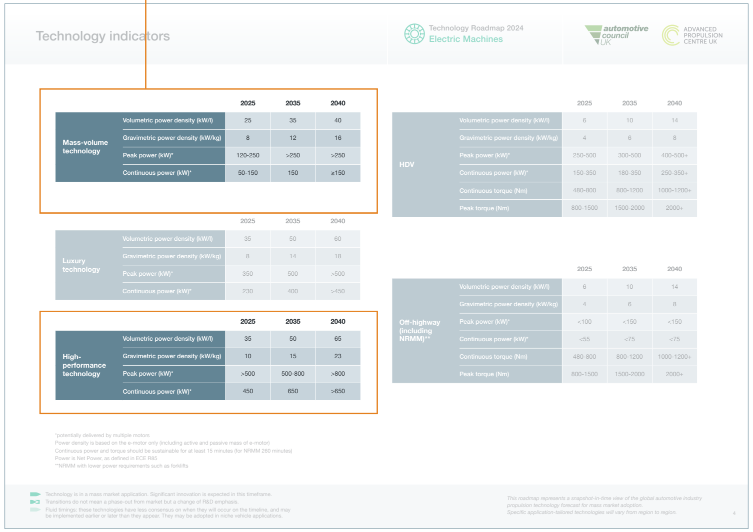
Significant cost reductions are achievable through economies of scale. For the targets listed here, reducing cost is crucial to support the uptake of electric vehicles. Power density is important to minimise weight and free-up packaging space.
All masses and volumes include the active and passive components of the motor only.

High-performance

High power densities are required with cost being a less decisive factor. Applications include performance passenger cars, buses and some medium-duty vehicles (800 V prevalent).

		2025	2035	2040
Mass-volume technology	Volumetric power density (kW/l)	25	35	40
	Gravimetric power density (kW/kg)	8	12	16
	Peak power (kW)*	120-250	>250	>250
	Continuous power (kW)*	50-150	150	≥150

		2025	2035	2040
High-performance technology	Volumetric power density (kW/l)	35	50	65
	Gravimetric power density (kW/kg)	10	15	23
	Peak power (kW)*	>500	500-800	>800
	Continuous power (kW)*	450	650	>650



Technology indicators

Technology Roadmap 2024
Electric Machines

		2025	2035	2040
Mass-volume technology	Volumetric power density (kW/l)	25	35	40
	Gravimetric power density (kW/kg)	8	12	16
	Peak power (kW)*	120-250	>250	>250
	Continuous power (kW)*	50-150	150	≥150

		2025	2035	2040
Luxury technology	Volumetric power density (kW/l)	35	50	60
	Gravimetric power density (kW/kg)	8	14	18
	Peak power (kW)*	350	500	>500
	Continuous power (kW)*	230	400	>450

		2025	2035	2040
High-performance technology	Volumetric power density (kW/l)	35	50	65
	Gravimetric power density (kW/kg)	10	15	23
	Peak power (kW)*	>500	500-800	>800
	Continuous power (kW)*	450	650	>650

		2025	2035	2040
HDV	Volumetric power density (kW/l)	6	10	14
	Gravimetric power density (kW/kg)	4	6	8
	Peak power (kW)*	250-500	300-500	400-500+
	Continuous power (kW)*	150-350	180-350	250-350+
	Continuous torque (Nm)	480-800	800-1200	1000-1200+
	Peak torque (Nm)	800-1500	1500-2000	2000+

		2025	2035	2040
Off-highway (including NRMM)**	Volumetric power density (kW/l)	6	10	14
	Gravimetric power density (kW/kg)	4	6	8
	Peak power (kW)*	<100	<150	<150
	Continuous power (kW)*	<55	<75	<75
	Continuous torque (Nm)	480-800	800-1200	1000-1200+
	Peak torque (Nm)	800-1500	1500-2000	2000+

*potentially delivered by multiple motors
Power density is based on the e-motor only (including active and passive mass of e-motor)
Continuous power and torque should be sustainable for at least 15 minutes (for NRMM 260 minutes)
Power is Net Power, as defined in ECE R85
**NRMM with lower power requirements such as forklifts

- Technology is in a mass market application. Significant innovation is expected in this timeframe.
- Transitions do not mean a phase-out from market but a change of R&D emphasis.
- Fluid timings: these technologies have less consensus on when they will occur on the timeline, and may be implemented earlier or later than they appear. They may be adopted in niche vehicle applications.

This roadmap represents a snapshot-in-time view of the global automotive industry propulsion technology forecast for mass market adoption.
Specific application-tailored technologies will vary from region to region.

4

Heavy-duty vehicles and off-highway

High power densities and reliability are needed for these applications, but efficiency is key to maximise energy use. Applications include 44 t trucks and large off-highway vehicles. Torque is included for heavy-duty and off-highway applications as this is more critical than peak power.

Non-road mobile machinery

Non-road mobile machinery (NRMM) in general requires more motors for auxiliary power. Auxiliary power is not explicitly covered by this roadmap. NRMM requires smaller, lighter, decentralised motors, with lower power requirements but high continuous speed and torque requirements.

		2025	2035	2040
HDV	Volumetric power density (kW/l)	6	10	14
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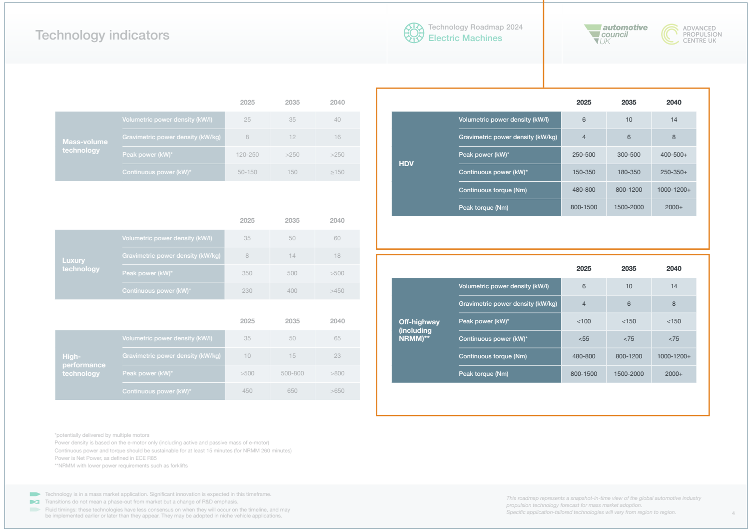

Technology indicators

Technology Roadmap 2024
Electric Machines

automotive council UK
ADVANCED PROPULSION CENTRE UK

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4

3.2 Electric Machines – technology themes

The next few pages of this report will look in-depth at each section of the Electric Machines Roadmap. It is recommended you have the document to hand. However, for ease of reference the relevant page is pictured.

Roadmap technology themes

(Click underlined links to jump to sections)

Machine architectures

Machine architectures show innovations in the magnetic and mechanical design of e-machines and how they are integrated into the wider powertrain system.

Thermal management

Thermal management techniques aim to improve the performance, efficiency, and cost-effectiveness of e-machines by dissipating heat efficiently and maintaining optimal operating temperatures. This is achieved through different cooling strategies and material developments detailed here.

