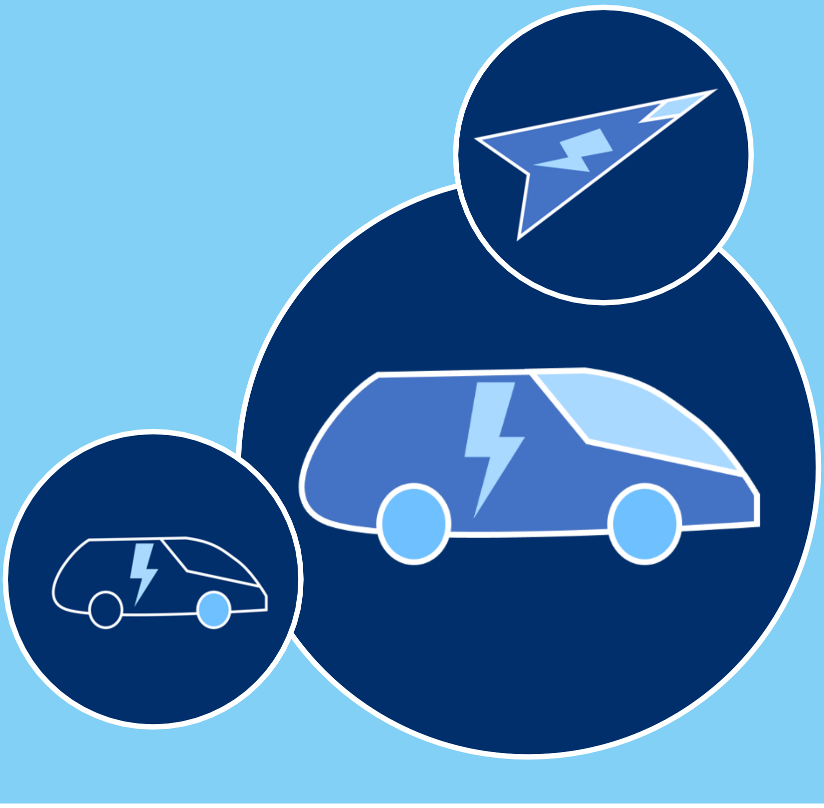
NPL

Measurement Challenges:

Electric and Hybrid Propulsion



npl.co.uk/electronic-magneticmaterials/
hybrid-propulsion

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Contents

Executive summary

This report identifies and prioritises measurement challenges affecting, or predicted to affect, innovation and development of power electronics, machines and drives for the automotive and aerospace sectors. It is the result of a consultation exercise across these sectors covering both industrial and research and technology organisations. Measurement challenges are identified relating to Design and Modelling, Materials, Manufacture, and In-service and End-of-life. The challenges identified were largely centred on materials aspects, reflecting the fact that engineering excellence is often hindered by the nuances of real materials' behaviour. Six key challenges have been identified as highest priority due to their high impact, cross-sectoral nature and requirement for a collaborative solution. These are: **Materials data quality**, **Magnetic properties measurement**, **Reliability of power electronics**, **Inspection tools for wide bandgap semiconductors**, **Accurate, robust sensors**, and **Failure prognosis**, as summarised in Figure 5. Based on our research covering market drivers, technology trends, supply chain and industry and research priorities, we make the following recommendations specific to the UK:

Recommendations

1. National focus should be devoted to the development of measurement science and infrastructure targeted at the highest priority measurement challenges identified in Section 3 (Figure 5). Addressing these challenges unlocks opportunities for the UK to become a technology leader and incentivises direct investment, whereas neglecting them will hinder competitiveness.
2. Funding agencies should find ways to support collaborative efforts in developing new industrial standards, participation in international standardisation activities and national coordination of standardisation efforts. Standards can act as an enabler or barrier for innovative companies to enter the supply chain. Taking a lead in the process unlocks barriers, promotes early adoption and reduces the costs of compliance. This could be achieved through programmes such as *Driving the Electric Revolution* (DER), the *Advanced Propulsion Centre* (APC) and the *Aerospace Technology Institute* (ATI).
3. Public and private R&D needs to embed Quality at its core, making it a key element of decision making and planning from the start. Quality-related issues are repeatedly raised as priorities, yet quality considerations (quality control, inspection, reliability) are often not considered until late in innovation cycles.
4. A coordinated national network should be created to increase access to magnetic properties measurements with agreed quality criteria and a single point of contact, possibly organised through DER Centres.
5. Work should be conducted to explore possible business models and funding sources to establish materials databases. These have been repeatedly raised by companies as an innovation that can accelerate capability. Such schemes may require coordination from a national laboratory using public funding for initiation.
6. With its focus on engine production, the UK's global position for car manufacture is vulnerable to predicted decline in combustion-powered cars. In other sectors, such as aerospace, the UK's expertise in high-value innovative products may be exploited to become a global leader in electrification. As with almost all areas of innovation in UK, there is a danger that we lead on innovation but fail to exploit. It's important to ensure that the UK's network of Research and Technology Organisations (RTOs) is supported with targeted strategic funding to enable it to provide support for commercialisation and scale up of new technologies emerging from universities [1].

1 Introduction

1.1 Industries in transition

We are at a critical stage in the electrification of transport. As a result of improved technology, emissions and climate targets and changing consumer tastes, the manufacture of electrical machines is now growing faster than ever before. Rapid innovations are occurring not only in technology, but also in manufacture and supply chains. Decisions will be made in the next few years that will have long-lasting impacts on manufacturing sectors.

