



Electric Machines

Industry Challenges 2020-2035+

This document outlines the R&D challenges for Electric Machines across a diverse range of automotive applications. The industry challenges are intrinsically linked with the 2020 Automotive Council roadmaps and should be read in conjunction with the narrative report to provide a context and background to the rationale behind the challenges.

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An introduction to the industry challenge report



The industry challenges present the technical barriers to commercialising automotive powertrain technology in the short, medium and long term. Developed via a consensus process, this report highlights the most significant technology themes and specific R&D examples to springboard innovation. A list of recommendations on how this content can be taken forward by industry, academia and government is provided below:



Industry

- Review in-house R&D priorities against the industry consensus challenges provided in this report
- Provide guidance to companies wanting to transition into low-carbon automotive propulsion technologies
- Provide a sense-check for start-ups to help guide their technology focus



Academia

- Address the long-term scientific challenges that need to be overcome
- Align internal university research with the needs of the automotive industry
- Build a bridge with industry to execute and industrialise research



Government

- Understand the R&D challenges required to industrialise low-carbon propulsion technologies
- Identify R&D challenges that may require additional funding
- Understand the challenges facing different mobility sectors and adjust policy, strategy and funding support accordingly

A guide to reading the industry challenges



Technology Challenge

A Technology Challenge is a broad issue that OEMs and the supply chain face when commercialising technologies for the automotive industry.

Examples of research topics

Examples of research topics illustrate potential projects that could overcome the Technology Challenge. These are not intended to be an exhaustive list but a snapshot of areas captured in the industry engagement process.

Time horizon

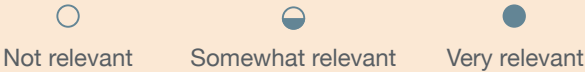
The filled bar represents when research is likely to be completed. For example:



Technology Challenge	Examples of research topics	Time Horizon	Cost effective, high volume	Power dense, high performance	High power, ultra-high efficiency
New machine designs and architectures to achieve a step change in performance	New rotor designs utilising advanced manufacturing methods to deliver low cost solutions.	2020-2025 			
	Design innovations that reduce rotor losses and allow for single tooth windings.				
	Permanent magnet machines (Surface permanent magnet and interior permanent magnet) designed for disassembly and recyclability that are focussed on enabling a circular supply chain.				

Attributes and vehicle applications

The columns refer to the different attributes or vehicle applications related to each technology theme. The dots represent how relevant overcoming this topic would be to each application area. The three attributes are explained in more depth in the following pages.