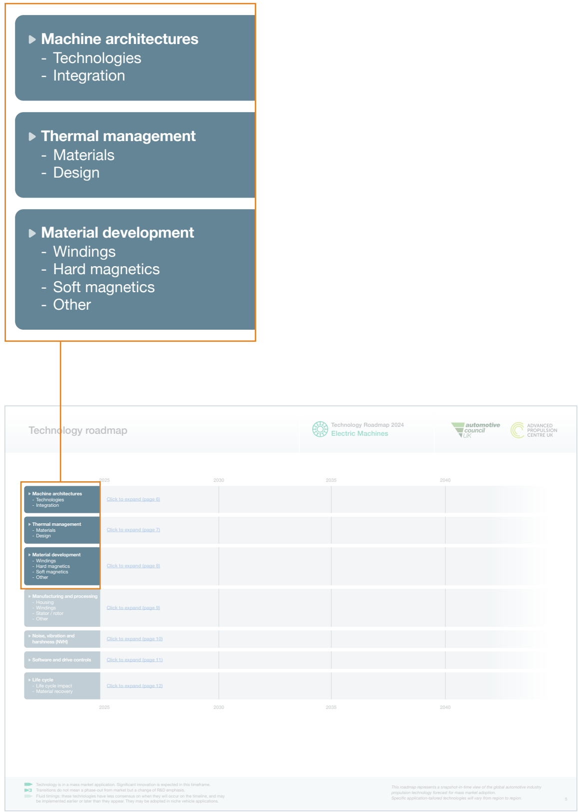
Material development

Windings: Critical components of e-machines, and material development aims to enhance their performance.

Hard magnetics: Represent the largest cost in most electric vehicle (EV) traction motors, so reducing the cost through material, supply-chain and manufacturing innovations is essential. Reducing the automotive industry’s reliance on primary rare earth materials and moving away from sintered neodymium iron boron (NdFeB) magnets are potential innovation areas.

Soft magnetic materials: Used in the core of electric machines. This section highlights material innovations for both electrical steels and soft magnetic composites.

Other: This covers material developments used in other parts of the motor.



Manufacturing and process

Manufacturing innovations and optimising manufacturing processes drives improvements to the efficiency, cost-effectiveness and sustainability of e-machine production. New winding techniques, advanced magnetic manufacturing methods and reducing wet processes in machine assembly are explained in this section.

NVH

Balancing NVH, efficiency and performance are key considerations in e-machine development. This section details the combinations of e-machine design, system-level design, countermeasures and system controls deployed.

Software and drive controls

Software and drive controls work with the e-machine and power electronics to control the electric drive unit (EDU) / e-axle. This section covers developments in this area considering performance and safety.

Life cycle

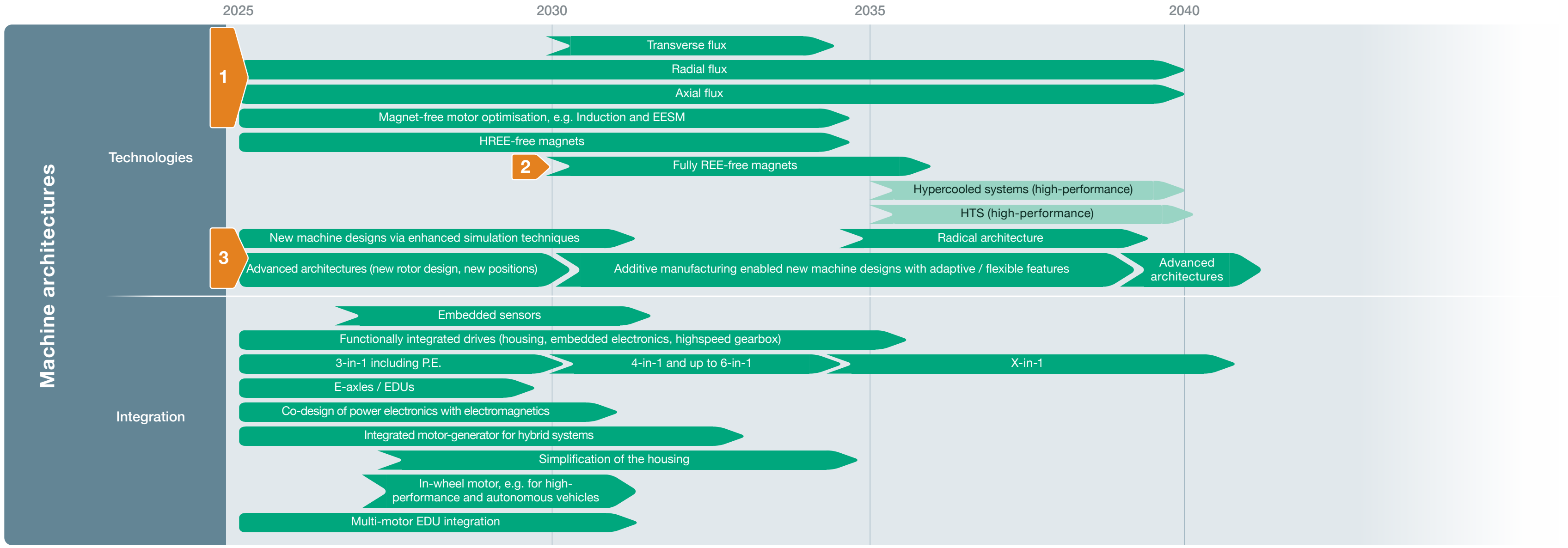
Life cycle impact includes the carbon intensity, environmental impact, resource consumption and recyclability of e-machines as well as their supply chains.

Only by improving all these elements can e-machines be a truly sustainable solution.

Material recovery details developments in recovery and recycling of material from e-machines.

- ▶ **Manufacturing and processing**
  - Housing
  - Windings
  - Stator / rotor
  - Other
- ▶ **Noise, vibration and harshness (NVH)**
- ▶ **Software and drive controls**
- ▶ **Life cycle**
  - Life cycle impact
  - Material recovery

This section looks in detail at the line-by-line activity on the Electric Machines Roadmap. The numbers will direct you to the line being discussed here in detail.



Machine architectures

1 A number of new motor designs are expected to be developed and improved in the near future:

Axial Flux Motors: These motors offer a higher power-to-weight ratio compared to radial flux motors, making them suitable for high-performance EVs. They are compact and can be designed to fit into limited spaces while providing high efficiency.

Radial Flux Motors: These are the traditional choice for many EVs, providing a good balance of performance, efficiency and manufacturability. Continued advancements in materials and design are making them more competitive in terms of power density and thermal management.