In 2019 petrol motor vehicles and civil aircraft components were the top two selling UK-manufactured products [2]. Electrification poses both a threat and a great opportunity. On one hand, the shift to electrification threatens thousands of jobs in engine manufacture and its supply chain and creates opportunities for disruptors to take market share away from the UK. This is particularly true for gas-turbine aircraft engines, where the UK is the world's second largest manufacturer. On the other hand, the UK's strength in research and advanced technology creates opportunities to lead the world in innovation for electric transport. In the near term, innovation is likely to be driven by the high-volume electric vehicle (EV) market, but it is important to exploit the synergies with electrification of aircraft for longer-term strategic benefit. For this reason, it is sensible to consider both sectors together.

Measurement technology, measurement infrastructure and standards are key enablers of research, design and manufacture of advanced technologies. Electrification will create many new challenges for measurement. It is important to make strategic investments to ensure that the UK is well prepared and that measurement challenges do not become barriers to innovation. If done well, the UK's strength in measurement science can be exploited to give the UK a competitive edge in creating and adopting new technology. This report informs such a strategy, providing insight into strategic measurement challenges in **power electronics, machines and drives** (PEMD) for the automotive and aerospace sectors. Challenges in other sectors, such as rail and marine, will be considered in future studies. Measurement challenges for batteries, which are also critical to electrification, are covered in a separate NPL report [3].

1.1.1 Automotive

Sales of conventional internal-combustion engine (ICE)-only powered vehicles are already in decline as they are displaced in the market by hybrid vehicles. Figure 1 shows the projected growth in different types of electric vehicles until 2025. By 2025, it is expected that hybrid and electric vehicles will make up more than half of all sales globally. Amongst hybrid vehicles, there are a spectrum of combinations of different battery, electric drive and petrol engine sizes coupled with different transmission configurations. These range from small (5 – 10 kW) drives with voltages up to 48 V supporting large ICEs to small ICE generators providing range-extending energy to otherwise fully-electric traction systems. For electric traction systems, powers of 50 – 150 kW are typical and DC operating voltage classes of 230 V, 400 V and 800 V are used [4].

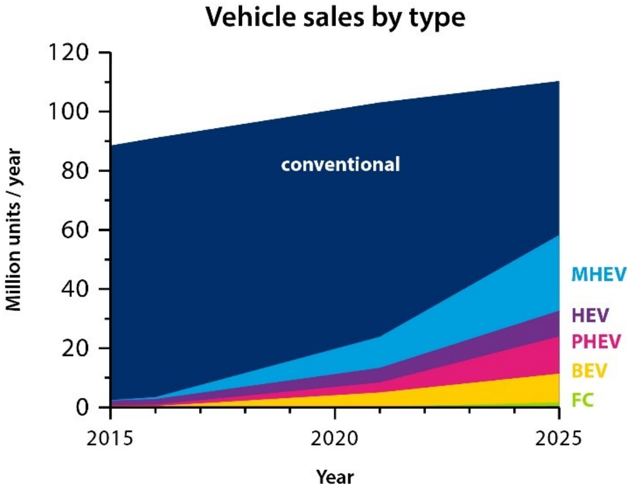


Figure 1 Projected global vehicle sales by propulsion type: Conventional (diesel and petrol), mild-hybrid electric vehicle (MHEV), hybrid electric vehicle (HEV), plug-in hybrid electric vehicle (PHEV), battery electric vehicle (BEV) and fuel-cell electric vehicle (FC) Source: AVL.

Adoption of electric vehicles is held back mainly by drive-range-anxiety and high prices. While long-range high-performance fully-electric vehicles do already exist, the challenge for PEMD is manufacturing high-performance subsystems at low cost and high volumes. For fully-electric vehicles, the driver of cost is the battery [5], but improvements in PEMD technology in terms of power density, higher voltages and efficiency will reduce the demands on battery size and enable lighter and more efficient hybrid vehicles.

1.1.2 Aerospace

The motivations for electrification of aircraft are similar to those for road-vehicles. Primarily, the aim is to reduce running costs, cut noise and air pollution and to meet climate change obligations while continuing to expand the civil aviation sector. The aviation industry in Europe has an innovation strategy based on the ACARE FlightPath 2050 goals, which include [6]:

1. In 2050 technologies and procedures available allow a 75 % reduction in CO_2 emissions per passenger kilometre and a 90 % reduction in NO_x emissions. The perceived noise emission of flying aircraft is reduced by 65 %. These are relative to the capabilities of typical new aircraft in 2000.
2. Aircraft movements are emission-free when taxiing.
3. Air vehicles are designed and manufactured to be recyclable.

In contrast to electric vehicles, the technology does not yet exist for fully electric passenger aircraft. The roadmap to electrification is less well defined than for cars. According to the Aerospace Technology Institute (ATI), the first applications of electric and hybrid aircraft could be in the growth of new markets for urban and sub-regional passenger aircraft [7]. Power requirements for these applications are about 200 kW and 2 MW respectively, which offer the opportunity to build upon PEMD technology developed for high-performance automobiles. Meanwhile, longer-range aircraft will be replaced with “more-electric” aircraft (MEA), and then gradually evolve into mild-hybrid aircraft (MHEA). MEA replace systems that are traditionally powered by compressed “bleed” air from the engines and hydraulic systems with electrically powered systems. This saves weight and improves fuel economy. MEA aircraft are powered using generators driven by the turbofan engines and an additional auxiliary gas turbine. In MHEA, larger electrical machines will provide bi-directional power flow between engines and batteries, leading to further reductions in fuel consumption and emissions. Fully hybrid electric aircraft (HEA, also known as series hybrid), in which a gas turbine generates electrical power but is not mechanically connected to the propellers or fans that generate thrust, offer many advantages in terms of design freedom but require radical redesign of aircraft architecture to take full advantage of these features. For this reason, it is unlikely that HEA or large fully electric (EA) will have any impact on the aircraft market for at least 15 years.