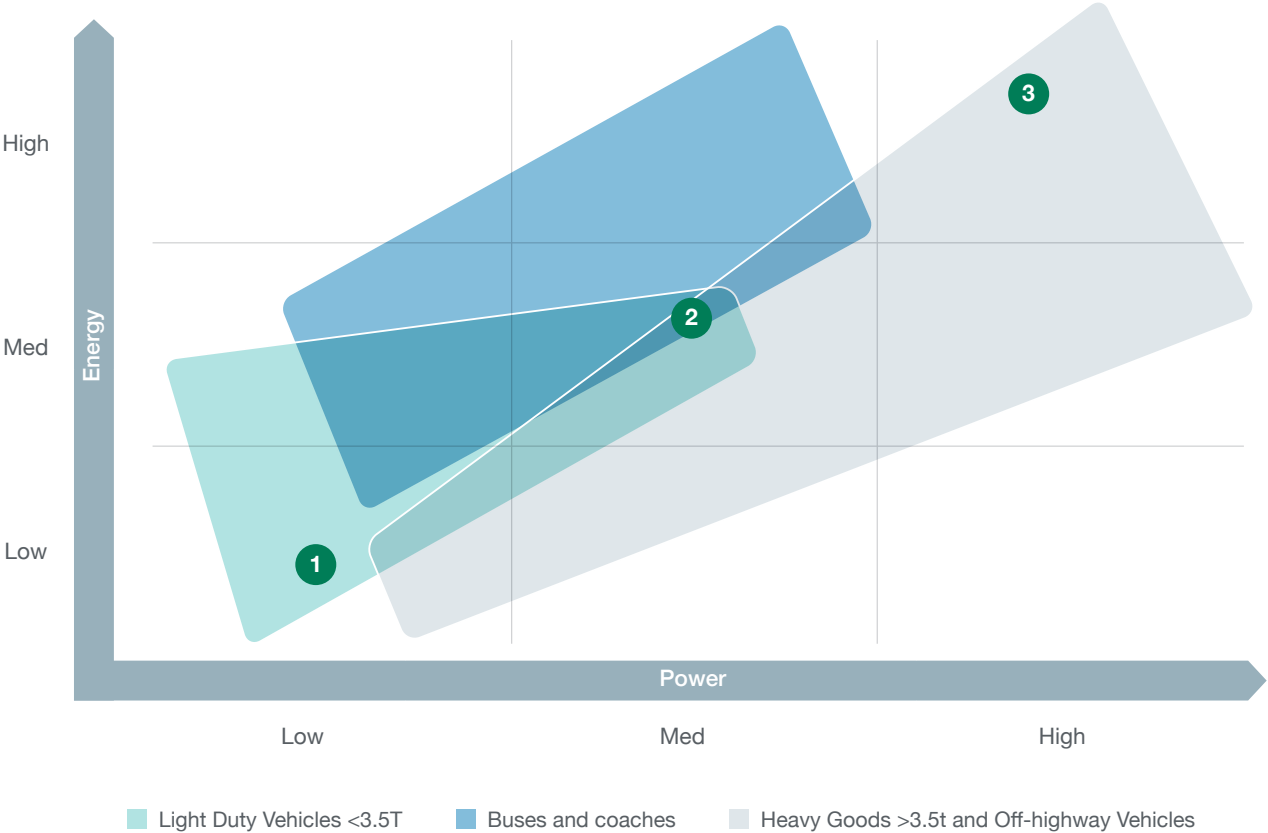


Attributes and vehicle applications



Energy-power spectrum across applications

Propulsion systems are tailored to specific power and energy demands, based on their use case and duty cycle. The graph below presents an outline of principle mass-market products.



The 2020 roadmap provides values for (1) Cost effective, high volume indicators.

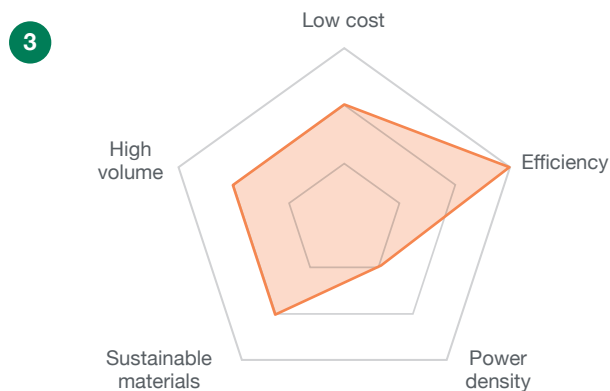
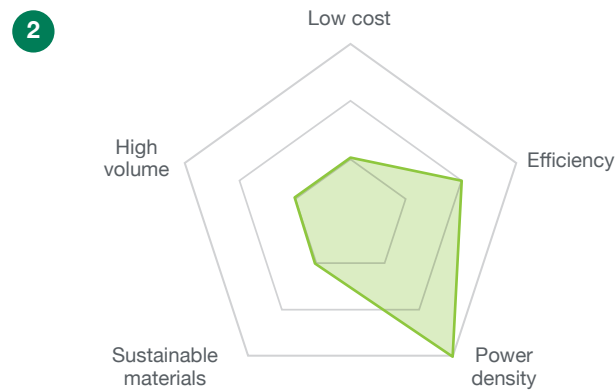
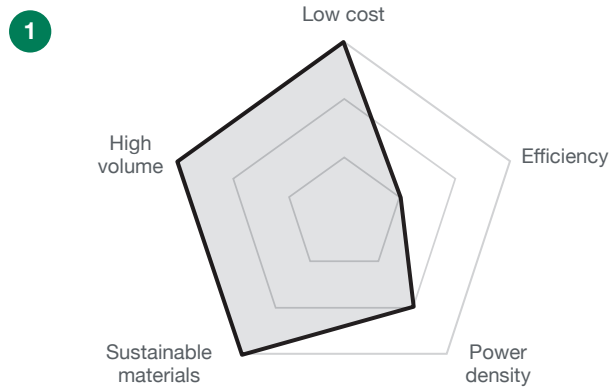
Values for (2) Power dense, high performance and (3) High power, ultra-high efficiency applications will be developed with industry in due course.

- 1 Cost effective, high volume orientated:**
Achieving economies of scale at a low cost is paramount for these products. Applications include high volume passenger car and delivery vans (majority 400V).
- 2 Power dense, high performance orientated**
High power densities are required with cost a less decisive factor. Applications include performance passenger cars, buses and some medium duty vehicles (800V prevalent).
- 3 High power, ultra high efficiency orientated**
High power densities and reliability are needed for these applications but efficiency is key to maximise energy use. Applications include 44 tonne trucks and large, off-highway vehicles (700-1,200V).



Attributes and vehicle applications – typical performance characteristics

The purpose of the radar plots is to demonstrate the attributes industry prioritise across this technology. Each attribute is ranked from 1-3 to show the varying emphasis per application. Note: the plots are not constructed using absolute values.



1 Cost effective, high volume orientated:

Achieving economies of scale at a low cost is paramount for these products. Applications include high volume passenger car and delivery vans (majority 400V).

2 Power dense, high performance orientated

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

3 High power, ultra high efficiency orientated

High power densities and reliability are needed for these applications but efficiency is key to maximise energy use. Applications include 44 tonne trucks and large, off-highway vehicles (700-1,200V).

Electric Machines

Technology challenges
and research topics



Technology challenges for electric machines

The technology challenges listed here represent the highest priority R&D themes that industry and academia regard as critical for innovation.