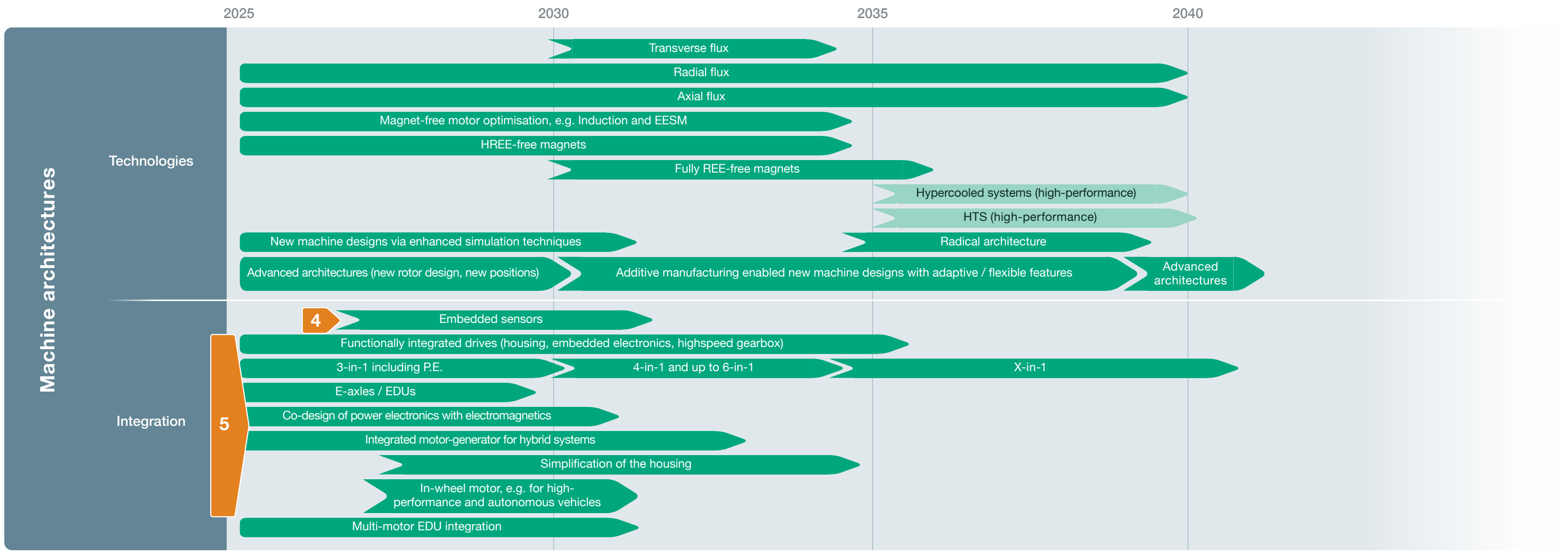
Induction Motors: These are robust and do not rely on rare earth-based magnets, making them cost-effective and sustainable. They are particularly suitable for high-performance EV applications due to their high reliability and thermal performance.

EESMs: Use an electromagnet instead of a permanent magnet, providing similar performance benefits without the dependency on rare earth materials. They offer advantages in terms of field-weakening capability and efficiency at high speeds.

Transverse Flux Motors: These motors provide high torque at low speeds making them ideal for EVs. They use magnetic flux paths that are transverse to the direction of rotor movement, enhancing efficiency and power density.

2 Environmental concerns and supply chain vulnerabilities are driving the reduction of the use of heavy REE. This is likely to lead to a more widespread adoption of rare-earth-free magnets.

3 New motor designs are to be developed using advanced simulation tools that allow for the precise modelling of electromagnetic fields and thermal behaviours, enabling better optimisation of motor designs before physical prototyping.



Machine architectures (continued)

4 Embedding sensors within the motor architecture allows for real-time monitoring of various parameters such as temperature, vibration, and magnetic field strength. This enhances the motor's performance, safety and reliability by enabling predictive maintenance and adaptive control strategies.

5 A developing trend is the integration of different functions and components into a motor, EDU or e-axle.

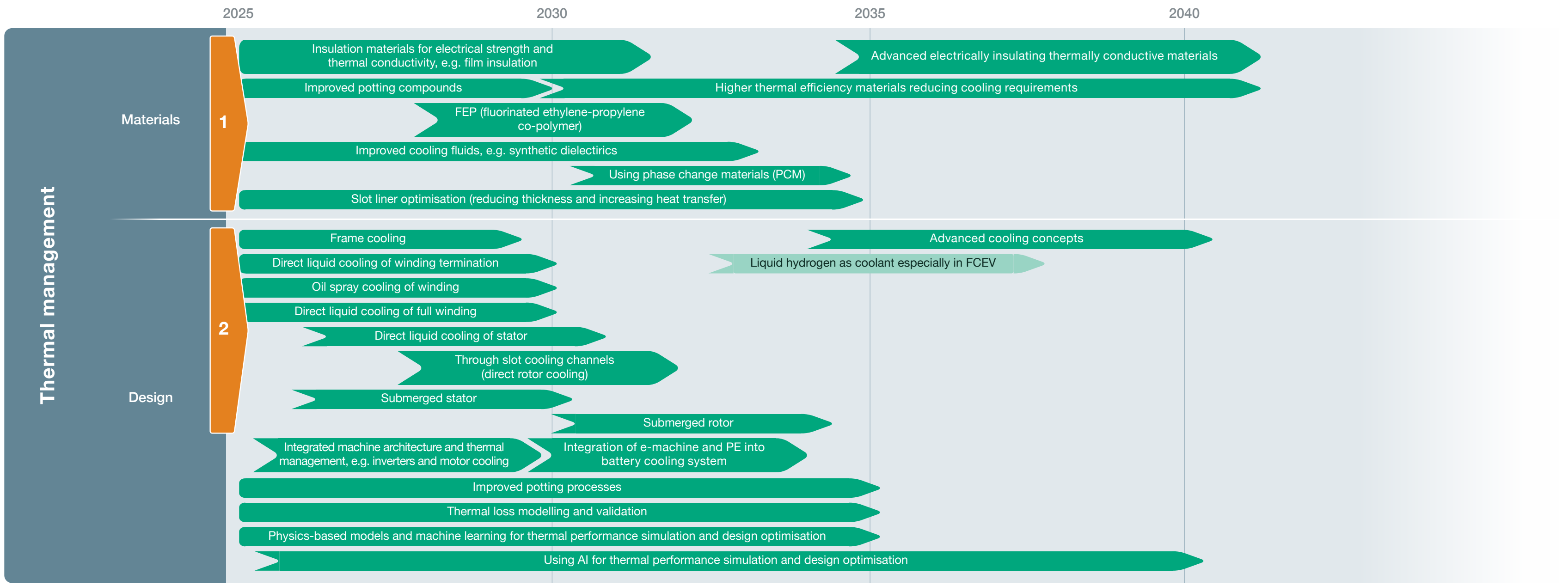
Housing Embedded Electronics: Integrating power electronics directly into the motor housing reduces the space and cooling requirements, contributing to a more compact and efficient design.

High-Speed Gearbox Integration: Combining the motor with high-speed gearboxes within a single housing helps achieve higher power densities and better thermal management.

Designing power electronics and electromagnetics together ensures optimal performance and efficiency. This holistic approach can reduce overall system losses and improve the integration of the motor with the vehicle's power management system.

In-Wheel Motors: Placing motors directly in the wheels can improve efficiency by eliminating mechanical losses in drivetrains, allowing for independent control of each wheel and enhancing vehicle handling and stability.

Hybrid Motors: There will be continued focus and improvement of integrating hybrid ICE transmission with electric motor-generator systems for HDVs.