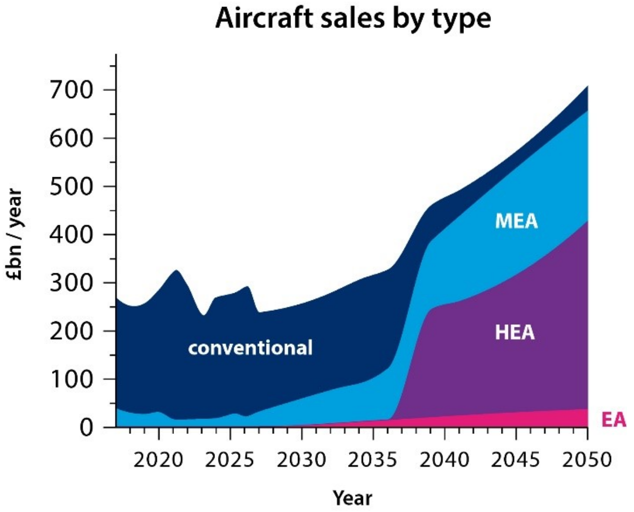


Figure 2 A projection of sales of civil aircraft by platform type: convetional, more electric aircraft (EA), hybrid electric aircraft (HEA) and fully electric aircraft (EA) Source: ATI [7].

While such concepts are far away from commercial reality, a few models do exist for short-range all electric aircraft used for training and some prototype electric urban aircraft. There are also prototype helicopters using electric tail rotors to reduce weight. Rival projects backed by Boeing (Zunum Aero) and Airbus (E-FanX) aimed to launch experimental hybrid platforms in 2020 with 1 – 2 MW on-board power generation and electric fan propulsion alongside conventional turbofans, although both projects have since been halted.

Key players in the UK include manufacturers such as Rolls-Royce, Airbus, GKN and Leonardo, but there are also more than 2300 micro-companies with less than 10 employees [8]. The strength and diversity presents opportunities for innovation, but long-term strategic planning is required to mitigate the risk to gas turbine manufacture.

1.2 Purpose and scope of this report

This report presents a summary of measurement challenges facing the electrification of the automotive and aerospace sectors. The report focusses on **power electronics**, **machines** and **drives (PEMD)**. Measurement challenges for batteries have already been covered separately by a previous NPL report that can be downloaded from .

The definition of PEMD used by Innovate UK is:

1. **PEMD** is a set of cross-sectoral technologies used to change fossil fuel-based systems into electric systems, powered by battery or some other electrical source.
2. **Power Electronics** refers to components used to control and convert electrical power, such as from direct to alternating current or from higher to lower voltages and vice versa.
3. **Electric Machines** are devices which convert electrical energy into mechanical work and vice versa, for example, electric motors and generators.
4. **Drives** refers to the combined control electronics, software and power electronics used to integrate the systems.

The UK government’s Industrial Strategy aims for a rapid increase in the manufacture of electric machines and vehicles in the UK. This includes the “Road to Zero” strategy [9] and the ban on sales of conventional cars and vans by 2030 and hybrid vehicles by 2035. In addition, the Industrial Strategy Challenge Fund is investing £80 million in the “Driving the Electric Revolution” programme [10], which aims to provide innovation to develop UK supply chains for the next generation of power electronics, machines and drives across seven industrial sectors including Aerospace and Automotive.

The National Measurement System (NMS) provides more than £50 million per year government funding for measurement science and capability that underpins industry and innovation in the UK and delivers the National Measurement Strategy [11]. The work leading to this report was carried out under that programme. It combines the outputs of a workshop and consultation exercise that engaged more than 50 stakeholders from industry, universities and research and technology institutes. This report aims to:

- Identify cross-sectoral challenges that will benefit from collaborative public-private and cross-industry projects.
- Inform national strategy for developing measurement capability in support of a competitive UK supply chain for electric and hybrid propulsion, feeding into future iterations of the National Measurement Strategy and other public and private innovation strategies.
- Ensure that the NMS funding is targeted to help the government deliver the Industrial Strategy and to support and protect the automotive and aerospace industries in the transition to low carbon transport. Select the highest priorities to maximise impact of NMS funding.
- Raise awareness in industry of measurement challenges, allowing them to plan future metrology development.

This report is intended to be used by companies, funding organisations and research organisations to help inform strategies and identify risks for investing in innovation in electrification. We hope that it will encourage those organisations to consider measurement issues and to help them to prioritise resources for dealing with upcoming measurement issues.