New machine designs and architectures to achieve a step change in performance

[See challenge](#)

Simulation, controls, sensors and intelligent monitoring to improve machine performance and reliability

[See challenge](#)

Machine designs suited for new mobility products

[See challenge](#)

Improved thermal management and insulation solutions

[See challenge](#)

Winding techniques and materials for cost-effective or high-performance applications

[See challenge](#)

Enhancing the material properties and production techniques for electrical steels and soft magnetic composites

[See challenge](#)

Hard magnetics solutions targeting cost improvements or high performance

[See challenge](#)

Innovate the existing rare earth magnet supply chain to mitigate against supply risk

[See challenge](#)

Towards rare earth free magnet electric machines

[See challenge](#)

Recycling, remanufacturing, lower energy consumption and circular economy supporting LCA

[See challenge](#)

LCA = Life cycle assessment

The above challenges are not listed in a prioritised order. They represent all the themes industry and academia regard as critical for innovation.



Electric machines – technology challenges and research topics (1/9)

The research topics listed below predominately focus on the **Machine Architecture and Integration** section of the electric machines’ technology roadmap, with linkages to themes on the **Manufacturing Innovations** section.

Technology Challenge See all challenges	Examples of research topics	Time Horizon	Cost effective, high volume	Power dense, high performance	High power, ultra-high efficiency
New machine designs and architectures to achieve a step change in performance	New rotor designs utilising advanced manufacturing methods to deliver low cost solutions.	2020-2025 <div></div>	<div></div>	<div></div>	<div></div>
	Design innovations that reduce rotor losses and allow for single tooth windings.		<div></div>	<div></div>	<div></div>
	Permanent magnet machines – surface permanent magnet (SPM) and interior permanent magnet (IPM) – designed for disassembly and recyclability that are focussed on enabling a circular supply chain.		<div></div>	<div></div>	<div></div>
	Machine designs delivering a step change in Noise, Vibration and Harshness (NVH) performance, e.g., using high speeds or alternative motor constructions.	2020-2035 <div></div>	<div></div>	<div></div>	<div></div>
	Modular machine construction and simplified winding processes to achieve economies of scale, lower costs and enable easy disassembly.		<div></div>	<div></div>	<div></div>
	Machines that are optimised for higher rotational speeds and switching frequencies enabled by innovations in wide-bandgap (WBG) materials.		<div></div>	<div></div>	<div></div>
	Machine designs achieving significantly lower field weakening and higher efficiency.		<div></div>	<div></div>	<div></div>
	Commercially viable electrostatic motors that can deliver the power and torque density required for automotive applications.		<div></div>	<div></div>	<div></div>
	Superconducting electric machines that leverage advances in high temperature superconductors.	2030-2035+ <div></div>	<div></div>	<div></div>	<div></div>

Notes: The examples of research topics are intended to provide topics emerging from industry workshops while developing the roadmaps. These are not a complete and exhaustive list and make no reference to priorities within R&D.



Electric machines – technology challenges and research topics (2/9)

The research topics listed below predominately focus on the **Machine Architecture and Integration** section of the electric machines’ technology roadmap, with linkages to several other themes on the roadmap.

Technology Challenge See all challenges	Examples of research topics	Time Horizon	Cost effective, high volume	Power dense, high performance	High power, ultra-high efficiency
Simulation, controls, sensors and intelligent monitoring to improve machine performance and reliability	Validate the accuracy of simulation for high volume machine manufacturing techniques.	2020-2025 <div></div>	<div></div>	<div></div>	<div></div>
	Develop high fidelity multi-physics simulation capability for virtual product verification.		<div></div>	<div></div>	<div></div>
	Develop encoders and speed sensors to increase machine performance and reliability.		<div></div>	<div></div>	<div></div>
	Initiatives to embed sensor technology and associated high-volume manufacturing techniques that increase knowledge of duty cycle performance for machine optimisation.		<div></div>	<div></div>	<div></div>
	Improved 3D modelling accuracy of oil spray cooling while reducing simulation times.		<div></div>	<div></div>	<div></div>
	Develop sensor and software techniques to monitor and report insulation state-of-health.	2020-2035 <div></div>	<div></div>	<div></div>	<div></div>
	Develop advanced condition monitoring systems for machine health, utilising embedded on-board technologies to accurately predict faults, service schedules and increase life.	2025-2035 <div></div>	<div></div>	<div></div>	<div></div>
	Initiatives to reduce the number of signals and sensors within machines that are used for prognostic data collection.	2025-2035+ <div></div> +	<div></div>	<div></div>	<div></div>

Notes: The examples of research topics are intended to provide topics emerging from industry workshops while developing the roadmaps. These are not a complete and exhaustive list and make no reference to priorities within R&D.



Electric machines – technology challenges and research topics (3/9)

The research topics listed below predominately focus on the **Machine Architecture and Integration** section of the electric machines’ technology roadmap.

Technology Challenge See all challenges	Examples of research topics	Time Horizon	Cost effective, high volume	Power dense, high performance	High power, ultra-high efficiency
Machine designs suited for new mobility products	Develop a better understanding of duty cycles for urban mobility, e.g. connected and autonomous vehicles (CAV), last mile delivery vehicles, to define design requirement and support cost, weight, performance, NVH optimisation for future vehicles.	2020-2025 <div></div>	<div></div>	<div></div>	<div></div>
	Low cost motorised concepts and designs for last mile delivery vehicles.	2020-2035 <div></div>	<div></div>	<div></div>	<div></div>
	Light-weight machine designs for new mobility solutions.		<div></div>	<div></div>	<div></div>
	Highly integrated, small package solutions for integrated drives including; e-machines, inverter and drivetrain combinations.		<div></div>	<div></div>	<div></div>

Notes: The examples of research topics are intended to provide topics emerging from industry workshops while developing the roadmaps. These are not a complete and exhaustive list and make no reference to priorities within R&D.