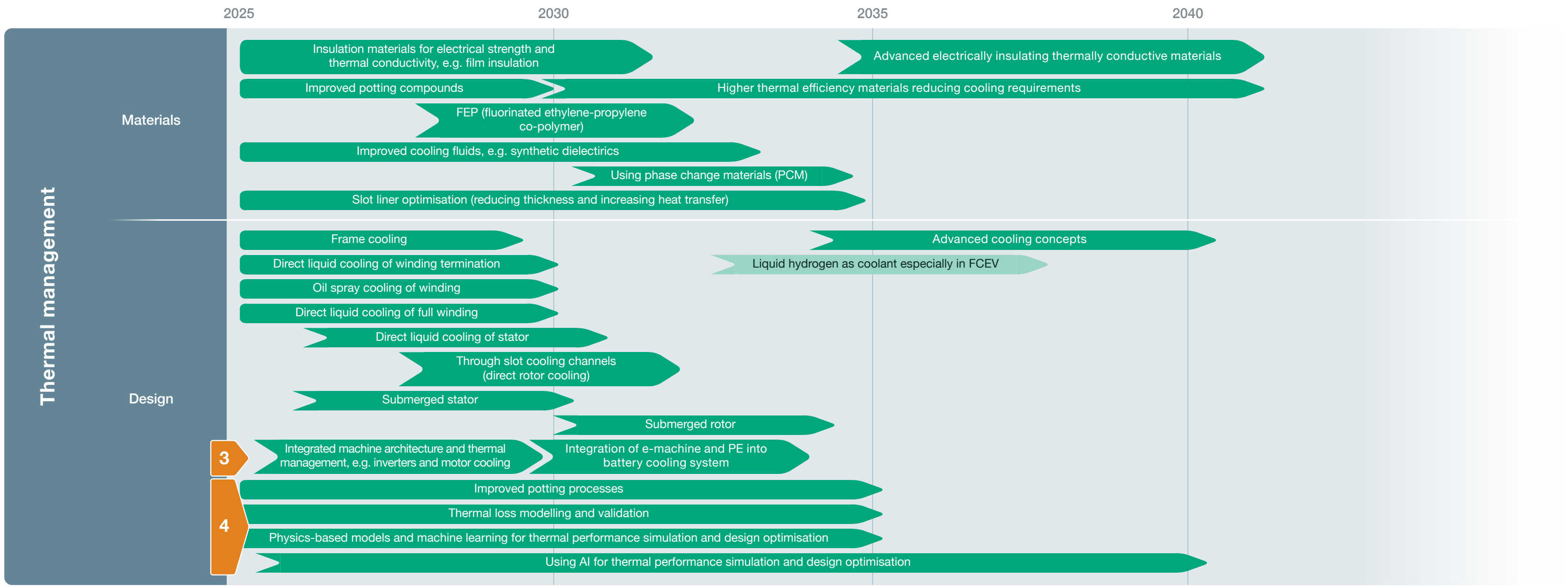
Thermal management

1 Material Advancements: The development of materials like fluorinated ethylene propylene (FEP) and phase change materials (PCM) enhances thermal conductivity while providing necessary electrical insulation. These materials facilitate better heat transfer away from critical motor components without compromising electrical performance.

Using composite materials, such as carbon fibres or graphene-based materials that combine high thermal conductivity with structural strength, can improve the overall thermal management system. These composites can be used in motor housings and other components to enhance heat dissipation.

2 Advanced Cooling Concepts – Direct Liquid Cooling: Utilising direct liquid cooling methods for winding, stator, and rotor components significantly enhances heat dissipation. This approach can help maintain optimal operating temperatures, thereby improving the motor's efficiency and longevity. Direct liquid cooling systems can also be designed to cool specific hotspots within the motor, providing targeted thermal management.

Submerged Rotor / Stator Techniques: Submerging the rotor and / or stator in a cooling fluid increases the surface area for heat exchange, leading to more effective cooling. This method helps manage the high heat loads associated with high-power density motors, ensuring stable performance, even under strenuous driving conditions.

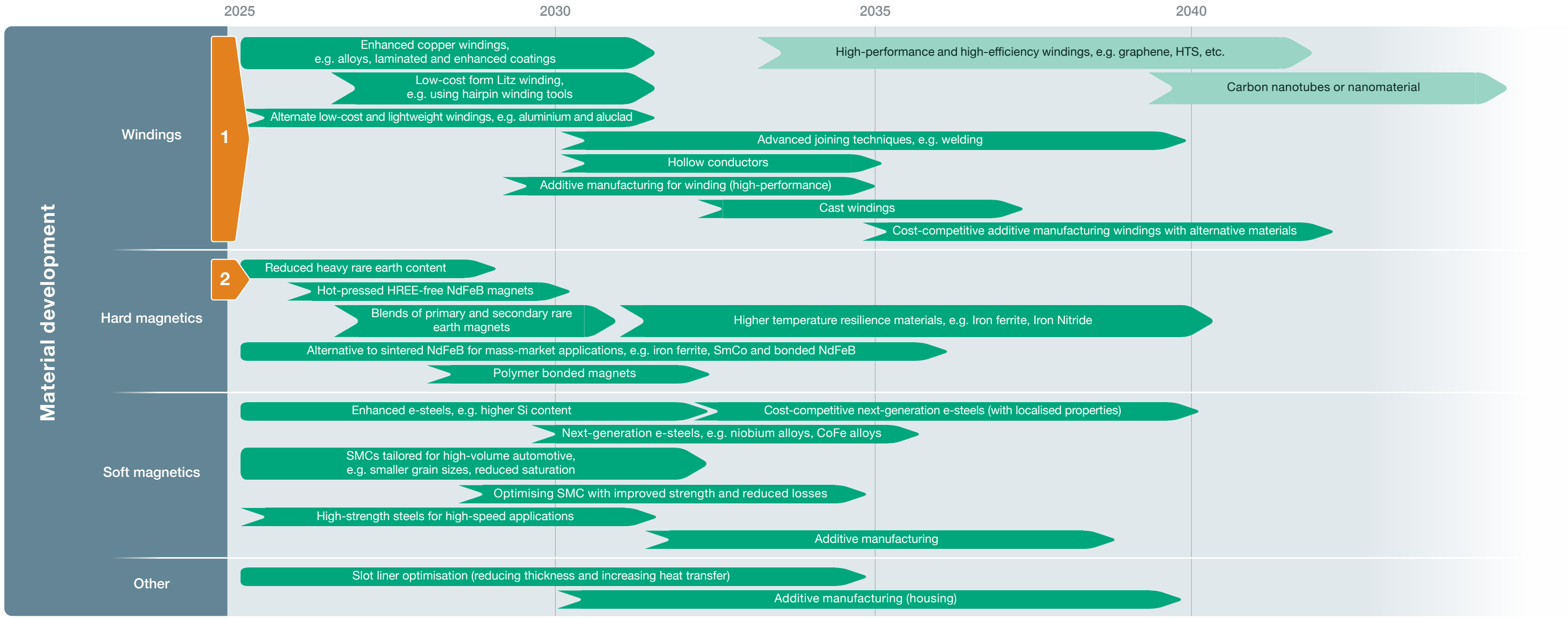


Thermal management (continued)

3 Integration with Vehicle Systems – Combined Cooling Systems: Integrating e-machine cooling systems with the vehicle's existing battery cooling infrastructure can lead to more efficient thermal management. By using a shared cooling loop, overall system complexity and weight can be reduced, which is beneficial for the vehicle's performance and range.