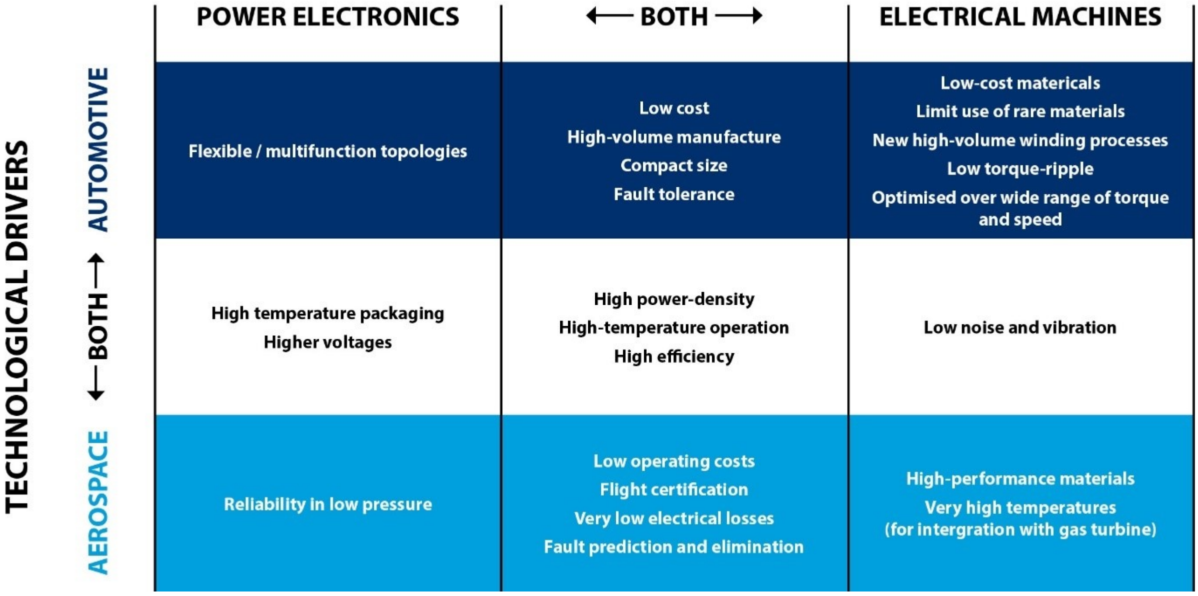
The automotive and aerospace sectors were chosen because of their significance to the UK manufacturing economy and the importance of the threats and opportunities to the UK’s global position that are brought about by electrification. The two sectors are synergistic in that the automotive industry will experience rapid change in the short-term, whereas the aerospace sector will benefit on a longer timescale from knowledge transfer and the development of local supply chains and expertise for high performance PEMD. This report summarises the technological drivers and innovation trends in the automotive and aerospace sectors and uses these as a framework to categorise and prioritise associated measurement challenges that need to be addressed as technological progress continues.

2 Technology trends and roadmaps

In terms of technological requirements, there is considerable overlap between the demands of the automotive and aerospace sectors. Some roadmaps suggest that the development of technology for both will be unified for some time, allowing opportunities for crossover between automotive and aerospace supply chains. In particular, the aerospace industry is expected to benefit from the high-performance and motor-sport end of the automotive market. In the longer term, it is expected there will be more divergence in component specifications as the motor industry increasingly pursues high-volume, low-cost components while the aerospace industry pushes into more aerospace-specific technology designed for low operating cost, high performance and much higher powers.

Table 1 outlines the main technological drivers for innovation in power electronics and electrical machines for both sectors. There is a common priority to increase power density, driven by the need to reduce weight and size while maintaining performance. However, the sectors diverge on cost: for automotive applications, high-volume, low-cost manufacture is critical to market success whereas for aerospace applications it is the operating costs and safety that are most important.

Table 1 Technological drivers for innovation.



TECHNOLOGICAL DRIVERS	POWER ELECTRONICS	⟵ BOTH ⟶	ELECTRICAL MACHINES
AUTOMOTIVE	Flexible / multifunction topologies	Low cost High-volume manufacture Compact size Fault tolerance	Low-cost matericals Limit use of rare materials New high-volume winding processes Low torque-ripple Optimised over wide range of torque and speed
⟵ BOTH ⟶	High temperature packaging Higher voltages	High power-density High-temperature operation High efficiency	Low noise and vibration
AEROSPACE	Reliability in low pressure	Low operating costs Flight certification Very low electrical losses Fault prediction and elimination	High-performance materials Very high temperatures (for intergration with gas turbine)

Various technological roadmaps have summarised the expectations and challenges for the evolution of these technologies over the coming decades [12] [13] [7] [14] [15]. Several evolutions and disruptions are expected to occur, each of which has its associated measurement challenges. We briefly summarise these innovations here and the associated challenges are examined in Section 3.

Light weight: Reduction in the overall weight of the system, achieved through: higher power densities, reduced material quantities, light-weight materials, light-weight insulators, low-density structural materials, integration of structural and active materials, reduced cooling power, integration of drive and machine.

Higher operating temperatures: A consequence of higher power densities is an increase in operating temperature. This is compounded by the desire to reduce the weight of cooling systems and provide closer integration of systems. New materials and technologies that can provide performance and reliability at higher operating temperatures are therefore a key enabler of improvement in overall performance.

Improved thermal management: A more integrated approach to thermal management to enable weight-efficient cooling of machine and power electronics. Materials and components will serve multiple functions, *e.g.* combining thermal and structural elements. Adaptive, intelligent, predictive control of cooling systems and drives to minimise thermal cycling stresses.

Integration: Machine, drive, cooling system and lubrication combined into a single sealed unit to reduce size and weight and to simplify assembly. This is also an enabler for high-volume, low-cost vehicles using off-the-shelf battery and traction systems.

Systems modelling: Greater accuracy and integration of models of the entire powertrain system, including dynamic multiphysics simulation and reliability.

Increased use of sensors and data: A trend toward using more sensors and more real-time processing of large volumes of data and intelligent sensors. Benefits will include intelligent control for optimised performance, fault tolerance, health monitoring and predictive maintenance.

Accelerated testing: Adaptations in existing accelerated test methodology in response to changes in technology. Increasing amounts of data will be acquired from single tests, enabling more complex and more realistic test cycles to be used with multiple stress components.

The overlapping technological drivers for aerospace and automotive electrification ensure that, for the near future, technology will develop in parallel with strong connections in R&D and supply chains between the two sectors. The automotive industry, with its more immediate market, is likely to be the early adopter of new technologies, which will later be adapted to aerospace. Later, the conflict between high-volume manufacture for automobiles and high efficiency for aerospace, might encourage more specific innovations for aerospace machines in the megawatt power range and the sectors' supply chains might diverge.