Electric machines – technology challenges and research topics (4/9)

The research topics listed below predominately focus on the **Thermal Management** section of the electric machines’ technology roadmap.

Technology Challenge See all challenges	Examples of research topics	Time Horizon	Cost effective, high volume	Power dense, high performance	High power, ultra-high efficiency
Improved thermal management and insulation solutions	Thinner, more robust insulation materials, capable of higher temperature operation and reduced thermal resistance.	2020-2025 <div></div>	<div></div>	<div></div>	<div></div>
	New methods and concepts for direct cooling of windings and slots.		<div></div>	<div></div>	<div></div>
	Over-moulded teeth solutions with high thermal conductivity materials.		<div></div>	<div></div>	<div></div>
	Dynamic cooling control to minimise circulation losses and thermal cycling.	2020-2035 <div></div>	<div></div>	<div></div>	<div></div>
	Alternative mass-market solutions to direct cooling (e.g. hollow conductors, flooded stator, oil spray).		<div></div>	<div></div>	<div></div>
	Next generation cooling concepts, including heat pipes and phase change materials, additive manufacturing of heat exchangers.		<div></div>	<div></div>	<div></div>
	Targeted cooling strategies within machine components e.g. cooling of rotor to allow lower grade magnets, or, better magnet temperature distribution to enable removal of heavy rare earth such as Dysprosium.		<div></div>	<div></div>	<div></div>
	Improved thermal conductivity (20W/mK) insulation materials.	2025-2035 <div></div>	<div></div>	<div></div>	<div></div>

Notes: The examples of research topics are intended to provide topics emerging from industry workshops while developing the roadmaps. These are not a complete and exhaustive list and make no reference to priorities within R&D.



Electric machines – technology challenges and research topics (5/9)

The research topics listed below predominately focus on the **Windings** section of the electric machines’ technology roadmap, with linkages to the **Manufacturing Innovations** section.

Technology Challenge See all challenges	Examples of research topics	Time Horizon	Cost effective, high volume	Power dense, high performance	High power, ultra-high efficiency
Winding techniques and materials for cost-effective or high-performance applications	Develop high volume automated production processes to increase packing density of windings at reduced costs.	2020-2025 <div></div>	<div></div>	<div></div>	<div></div>
	Innovation in wire joining and phase tray techniques.		<div></div>	<div></div>	<div></div>
	Cost effective multi stranding (e.g. Litz) and lamination of windings.		<div></div>	<div></div>	<div></div>
	Develop insulation technology specific to wide-bandgap (WBG) power electronics integration into e-machines and electric drive units (EDU).		<div></div>	<div></div>	<div></div>
	Windings designs and production techniques that minimise end turning heights.		<div></div>	<div></div>	<div></div>
	Manufacturing processes with shorter cycles for windings insulation materials that operate at higher temperatures (e.g. 300°C).	2020-2035 <div></div>	<div></div>	<div></div>	<div></div>
	High volume additive layer manufacturing for windings.		<div></div>	<div></div>	<div></div>
	Lower cost machines with aluminium windings that maintain the weight, size and power density as copper wound machines.		<div></div>	<div></div>	<div></div>
	New winding materials with improved electrical conductivity suitable for high-volume production, including aspects such as carbon nanotubes.		<div></div>	<div></div>	<div></div>
	Scaling up high temperature superconductor materials for niche, high power automotive applications.	2030-2035+ <div></div>	<div></div>	<div></div>	<div></div>

Notes: The examples of research topics are intended to provide topics emerging from industry workshops while developing the roadmaps. These are not a complete and exhaustive list and make no reference to priorities within R&D.



Electric machines – technology challenges and research topics (6/9)

The research topics listed below predominately focus on the **Soft Magnetism** section of the electric machines’ technology roadmap, with linkages to the **Manufacturing Innovations** section.

Technology Challenge See all challenges	Examples of research topics	Time Horizon	Cost effective, high volume	Power dense, high performance	High power, ultra-high efficiency
Enhancing the material properties and production techniques for electrical steels and soft magnetic composites	Fast, flexible laminate cutting without impairment to the material properties.	2020-2025 <div></div>	●	●	●
	Very thin, low cost laminations, permitting increased frequency operation (e.g. Amorphous iron).		◐	●	◐
	Optimised soft magnetic composites (SMC) for high frequency operation.		◐	●	●
	Treatment of laminations to modify permeability and saturation.	2020-2035 <div></div>	●	●	●
	Additive layer manufacturing of SMC at high-volume production rates.		◐	●	◐
	Lower loss steels, with increased silicon content, at lower prices.		●	●	●

Notes: The examples of research topics are intended to provide topics emerging from industry workshops while developing the roadmaps. These are not a complete and exhaustive list and make no reference to priorities within R&D.



Electric machines – technology challenges and research topics (7/9)

The research topics listed below predominately focus on the **Hard Magnetics** section of the electric machines’ technology roadmap, with linkages to the **Manufacturing Innovations** section.