Thermal Management for Power Electronics: Effective cooling solutions for power electronics are crucial as they generate significant heat during operation. Integrating the cooling of power electronics with the motor cooling system ensures comprehensive thermal management for the entire drivetrain.

4 Simulation and Design Optimisation: AI is used to simulate thermal performance and optimise cooling system designs. AI algorithms can analyse vast amounts of data to predict thermal behaviour and suggest design modifications that enhance cooling efficiency. This results in more reliable and efficient thermal management systems tailored for specific EV motor configurations.



Material development

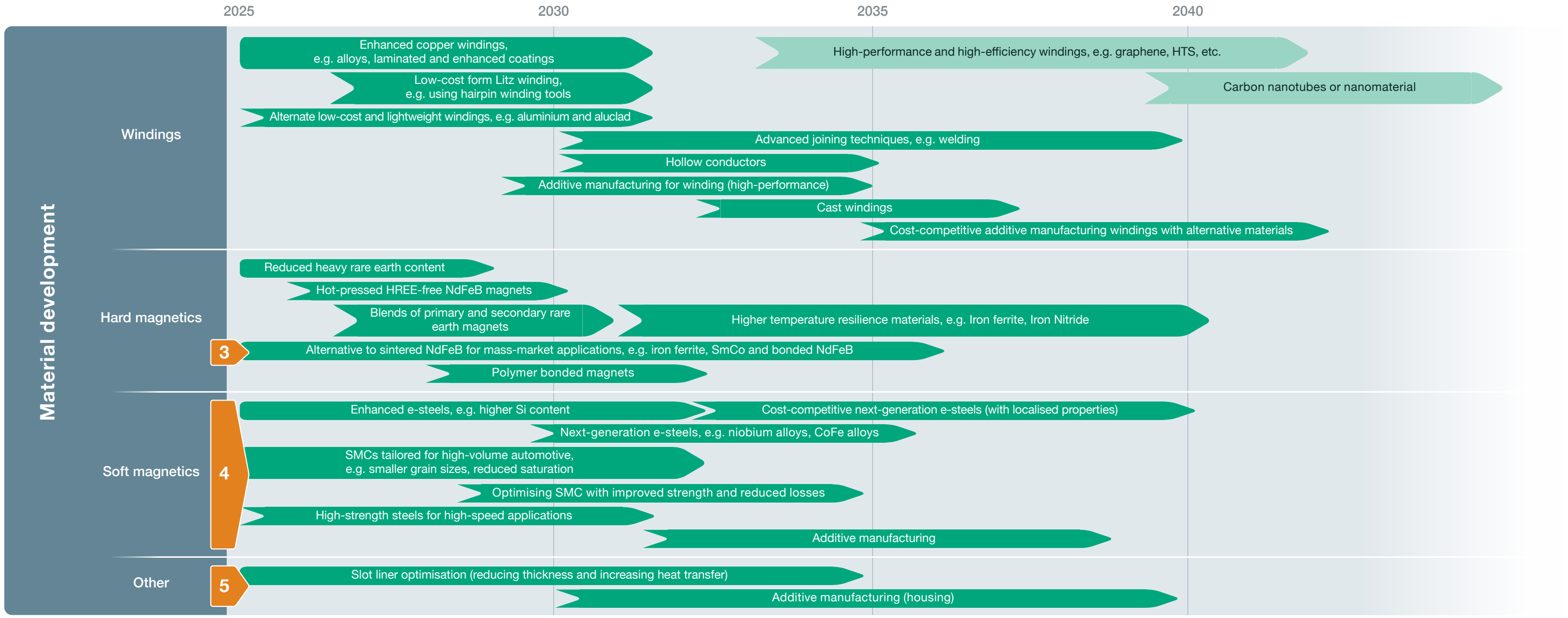
1 Copper Windings: Copper remains the standard material for windings due to its excellent electrical conductivity. Advances in winding techniques, such as hairpin winding, improve the fill factor and reduce resistance, enhancing motor efficiency.

Additive Manufacturing: Utilising additive manufacturing for windings enables more complex designs and optimisation of the winding layout. This can lead to improved thermal management and reduced material wastage.

Alternative Materials: Exploring materials like graphene and high-temperature superconductors (HTSs) for windings offers potential for significant improvements in conductivity and efficiency, though these technologies are currently still in the research phase.

2 Heavy Rare Earth Element Reduction: Efforts to reduce or eliminate heavy REEs (such as dysprosium and terbium) in magnets aim to lower costs and dependency on these critical materials. This involves developing magnets that use less of these elements while maintaining performance.

Blended Primary and Secondary REE Magnets: Combining primary REEs with recycled materials to create magnets that have a reduced environmental impact and improve sustainability. This approach also helps manage supply chain risks associated with REEs.



Material development (continued)

3 Iron Ferrite: As a cost-effective and abundant material, iron ferrite is being explored as an alternative to sintered NdFeB magnets. Though it has a lower magnetic performance, its use can reduce dependency on REEs, making it suitable for mass-market EV applications where cost is a critical factor.

Samarium-Cobalt (SmCo): SmCo magnets offer high thermal stability and resistance to demagnetisation, making them a good alternative for high-performance EV applications. They are more expensive than NdFeB, but provide better performance in high-temperature environments.

4 Higher silicon content: Increasing the silicon content in electrical steels improves their magnetic properties and reduces core losses, which enhances motor efficiency. These advanced steels are crucial for developing motors with higher efficiency and better performance.

Next-generation soft magnetics: Developing new grades of electrical steels and soft magnetic composites (SMC) that offer a balance between cost and performance is essential for making EVs more affordable. These materials aim to provide higher magnetic permeability and lower losses.

5 Other material innovations include improving the slot lining to increase heat transfer and ultimately the motor efficiency, as well as developing material suitable for additive manufacturing of the housing.

Manufacturing and processing

1 Housings can be highly optimised for specific performance targets. This is increasingly driven by machine learning (ML) and AI. Additive manufacturing (3D printing) enables the production of complex motor components that would be difficult or impossible to create using traditional manufacturing methods. This includes intricate cooling channels, optimised geometries for reduced weight and integrated functionalities.

2 There is a focus on efficiency in winding techniques and design. Techniques, such as hairpin winding and concentrated winding, allow for a higher fill factor, which means more conductor material can be packed into the stator slots. This reduces electrical resistance and improves motor efficiency. High fill-factor windings are particularly beneficial for high-performance EV motors where efficiency and power density are critical.

Advanced winding techniques aim to minimise material wastage during the manufacturing process. This not only reduces costs, but also contributes to more sustainable manufacturing practices.

3 Advanced joining techniques are being developed to ensure connections in wires, particularly where multiple gauges might be used, remain robust while ensuring losses due to joins are kept to a minimum.