2.1 Power electronics and electrical systems

Figure 3 shows the main approaches that may be used to increase power density in power modules of the future. Improvements in all these areas will be required.

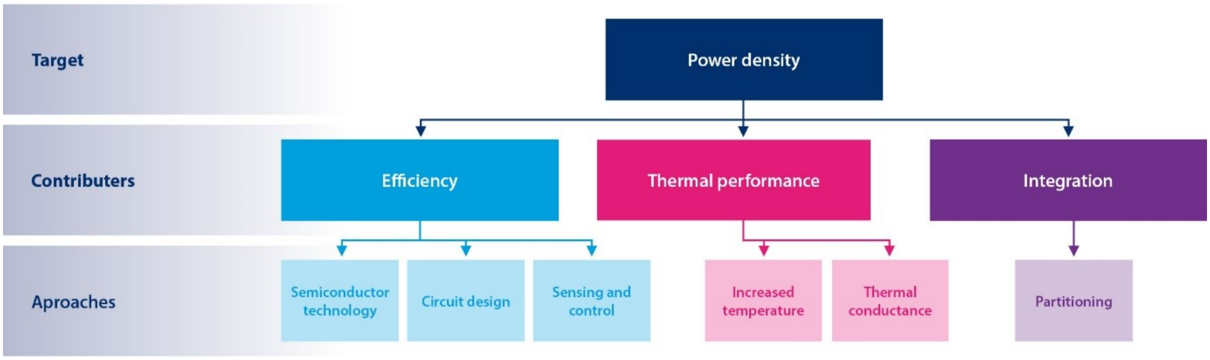


Figure 3 Approaches to improving power density in power modules.

Wide band gap semiconductors such as SiC or GaN enable significantly higher switching frequencies, reduced switching losses and higher power densities while working reliably at considerably higher temperatures than traditional silicon-based electronics. They also enable higher voltage classes to be used [5]. SiC and GaN-based power modules are already widespread within the electric vehicle market, though high costs and difficulty of high-volume manufacture are limiting the rate of adoption. For aerospace applications, reliability and flight certification are key.

In order to exploit the benefits of wide bandgap semiconductors fully, **module packaging** is being developed for higher temperature operation. The module package provides electrical and thermal interfaces to the semiconductor as well as mechanical support and protection against the environment. Traditional packages are designed to operate at temperatures up to about 150 °C. At higher temperatures failures occur, typically in wire bonds or interface materials. There is also demand for improved power cycle and long-term reliability (more than 15 years for automotive applications) as applications become more demanding. New technologies such as aluminium-clad copper and wire-bond free packages are being developed to overcome these issues. The target is to achieve reliable operation at temperatures in the region of 250 °C, which can lead to significant improvements in cooling efficiency and therefore higher power densities and higher overall performance. At present, there is a diverse range of new package materials and concepts competing in the market and many new concepts in R&D phases [4] [16] [17] [18], presenting a challenge for standardisation and qualification.

There is also a trend towards **higher operating voltages**. Higher voltages reduce conduction losses and enable faster charging speeds and higher power density and performance. However, they present challenges for insulators, connectors, passives, such as capacitors, and safety. While technology for higher voltages is currently available, developments in materials and topologies will continue to reduce the size and weight of high-voltage systems. In doing so, reliability issues such as partial discharge (especially at low pressures for aircraft) and failures relating to electromigration must be overcome.

Another way to conserve space and weight is to provide greater **integration** of power electronics. This includes the use of reconfigurable, **multifunctional** power modules that could reduce the overall number of power modules needed in a system. However, this would come at the cost of additional complexity and longer development times. It is likely that such technology will find its way into highly integrated electric vehicles of the future.

In the longer term, yet unproven disruptive technologies will be needed to deliver targets for improved power densities and efficiency. These include **emerging semiconductor materials** such as gallium oxide or diamond and **structural electronics**. The latter involves the integration of electronics and conductors into structural elements of a vehicle or aircraft, which could reduce space and weight and improve cooling performance. This is especially important as the number of sensors and electronic devices is rapidly growing. This represents the most extreme case of the trend towards greater integration of functions that are traditionally treated as separate subsystems.

Regarding the UK power electronics industry, there is strength in the design of advanced drives and expertise in wide bandgap semiconductors at the wafer level. However, there are significant gaps in the supply chain that need to be plugged in order to create a complete high-value supply chain. In particular, module packaging and high-volume die manufacture are lacking and large investments in automated manufacture are needed.

2.2 Electrical machines

As with power electronics, development of electrical machine technology is focussed on delivering higher power densities in a smaller space and at a lower cost. Roadmaps [7] [12] [14] predict that mass adoption of electric vehicles will bring about rapid improvements in the next ten years; costs will fall by nearly 50 % while power densities will more than double in this period. These improvements will be accompanied by fast growth in supply chains and the use of higher volume, more automated advanced manufacturing.

Many of these changes will be brought about by greater **integration**, including closer coupling of components and **targeted cooling**. Co-development of power drives, machines and transmission will lead to vast improvements, such as making the most efficient use of cooling systems.

At present, the electric vehicle industry has yet to converge onto a single type of electrical machine: permanent magnet machines, induction machines and switched reluctance motors are all used in current production models. Each has its own advantages and disadvantages. **Permanent magnet machines** are a popular choice, though the dependence on rare-earth metals (*e.g.* neodinium and dysprosium in NdFeB magnets) is a concern as the supply is controlled by China. Alternative **rare-earth-free hard magnetic materials** are being sought, but the current alternatives lack the qualities for high performance machines.