Technology Challenge See all challenges	Examples of research topics	Time Horizon	Cost effective, high volume	Power dense, high performance	High power, ultra-high efficiency
Hard magnetics solutions targeting cost improvements or high performance	Design motors that use “dry retention” systems for the permanent magnets, eliminating the use of adhesives.	2020-2025 <div></div>	<div></div>	<div></div>	<div></div>
	Improving the robustness of magnets for high-volume production and automated processes.		<div></div>	<div></div>	<div></div>
	Net (or near net) shape manufacturing techniques for permanent magnets (e.g., metal injection moulding, casting rotor magnets onto rotor shaft, 3D printing).		<div></div>	<div></div>	<div></div>
	Design motors based on alternative high performance permanent magnet materials, e.g., hot formed Neodymium Iron Boron magnets (MQ3), net-shaped or laminated.		<div></div>	<div></div>	<div></div>
	Permanent magnets that have improved strength, durability, electrical resistivity and higher temperature capability.	2020-2035 <div></div>	<div></div>	<div></div>	<div></div>
	New techniques to create laminated (rolled) permanent magnets <2mm thickness without machining losses and grains <1micron.		<div></div>	<div></div>	<div></div>
	Lower cost and improved environmental rare earth processing methods i.e. from rare earth oxides to alloy powders.		<div></div>	<div></div>	<div></div>

Notes: The examples of research topics are intended to provide topics emerging from industry workshops while developing the roadmaps. These are not a complete and exhaustive list and make no reference to priorities within R&D.



Electric machines – technology challenges and research topics (8/9)

The research topics listed below predominately focus on the **Hard Magnetics** section of the electric machines’ technology roadmap, with linkages to the **Life Cycle** and **Machine Architecture and Integration** sections.

Technology Challenge See all challenges	Examples of research topics	Time Horizon	Cost effective, high volume	Power dense, high performance	High power, ultra-high efficiency
Innovate the existing rare earth magnet supply chain to mitigate against supply risk	Develop alternative supply routes for permanent magnet materials (i.e. recycled hard disk drives, phosphates from fertiliser production).	2020-2025 <div></div>	<div></div>	<div></div>	<div></div>
	Develop recycling processes to recover high-value materials from e-machines in a cost effective, clean, safe and an energy efficient manner.		<div></div>	<div></div>	<div></div>
	Improve magnet material scrap recovery and re-use within a circular supply chain.	2020-2035 <div></div>	<div></div>	<div></div>	<div></div>
Towards rare earth free magnet electric machines	Develop rare earth free architectures, minimising material cost and environmental impact. Improve efficiency and power density to provide a competitive performance.	2020-2025 <div></div>	<div></div>	<div></div>	<div></div>
	Develop structural NVH mitigation solutions for switched reluctance machines.		<div></div>	<div></div>	<div></div>
	Develop rotor cooling strategies that allow reduced heavy rare earth content in magnets.	2020-2035 <div></div>	<div></div>	<div></div>	<div></div>

Notes: The examples of research topics are intended to provide topics emerging from industry workshops while developing the roadmaps. These are not a complete and exhaustive list and make no reference to priorities within R&D.



Electric machines – technology challenges and research topics (9/9)

The research topics listed below predominately focus on the **Life Cycle** section of the electric machines’ technology roadmap.

Technology Challenge See all challenges	Examples of research topics	Time Horizon	Cost effective, high volume	Power dense, high performance	High power, ultra-high efficiency
Recycling, remanufacturing, lower energy consumption and circular economy supporting LCA	Minimising or eliminating wet processes and use of adhesive in machines.	2020-2025 <div></div>	<div></div>	<div></div>	<div></div>
	Improved rare earth processing techniques (e.g., better separation, improved solvents, oxide-to-alloy manufacturing methods) for life cycle analysis (LCA).				
	Reduce the amount of packaging materials used for protecting machine components prior to system assembly.				
	Improve extraction and refining processes of raw materials to reduce environmental impact and increase use of renewable energy.	2020-2035 <div></div>			
	Design for recyclability and repair, including assembly and disassembly processes, with lowest environmental impacts and low energy utilisation. Include component traceability enablers.				
	Low-cost, automated manufacturing with minimised carbon footprint. Include automated processes, cheaper material, LCA, low energy utilisation, increased renewable energy use in production.				
	Develop mechanical assembly and disassembly processes for integrated EDUs (power electronics and transmissions) that allow efficient recyclability.				
	Develop common recycling processes across various machine and types that can be automated and operated at scale.				

Notes: The examples of research topics are intended to provide topics emerging from industry workshops while developing the roadmaps. These are not a complete and exhaustive list and make no reference to priorities within R&D.

Integrated Drives

Technology challenges
and research topics

Technology challenges for integrated drives

Integrated motor-drive systems combine an electric motor and a drive unit at the very least, and most commonly a power electronics system. The technology challenges listed here represent the highest priority R&D themes that industry and academia regard as critical for innovation.