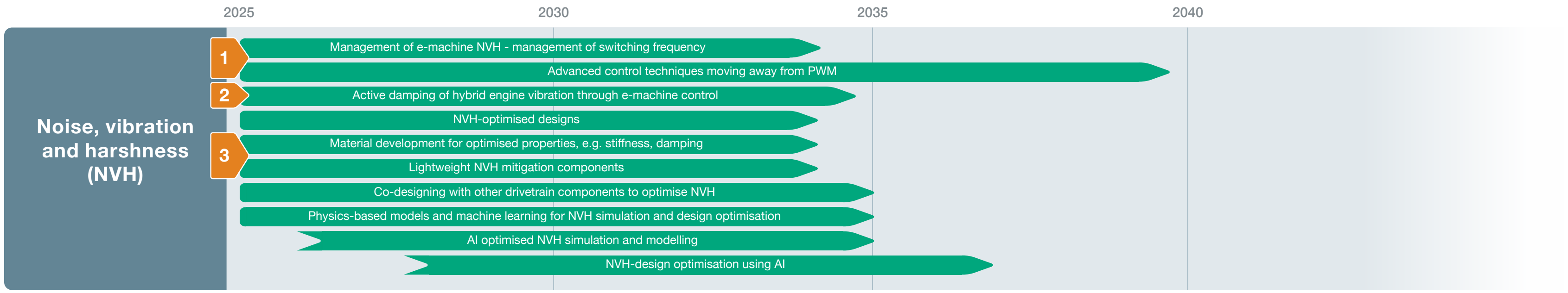
Manufacturing and processing (continued)

4 There is a focus on reducing waste material in multiple parts, including stator and rotor, through design and improved manufacturing techniques. This reduces cost and, by reducing the amount of material used, reduces the life cycle impact.

5 Submerged rotor cooling has the potential to be a very effective cooling technique but is not without challenges. Some of those challenges come in manufacturing a rotor suitable for submerged cooling. These challenges need to be overcome for submerged-rotor cooling to reach full potential.

6 There is a need to remove wet processes and reduce the use of adhesive and potting materials. Moving away from traditional wet processes (such as varnish impregnation) to dry processes can simplify manufacturing and reduce the environmental impact. Dry processes also tend to be faster and less labour intensive. The use of adhesives and potting materials inhibit the recyclability of e-machines. Reducing the use of these structural materials aids in the effort to increase recyclability.

7 AI is used to optimise various manufacturing processes. AI algorithms can analyse production data to identify inefficiencies and suggest improvements, leading to faster production times, reduced costs, and higher-quality products. Implementing AI-driven metrology systems allows for real-time monitoring and control of the manufacturing process. This ensures that each component meets the required specifications, reducing the need for rework and improving overall product quality.



Noise, vibration and harshness (NVH)

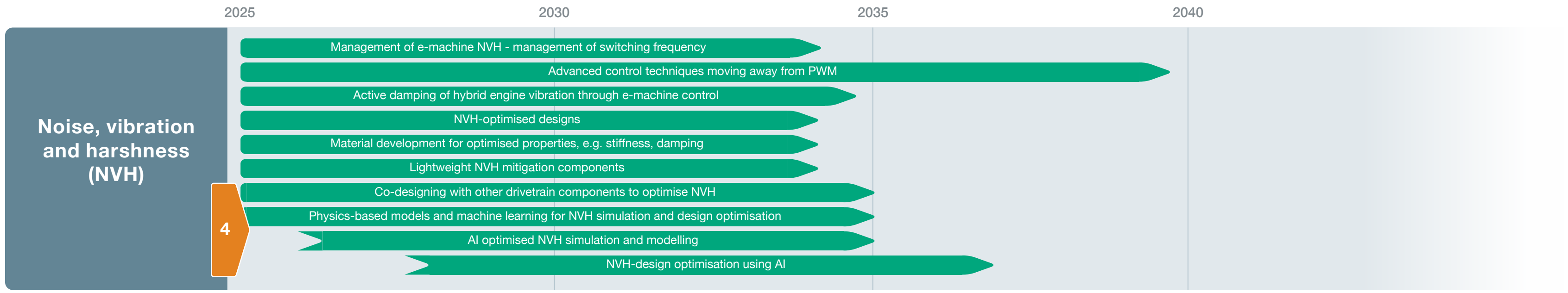
1 By leveraging advanced motor control strategies, such as dynamic torque adjustments and phase shifting, active damping can effectively reduce NVH levels. This is particularly important for maintaining cabin comfort in EVs.

2 Active damping techniques involve using electronic control systems to counteract vibrations generated by the motor. In hybrid engines, these systems can adjust motor parameters in real-time to mitigate vibrations, leading to a smoother and more comfortable ride.

3 Developing materials with optimised stiffness and damping properties helps in absorbing and reducing vibrations. These materials are used in various motor components, such as mounts, housings, and enclosures, to isolate vibrations and minimise noise transmission to the vehicle cabin.

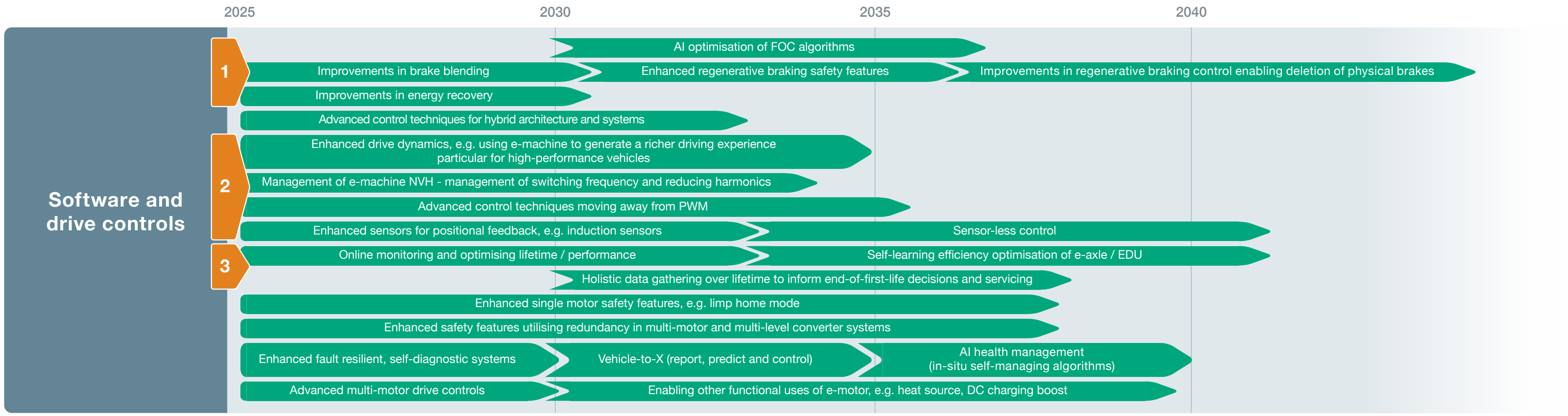
The use of composite materials, which combine different properties such as high strength and excellent damping characteristics, further enhances NVH performance. These materials can be engineered to target specific NVH issues in the motor design.

Lightweight materials and innovative design approaches are used to create NVH mitigation components that do not add significant weight to the vehicle. These components, such as sound-dampening panels and vibration isolators, are crucial for maintaining overall vehicle efficiency while improving NVH characteristics. Integrating NVH mitigation components into the motor design itself, rather than adding them as separate parts, helps in achieving a more compact and efficient solution. This integration also reduces the overall complexity and cost of the motor system.