Switched reluctance machines have been avoided for electric vehicle applications because of issues with torque ripple and noise [19], although improvements in drives, control and advanced architectures are overcoming these problems. With high performance power electronics, high-frequency machines with six or more current phases are now common, and these might be the mainstream solution to the problem of rare-earth supply.

The aerospace industry faces the same choice of machine type, although the priorities are somewhat different [20]. Here the use of permanent magnet machines with SmCo magnets may dominate for high-value, low-volume applications where high efficiency and high-temperature operation are critical. In both industries, the combination of different machine types is an option. For example, current Tesla models combine induction motors for high-torque performance with switched reluctance machines for efficiency at high speed. It is possible that aerospace applications could follow the same approach to maximise efficiency across the full operating range. In general, the trend is toward **more complex motor geometries** that combine the benefits of the traditional machine types for improved efficiency and will be increasingly dependent on advanced manufacturing techniques.

Winding technology is one area where vast improvements will be seen. Development of automated winding methods will be critical to increasing supply chain capacity and to providing higher reliability and power densities. Changes to the shape and material of winding conductors (e.g. aluminium in place of copper) are needed, and disruptive changes might include, for example, the use of additive manufacturing to produce advanced winding geometries.

Many of the expected developments will arise for the use of **new materials**, and much research effort is devoted to the search for these. Currently, the operating temperatures of motors are limited by winding insulators. The development of new **high-temperature insulators** would enable higher power densities and cooling efficiency. Similarly, improvements in hard and soft (*e.g.* Fe-Si and Fe-Co) magnetic materials and manufacturing techniques to enable thinner laminations would reduce high-frequency losses. In parallel, combination of structural and magnetic properties in composite materials would provide further design freedom to optimise efficiency.

Finally, lifecycle issues will become increasingly important as **sustainability** at high volumes becomes a challenge. There will be increasing focus on long lifetimes, reuse and recycling, particularly of rare magnetic materials.

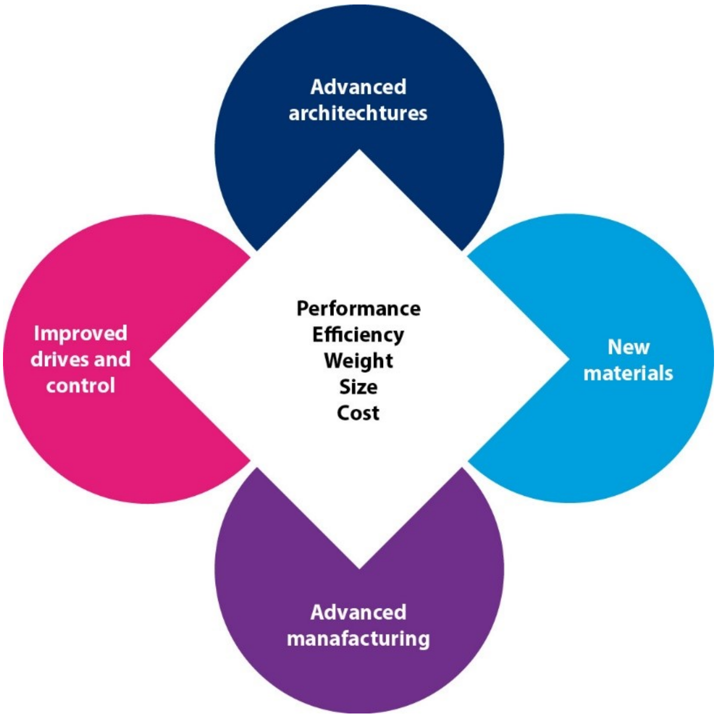


Figure 4 The four main areas of technological development that will lead to advanced electrical machine development in the next ten years.

Overall, four main development areas will enable these great advances in machine performance as shown in Figure 4: materials, manufacturing, new architectures and improved electronics. The most important gains will come from the integration of all these elements into a unified design process: a deep understanding of materials properties combined with design for manufacture, inspection, lifecycle design and systems integration.

3 Summary of measurement challenges

The following sections describe a selection of the measurement challenges faced by industry on the route to electrification of vehicles and aircraft. They are broken down into four categories: **Design and Modelling**, **Materials**, **Manufacture**, and **In-service and End-of-life**. This is not an exhaustive list, but aims to cover the most important issues that challenge multiple organisations. Generally, most of these challenges apply to both the automotive and aerospace sectors, though the particular details, such as temperature range, power, materials, *etc.* are application-specific.

These measurement challenges, which are summarised in Table 2, were identified through desk-based research, in-depth interviews with key stakeholders and through a dedicated workshop on this topic featuring key representatives from industry and academia.

In this table, we have highlighted key challenges which have been repeatedly identified across different organisations and both sectors as being the most critical challenges where a collaborative effort could yield the most impact. Importantly, none of these key challenges can be solved by a single organisation alone, they will require multi-partite effort to be addressed and mastered. The intervention of industrial collaborations and independent research and technology organisations is essential. These key challenges are presented in Figure 5. Sections 4-7 describe each of the challenges in more detail.

Materials data quality

Description: Improving and harmonising practice for collecting material data and datasheets.

Challenge: Properties of processed materials differ from those on datasheets.

Impact: Sub-optimal performance and increased redundancy in designs.

Magnetic properties measurement

Description: Accurate measurement across wider range of conditions (temperature combined with mechanical stress) and characterisation of aged materials.

Challenge: Magnetisation and loss curves needed for components under extreme thermal mechanical and corrosive stress. Understanding degradation of magnetic materials in these conditions.

Impact: Conservative design and operation of machines, reduced maximum power density. Reliability and design of electrical machines for whole life-cycle performance.