These research challenges are across multiple disciplines, including:

- Transmissions / driveline components
- Electric motors
- Power electronics
- Control systems
- Lightweight materials and design
- Packaging and integration
- Modular construction, assembly and disassembly

Lightweight, high performance integrated electrical drive units	See challenge
Managing noise, vibration and harshness	See challenge
Enhancing the efficiency of electric drive units	See challenge
Integrated thermal management for electrification propulsion systems	See challenge
Assembly and disassembly solutions for integrated drives, serviceability and fault avoidance	See challenge
Control systems capable of electrified system health management, correction and telemetry	See challenge

The above challenges are not listed in a prioritised order. They represent all the themes industry and academia regard as critical for innovation.

Integrated drives – technology challenges and research topics (1/3)

Cross-cutting research topics for **Integrated Drives** that relate to the **Electric Motors** and **Power Electronics** roadmaps.

Technology Challenge See all challenges	Examples of research topics	Time Horizon	Cost effective, high volume	Power dense, high performance	High power, ultra-high efficiency
Lightweight, high performance integrated electrical drive units	Cost effective processes to produce thin walled, integrated housings for motors, power electronics and transmissions with embedded cooling channels.	2020-2025 <div></div>	<div></div>	<div></div>	<div></div>
	Improved multi-physics simulation to drive EDU design optimisation and component integration to deliver low cost, high performance and reliable driveline, e-motors and power electronics systems which leads to cooling, NVH, power density, efficiency, cost attributes etc being optimised.	2025-2035 <div></div>	<div></div>	<div></div>	<div></div>
	Enhanced converter architectures, designs and assembly processes to facilitate integration of power electronics inside the motor (e.g., on the endplate or stator iron).		<div></div>	<div></div>	<div></div>
	Multi-material casing and housing solutions to reduce weight and maintain structural integrity (i.e., metal matrix composites in rotors, composite housings).		<div></div>	<div></div>	<div></div>
Managing noise, vibration and harshness	Skewing motors and adjusting electronics to offset NVH without compromising efficiency or increasing costs significantly.	2020-2025 <div></div>	<div></div>	<div></div>	<div></div>
	NVH mitigation techniques for switched reluctance machines	2020-2035 <div></div>	<div></div>	<div></div>	<div></div>
	Materials and packaging techniques to protect electronics against vibration and mechanical stress from the motor and transmission	2025-2035 <div></div>	<div></div>	<div></div>	<div></div>
	Electrical isolation of power electronics and windings to reduce electrical interference and harmonics		<div></div>	<div></div>	<div></div>

Notes: The examples of research topics are intended to provide topics emerging from industry workshops while developing the roadmaps. These are not a complete and exhaustive list and make no reference to priorities within R&D.

Integrated drives – technology challenges and research topics (2/3)

Cross-cutting research topics for **Integrated Drives** that relate to the **Electric Motors** and **Power Electronics** roadmaps.

Technology Challenge See all challenges	Examples of research topics	Time Horizon	Cost effective, high volume	Power dense, high performance	High power, ultra-high efficiency
Enhancing the efficiency of electric drive units	High speed bearings and e-axles co-developed alongside electric motors and transmissions.	2020-2025 <div></div>	<div></div>	<div></div>	<div></div>
	Advanced bearings materials to minimise losses (e.g., ceramic, air, magnetic).	2025-2035 <div></div>	<div></div>	<div></div>	<div></div>
	Integration of wide bandgap (WBG) power electronics into EDUs to improve system reliability and reduce cost as WBG is expected to make e-machines smaller, faster, and more efficient.		<div></div>	<div></div>	<div></div>
	E-machine topologies / use of materials for improved high-speed performance (i.e.. exploiting the WBG capability)		<div></div>	<div></div>	<div></div>
Integrated thermal management for electrification propulsion systems	Techniques to thermally, mechanically and electrically isolate the motor from the power electronics to reduce semiconductor failure rates.	2020-2025 <div></div>	<div></div>	<div></div>	<div></div>
	Integration of thermal systems within the electric drivetrain, including; advances in phase change materials and heat management across the complete vehicle.	2025-2035 <div></div>	<div></div>	<div></div>	<div></div>
	Single cooling loops for motors, power electronics and battery packs.		<div></div>	<div></div>	<div></div>

Notes: The examples of research topics are intended to provide topics emerging from industry workshops while developing the roadmaps. These are not a complete and exhaustive list and make no reference to priorities within R&D.

Integrated drives – technology challenges and research topics (3/3)

Cross-cutting research topics for **Integrated Drives** that relate to the **Electric Motors** and **Power Electronics** roadmaps.

Technology Challenge See all challenges	Examples of research topics	Time Horizon	Cost effective, high volume	Power dense, high performance	High power, ultra-high efficiency
Assembly and disassembly solutions for integrated drives, serviceability and fault avoidance	Modular inverters for segmented and integrated drives with multiple motor types.	2020-2025 <div></div>	<div></div>	<div></div>	<div></div>
	Modular & flexible approach to EDU component integration, taking libraries of power electronics, e-motors, cooling systems, insulation and drivelines to develop a configuration-to-specification approach.	2025-2035 <div></div>	<div></div>	<div></div>	<div></div>
	Reversible joints and modular parts to ease serviceability and aid mechanical separation of key components for recycling.		<div></div>	<div></div>	<div></div>
	Package architecture and assembly processes to facilitate integration of power electronics inside the motor by co-manufacturing within the stator, rotor or housing.		<div></div>	<div></div>	<div></div>
	Additive layer manufacturing of high performance, functionally integrated drives that achieve a step change in power density	2030-2035+ <div></div>	<div></div>	<div></div>	<div></div>
Control systems capable of electrified system health management, correction and telemetry	EDU level master control system to maximise transmission, electric motor and power electronics efficiency.	2020-2025 <div></div>	<div></div>	<div></div>	<div></div>
	Sophisticated torque vectoring and control systems to enable efficient hub motor solutions.	2025-2035 <div></div>	<div></div>	<div></div>	<div></div>
	Integrated, predictive state of health systems enabling preventive maintenance		<div></div>	<div></div>	<div></div>