Noise, vibration and harshness (NVH) (continued)

4 Advanced simulation tools, powered by AI, enable precise modelling of noise, vibration and harshness characteristics in EV motors and can model the entire powertrain or vehicle system. These tools help engineers predict how different motor designs and materials will behave, allowing for optimisation before physical prototypes are built. This leads to quieter and smoother motor operations. AI algorithms can analyse simulation data to suggest design changes that reduce NVH. This iterative optimisation process ensures that the final motor design minimises unwanted noise and vibration, enhancing the driving experience.



Software and drive controls

1 Improvements to brake blending and energy recovery will improve vehicle efficiency. As regenerative braking improves, this enables the deletion of physical brakes, which are considered a source of particulate emissions.

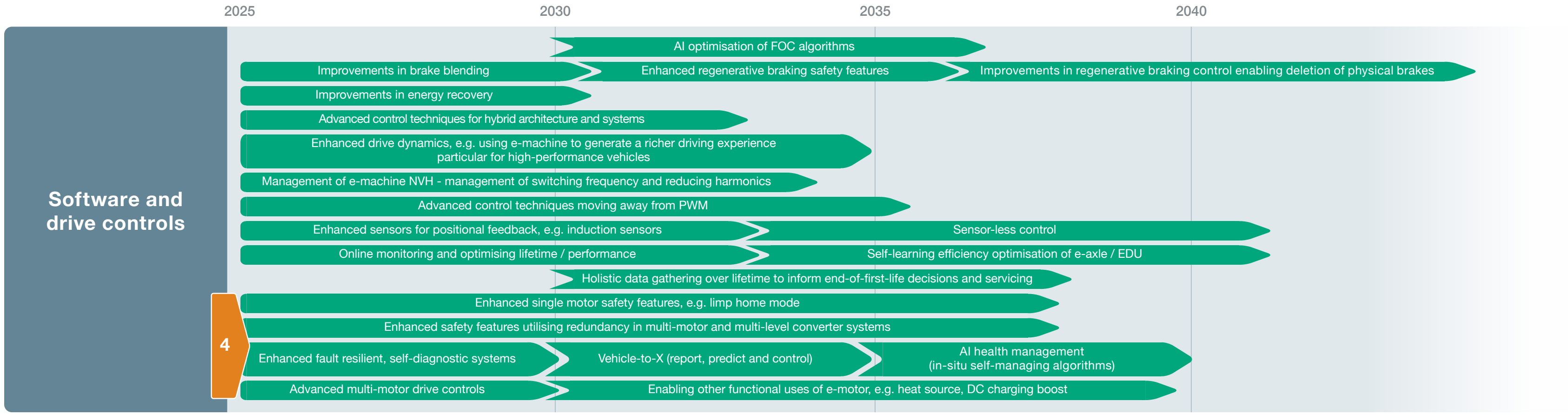
Field oriented control (FOC) algorithms decouple the control of the magnetic flux and torque, allowing for precise and independent control of these parameters. This results in smoother and more efficient motor operation, especially under varying load conditions.

The ability to precisely control torque and flux improves the motor's dynamic response, enhancing performance during acceleration and deceleration. This is crucial for providing a responsive and engaging driving experience in EVs. Efficiently managing regenerative braking through FOC algorithms allows EVs to recover and reuse energy that would otherwise be lost.

2 Integrating motor control with the vehicle's overall control system allows for better coordination between different vehicle subsystems. This includes coordinating with the battery management system (BMS), regenerative braking, and thermal management systems to optimise performance and efficiency. By optimising the interaction between the motor and other vehicle components, integrated vehicle control can significantly enhance energy efficiency. This leads to longer driving ranges and better utilisation of battery capacity.

3 Embedded sensors can be used to monitor motor performance and feed into model predictive control (MPC) techniques. MPC uses dynamic models of the motor and vehicle to predict future states and optimise control inputs. This results in more precise and efficient motor control, enhancing performance and reducing energy consumption.

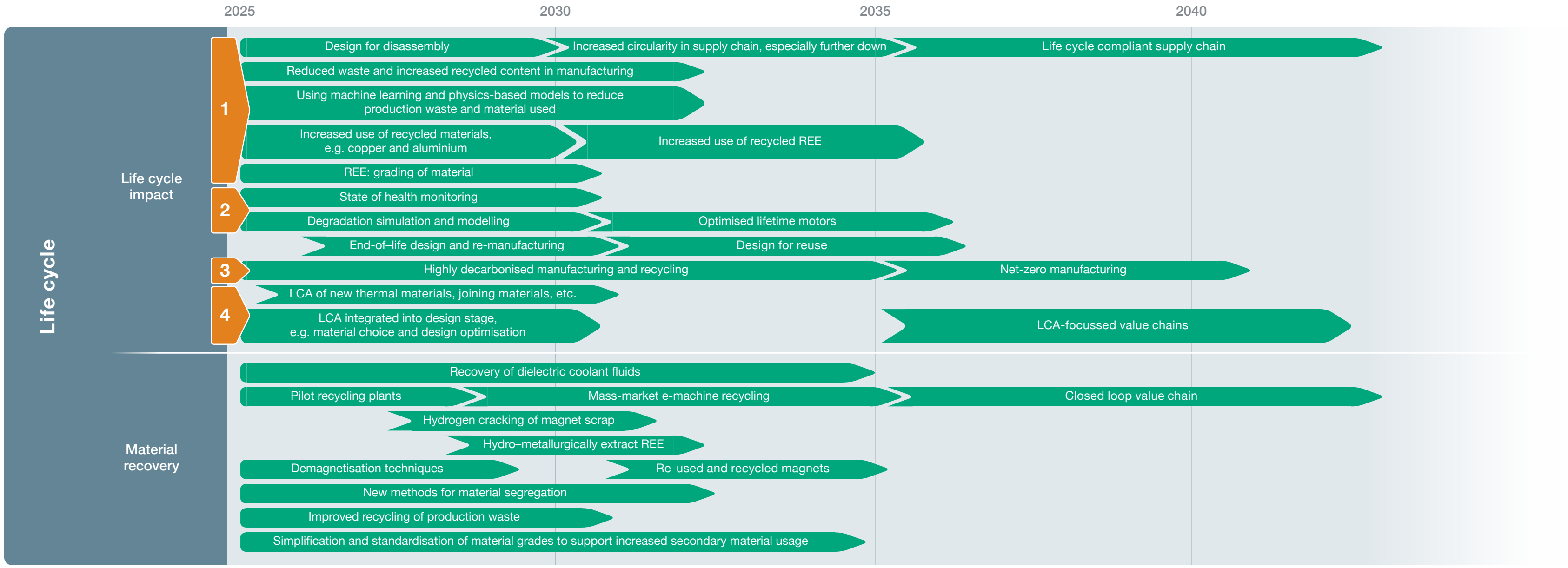
MPC can adapt to changing driving conditions in real time, ensuring optimal motor performance under various scenarios. This includes adjusting to different loads, speeds, and road conditions, thereby improving the overall driving experience. This data can also feed into models of the lifetime of the motor, informing service and end-of-life decision-making.



Software and drive controls (continued)

4 Incorporating fail-safe mechanisms and redundancy in drive control systems ensures that the motor can continue to operate safely, even in the event of a control system failure. This is critical for maintaining vehicle safety and reliability.