Reliability of power electronics

Description: Evaluating reliability of power electronics in harsh environments.

Challenge: Ensuring reliability under increasingly extreme temperatures with vibration, humidity, low-pressure etc.

Impact: Lifetime of power electronics, new packaging concepts, adoption of wide bandgap devices.

Inspection tools for wide bandgap semiconductors

Description: Defects are an issue in wide bandgap semiconductors limiting ability to manufacture in high volume. New tools are needed to assist quality control.

Challenge: Imaging and identification of defects over large areas is difficult and understanding of the correlation to device performance and reliability is lacking.

Impact: Upscaling of wide bandgap semiconductors is limited resulting in high costs.

Accurate robust sensors

Description: Accurate, robust sensors are crucial for accurate prognostics, prototype and model validation.

Challenge: Develop, validate and integrate new sensors for harsh conditions with simple (self) calibration.

Impact: Maintenance costs, model accuracy, prerequisite for prognosis and digital twins.

Failure Prognosis

Description: Data-driven approaches to early prediction of failures and estimation of remaining component lifetime.

Challenge: Validation and harmonisation of best practice for collection and application of sensor data to maintenance programmes.

Impact: Over-replacement of components, service life, failure rates.

Figure 5 Key measurement challenges identified in the consultation process.

Table 2 Summary of measurement challenges. The most critical challenges have been highlighted.

Theme	Measurement challenge	Description	Priority
Design and Modelling	Accurate component modelling	Design for whole service-life performance: implementation of ageing models.	High
		Modelling the influence of manufacture processes on material properties: Specimen, prototype and production versions of materials have different properties.	Medium
		Close the loop on modelling: Understand differences between modelled behaviour and actual behaviour.	Medium
	Materials data	Material databases: Improving availability of materials characterisation data.	Medium
		Improving and harmonising practice for collecting material data and reporting in datasheets. Understanding the differences between materials supplied and materials measured.	Highest
		Data on material variability and aging curves.	High
	Digital twins	Validation of models for different components. Improving confidence in decision making.	Medium
		Data collection strategies for digital twins. Knowing what to measure in order to create a useful digital twin.	Low
Materials	Magnetic properties measurements	High-volume, low-cost magnetic properties measurements for rapid comparisons, quality control and improved understanding of statistical variations.	High
		Accurate measurement across wider range of conditions (temperature combined with mechanical stress).	Highest
		Characterisation of magnetic materials after combined stress (*e.g.* corrosive environment, thermal cycling, mechanical stress).	Highest
		Upscaling measurements from test coupons to stacks to full components.	Medium
	Power electronics characterisation	Performance in realistic operating conditions (voltage, temperature, pressure, frequency, transients and harmonics).	High
	Thermal properties	Accurate characterisation of thermal properties of as-manufactured materials before and after aging.	High
	Ageing and corrosion	Defining harmonised test cycles for system and components.	High
		Characterisation of aging in insulators with combined stress (voltage spikes combined with temperature and coolant).	High

		Reliability testing and fault diagnosis for reducing failures in wide bandgap power modules for high-temperature operation.	
		Reliability tests for power-electronics modules and components under harsh combined stress conditions (high-voltages, extreme thermal cycling, corrosives, low-pressure, humidity, vibration).	Highest
Manufacture	Inspection and data analysis	Data-driven tools for early identification of manufacture issues.	Medium
		Developing / sharing best practice on what needs to be measured for manufacture.	Medium
		NDT of a range of properties to diagnose component failures.	High
	Wide bandgap semiconductors	Characterisation and inspection tools for upscaling manufacture.	Highest
	Flexible manufacturing	Inspection tools that can adapt rapidly to changes in manufacture process to maintain quality control in a flexible manufacturing environment.	Medium
		Standards and procedures to verify and validate changes of the manufacturing process.	Medium
		Open innovation platform for developing metrology for new processes.	Low
In-service and End-of-life	*In-situ* test and measurement	Hot-spot measurement in windings.	Medium
		Direct measurement of magnet temperature in operation.	Medium
		Open test platform for sensors.	High
	Failure prognosis and analysis	Data-driven approaches for early prediction of failures and estimation of remaining component lifetime. (component level)	Highest
		Use of sensor networks for data-driven failure analysis; understanding how components interact normally and abnormally. (system level)	Medium
		Accurate, robust sensors for condition monitoring in harsh environments.	Highest
	Recycling and re-use	Development of screening tests and standards for repurposed components and materials.	Medium

4 Design and modelling

4.1 Accurate modelling

Design for whole service-life performance: Understanding how materials' properties change during a product's lifetime enables development of products designed to operate efficiency throughout their service life. The ageing of installed components due to environmental and maintenance deviation effects are not always well understood, and accurate modelling in this field will help to achieve cost-effective design while avoiding unnecessary warranty claims. Currently, models use off-the-shelf datasheets. Parameters are extrapolated from sparse information on reference materials that are not necessarily representative of the actual materials supplied, and that are measured under different conditions to those that will be experienced in operation. Improving modelling of life-time performance is a complex challenge encompassing the collection of material ageing data (see below), development of component- and system-level ageing models, and validation, possibly through destructive testing of prototypes. Achieving this would have a great impact in several engineering fields.

Modelling the influence of manufacturing processes on material properties: Different manufacturing processes affect material parameters in different ways. For accurate modelling, one needs to use parameters for materials that have gone through one's own process; each process-change needs recalibration of the model. Therefore, it is desirable to develop predictive models for the impact of manufacturing process on material characteristics. This will enable more accurate design-for-manufacture approaches.