Notes: The examples of research topics are intended to provide topics emerging from industry workshops while developing the roadmaps. These are not a complete and exhaustive list and make no reference to priorities within R&D.

Technology roadmaps



Roadmap 2020

Electric Machines**Technology Roadmap**Technology indicators for
2020-2035 can be seen on page 2

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.



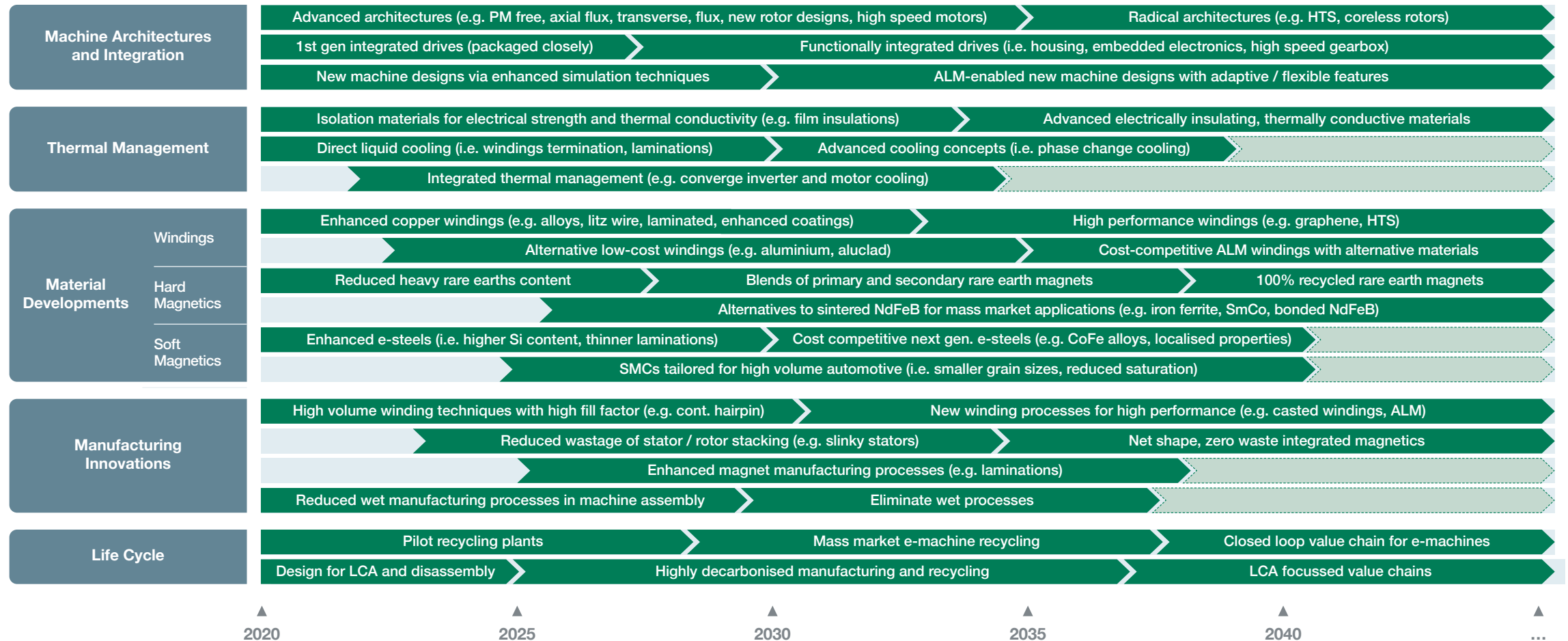
Dark bar:
Technology is in a mass market application. Significant innovation is expected in this time frame



Transition:
Transitions do not mean a phase out from market but a change of R&D emphasis



Dotted line bar:
Market Mature – technology has reached maturity. Likely to remain in mass market until it fades out where it's superseded



Changing powertrain technology options across a range vehicle applications in the short, medium and long term