AI can be used to detect anomalies and diagnose potential issues in the motor control system. Early detection of faults allows for timely maintenance and reduces the risk of unexpected failures.



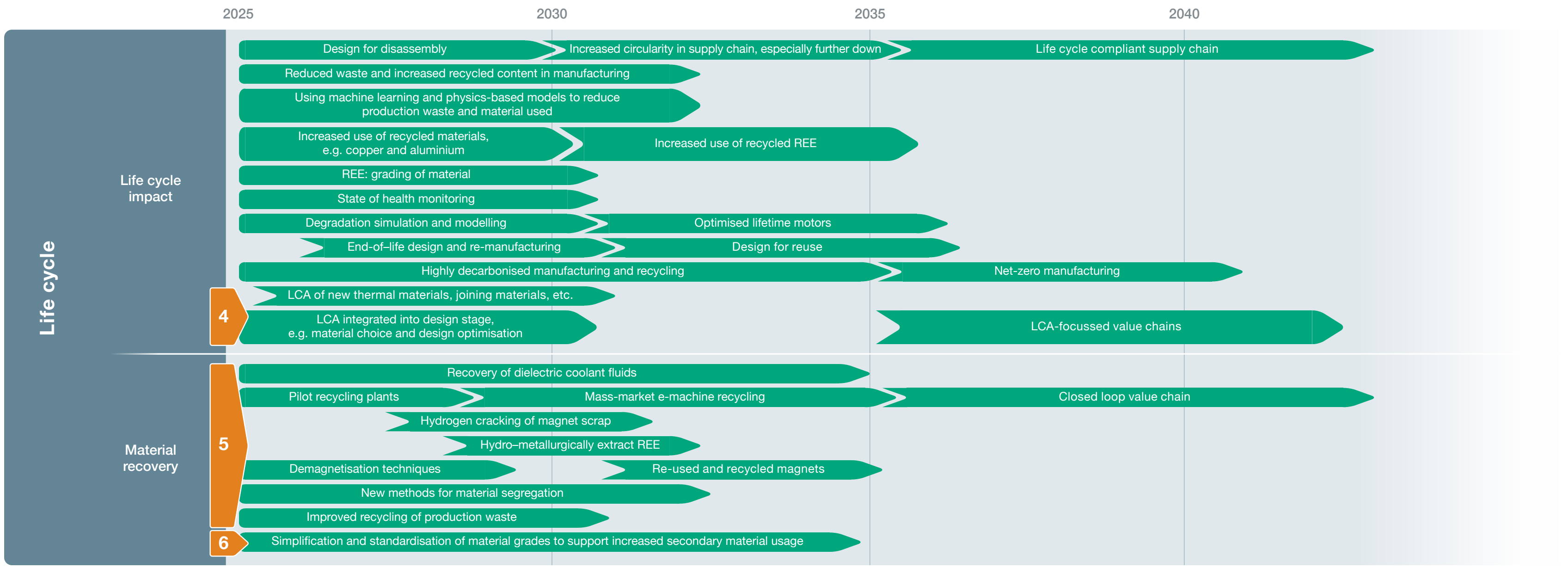
Life cycle

1 To improve circularity, production waste will be reduced and more recycled content will be integrated into the production phase. To increase the amount of recycled material available, there is a need to design for disassembly. With some designs that have a high level of integration with other vehicle components, it could be challenging. It is possible that regulation will be introduced to govern recycled content, most likely for REE magnets, similar to batteries to govern critical mineral recycling efficiencies and recycled content.

ML and AI are being leveraged in the production design phase to help reduce waste and test tolerance for different material grades that come from recycling pathways.

2 Improvements in state-of-health monitoring and the simulation of motor-lifetime degradation will enable optimised designs that improve lifetime and potentially enable reuse of components. Through better understanding from real-world monitoring and simulation, designs can be improved to better enable reuse and re-manufacturing.

3 Manufacturing and recycling are expected to be decarbonised through the use of local power generation and microgrids. Achieving true net-zero manufacturing with CO_2 emissions is somewhat harder as the entire supply chain needs decarbonising, but it is possible this will happen in some regions within the timeframe of this roadmap.



Life cycle (continued)

4 Life cycle analysis (LCA) is being used in the design phase to inform material choice and optimise material usage. As new materials are introduced, they will require assessing against life cycle impact. Currently, the focus is generally on the manufacturing of the parts, but moving forward the scope of LCA will broaden to encompass the full value chain, including use, reuse, re-manufacturing and recycling.

5 To achieve a closed loop value chain, a great deal of development is needed in the recycling materials used in electric motor manufacturing. Particular focus is being paid to magnets as they are a high-value component. However, new methods for material segregation are being developed, not only to segregate magnet material, but also to ensure high-grade copper can be segregated for reuse alongside segregating the steel and aluminium.

6 To enable greater use of recycled material, there is a need for the simplification of material grades across all materials. Each manufacturer tends to have their own material card or unique design, this is especially true of magnets. When recycling is conducted via a hub and spoke model, where vehicles are broken down and parts sent to a hub for recycling, different compositions or material grades become mixed and become unusable in a new product without extra processing. Simplifying grades to enable recyclers to produce material grades at scale would improve the economics of recycling and using recycled materials.

Glossary

APC	Advanced Propulsion Centre UK
AI	Artificial intelligence
BEV	Battery electric vehicle
BMS	Battery management system
CO2	Carbon dioxide
CO_2-eq	Carbon dioxide equivalent greenhouse gas effect
EDU	Electric drive unit
EESM	Electrically excited synchronous motors
EV	Electric vehicle
EU	European Union
FOC	Field oriented control
FEP	Fluorinated ethylene propylene
FCEV	Fuel cell electric vehicle
HDV	Heavy-duty vehicle
HTS	High-temperature superconductors
ICE	Internal combustion engine
IoT	Internet of things
LLM	Large language models
LCA	Life cycle analysis
LDV	Light-duty vehicle
ML	Machine learning
MPC	Model predictive control
NEV	New energy vehicle
NdFeB	Neodymium iron boron
NRMM	Non-road mobile machinery
NVH	Noise, vibration and harshness
OEM	Original equipment manufacturer
R&D	Research and Development
REE	Rare earth elements
SMC	Soft magnetic composites
SmCo	Samarium-cobalt
xEV	Electromotive vehicle
ZEV	Zero emissions vehicle

System-Level Roadmaps

- Mobility of People
- Mobility of Goods

Technology Roadmaps

- Electric Machines
- Power Electronics
- Electrical Energy Storage
- Lightweight Vehicle and Powertrain Structures
- Internal Combustion Engines
- Hydrogen Fuel Cell System and Storage

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ADVANCED PROPULSION CENTRE UK

Established in 2013, the Advanced Propulsion Centre UK (APC), with the backing of the UK Government's Department for Business and Trade (DBT), has facilitated funding for 304 low-carbon and zero-emission projects involving 538 partners. Working with companies of all sizes, this funding is estimated to have helped to create or safeguard over 59,000 jobs in the UK. The technologies and products that result from these projects are projected to save over 425 million tonnes of CO_2.

The APC would like to acknowledge the extensive support provided by industry and academia in developing and publishing the roadmaps.

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