		Short Term (2020-2025)	Medium Term (2025-2035)	Long Term (2035+)
LDV		Significant growth in vehicle electrification, to be supported by higher battery energy density, faster charging and lower costs.	Mature battery electric vehicle platforms achieving cost parity with conventional ICE and an increasing number of PEM fuel cell vehicles for long range journeys.	New battery chemistries, based on access to raw materials, LCA focus and low-energy production. Mature fuel cell applications with associated hydrogen infrastructure.
HGV and OH		Focussed propulsion selection tailored to vehicle type, duty cycle and use case aiming for net-zero carbon emissions; optimised for TCO.	Growth in fuel cells for heavy goods vehicles together with maturing net-zero combustion engines and more efficient BEV platforms.	Emerging catenary transport for certain heavy goods vehicles with collaborative support and infrastructure from government.
Bus and Coach		Operator specific actions to increase electrification and PEM fuel cells fleet migration.	Mature BEV and fuel cell platforms designed with second use, higher utilisation and increased economic return.	Tailored public transport solutions, new vehicle types and route management for customised journeys.
All vehicle types		Continued innovation in thermal propulsion systems achieving decarbonisation through net-zero fuels		
		Increasing LCA focus across all activities to deliver environmentally sustainable manufacturing and products		

LDV: Light Duty Vehicle
ICE: Internal Combustion Engine

HGV: Heavy Goods Vehicle
LCA: Life Cycle Assessment

OH: Off-highway
TCO: Total cost of ownership

BEV: Battery Electric Vehicle
PEM: Proton Exchange Membrane

Appendix

Background to the industry challenge report



The opportunities for industry research (and academic)

This report aims to bring industrial research to market-readiness faster, with a fresh approach to R&D challenges, directly linked to the technology roadmaps published by the Advanced Propulsion Centre (APC) on behalf of the Automotive Council UK in 2020.

For electrification technologies (Electrical Energy Storage, Electric Machines and Power Electronics) the challenges are matched to cost and performance metrics related to electrified powertrains. The Thermal Propulsion System, Lightweight Vehicles and Powertrain Structures and Fuel Cell technology challenges are matched to the relevant product types; light duty, heavy goods and off-highway and bus and coach.

Separate challenges are provided for integrated electric drives within the Electric Machines and Power Electronics reports.

All technology solutions will need a balanced selection from the challenges, specific to each application, and require careful management of their trade-offs.

Industry and academia working together

The report provides a common platform for industry and academia to collaborate in a drive to overcome technology challenges and advance net-zero propulsion systems. Many topics involve fundamental research that can later be industrialised into market-ready products.

Links to the Automotive Council Roadmaps

The industry challenges have been developed to support the net-zero Automotive Council roadmaps published by the APC in November 2020.

The roadmaps and the Industry Challenges report can be used by organisations and institutions to prioritise their research objectives to meet their technology goals.



Developing the industry challenges

Data collection, engagements and validation

The data analysed and shaped into the Industry Challenges report came from several sources:

Roadmap survey responses

We received a total of 130 responses from different types of organisations such as; vehicle manufacturers, SMEs, technology developers, engineering consultancies and service providers, Tier 1, Tier 2 or below, academia, local/national government and research technology organisations. Whilst around 60% of the respondents were UK-based, contributions were also received from Germany, USA, Japan, China, Belgium, and Sweden.

APC competitions insights

Information has been gathered from the APC competitions where specific technical challenges have been highlighted.

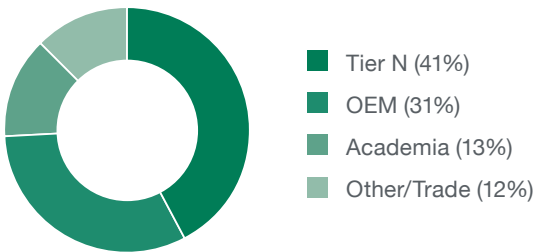
APC Spoke specialists

Data compiled from the survey responses and insights were validated through the APC Spokes. Where necessary more input was provided to fill in specific gaps. The 2017-2018 research challenges were reviewed to include the relevant ones into the new industry challenges list.

Industry workshops

Six events were held, one for each technology area: Electrical Machines, Power Electronics, Electrical Energy Storage, Thermal Propulsion Systems, Fuel Cells and Lightweighting. Industry experts provided feedback on technology challenges and details of research topics for each technology relevant to the product types (Light-duty Vehicles, Heavy Goods Vehicles and Off-Highway, Bus and Coach). A split by organisation type attending the industry challenges workshops is shown below.

Organisation types at the industry workshops





The APC approach to defining the industry challenges

In order to provide a well-informed industry and academia-led propulsion technology list of research challenges that informs and mobilise innovation in propulsion technologies, the APC approached the work as follows:

August 2020

April 2021

Roadmap workshops and online survey

This was completed prior to the industry challenges workstream and fed into the technology roadmap development - a precursor to the industry challenges.

Our online survey collected data from a wide range of stakeholders by asking experts for specific challenges. These have been analysed according to the main technology themes.

Updated technology roadmaps

These were launched at LCV2020, followed by supporting narrative reports for each technology roadmap detailing context, background data and insights that fed into updated technology roadmaps.

APC Spokes challenges (Academia)

A fresh eyes review of the 2017-2018 research challenges by the APC Spokes provided an up-to-date list for the current report.

Further research topics were added from the roadmap workshops output.

Industry workshops and consensus (Industry)

Six industry workshops were run with roadmaps experts to develop, validate and further populate the examples of the research list.

A draft of the Industry Challenges was provided for comment in order to gather final consensus from the workshop groups.

Industry Challenges published

The report is ready and available to download from the APC website.

www.apcuk.co.uk/technology-roadmaps

Find all the technology roadmaps and industry challenges at
www.apcuk.co.uk/technology-roadmaps

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