Close the loop on modelling: Advanced prototype and accurate *in-situ* measurement are needed to understand differences between modelled behaviour and actual behaviour. Model validation is critical: models are used for decision making, if the models are not properly validated and there is little confidence in the decisions based on them, then they become ineffective.

4.2 Materials data

One of the largest challenges in modelling is providing suitable material parameters as inputs that are representative of the behaviour of real materials in operation. These parameters are taken from measurements performed on similar materials, but need to take into account factors such as:

- Variability and inconsistency in supply of materials; batch-to-batch variability and variability within a batch.
- Variations between different grades of materials and different suppliers.
- Sample selection methods (the measured sample may not be representative of supplied material).
- Measurements performed on idealised geometries compared to manufactured geometries.
- Measurements performed under different conditions to the operating conditions.
- Effects of manufacturing process on material properties.
- Material ageing.
- Measurement accuracy, measurement technique and poor measurement practice.

Often the available data are sparse, and modelling is performed using the best matching data set, which is "calibrated" by applying adjustments to match modelled performance to real performance. Uncertainty in parameters necessitates increased redundancy in designs, or else creates pressure for tighter specifications from suppliers at increased cost.

Material databases: A lack of comprehensive publicly available data means that multiple companies can duplicate efforts to research and test very similar properties on the same materials. This is particularly true of magnetic materials. Collaborations and business models should be explored to allow publicly or privately-funded sharing of high-quality material data. Such databases could also enable a more strategic approach by targeting gaps in knowledge and they can be used to ensure data provenance and measurement standards are adhered to.

Key challenge - Improving and harmonising practice for collecting material data and datasheets. While many materials are measured to international standards, there is still much variability between materials supplied and their respective datasheets. Improvements in industry-wide best practice are needed to ensure that material samples are truly representative, and that data presented by suppliers are reliable.

Data on material variability and aging curves: There is a need to improve understanding of the uncertainty in the testing and variability in the materials supplied to feed into modelling, design and manufacturing. This requires a statistical approach, using a high-volume of measurements to generate an understanding of the variations introduced by the different factors listed above.

4.3 Digital twins

Digital twins are used to optimise maintenance cycles of high-value assets, such as aircraft engines, and are therefore currently more applicable to aerospace than automotive sectors. To be effective, digital twins require both accurate, validated models and high-quality data collected from robust sensors and inspection procedures.

Validation of models for different components: Digital twins operate by comparing live sensor data from machines in operation to the expected sensor output generated by a model of the system. Differences between the expected and actual data indicate possible faults, triggering further inspection. Currently there is not enough confidence in models for large electrical machines. Confidence in the models can only be reached by the collection of large quantities of sensor data from real machines in test cycles and in operation. IPR issues hampering sharing of such data are a potential hindrance to progress.

Data collection strategies for digital twins: Knowing what to measure and how often is crucial to the development of a reliable digital twin. While models will adapt and improve within a product's lifecycle on the basis of emerging field data, the measurement strategy needs to be determined early in the lifecycle. Here, sharing and harmonisation of best practice as well as agreements on how to share sensor data will pay off.

5 Materials

5.1 Magnetic properties measurement

Reliable and complete characterisation of magnetic properties of hard and soft magnetic components is necessary for accurate modelling of electrical machines. Uncertainty in these properties is compensated for by introducing larger tolerances into designs, ultimately limiting the ability to improve performance, weight and size while maintaining reliability. A complete understanding of their behaviour is needed, accounting for the wide variety of materials and conditions encountered.

High-volume, low-cost measurements: There is a large variety of material variants, suppliers and batches, but a limited capacity to measure them all under all conditions. To obtain a statistical description of these variations for quality control and design optimisation requires a leap in UK measurement capacity, ideally through fast, low-cost measurements. This will improve machine optimisation, material selection and quality control. This capability is particularly important to support targets for high-volume manufacture of electrical machines for the automotive industry.

Key Challenge - Measurement under realistic operating conditions: Accurate magnetisation curves are needed for permanent magnets in simulated operating conditions, including extreme temperature ranges combined with mechanical forces. For soft-magnetic materials, loss curves under these conditions at high frequencies (exceeding 100 kHz for high-speed machines) and flux densities and with complex waveforms are also needed.

Key Challenge - Ageing and corrosion of magnetic materials: To understand reliability of electrical machines, information about the influence of ageing on all components is needed. For permanent magnets, corrosion and temperature-induced demagnetisation are issues. Meanwhile, soft magnetic materials have mechanical and magnetic properties that are strongly temperature-dependent. In high-performance electrical machines they operate around the annealing temperature, causing evolution of all physical properties. This requires the ability to characterise materials fully after, or during, combined-stress test-cycles, including the harmonised test-cycles defined above. Stress conditions include high temperatures, thermal cycling, mechanical stress, as well as corrosive environments. The results will enable the design of more reliable machines, as well as machines that operate more efficiently across their life-cycles, instead of being optimised for initial performance only.

Measurement of real geometries: Measurements performed on test-sample geometries are not fully representative of the final product. There is a need to understand the impact of manufacturing processes on material properties by performing measurements on magnet stacks and components in as-manufactured geometries to compare with test-samples.

5.2 Power electronics characterisation

Creating optimal designs for high-density power-electronics and integrating these with other components relies of the ability to model and characterise their behaviour accurately in a range of conditions.

Performance in realistic operating conditions: Performance characteristics (efficiency, impedance, power quality, heat output, *etc.*) need to be measured across a wide range of conditions, including extremes of temperatures in the presence of harmonics and transients and, for aircraft, air pressures. Under these conditions, outputs may induce further transients and harmonics, reducing efficiencies and having knock-on impacts on system integration. Testing routines for acquiring such data for automotive power modules and DC-link capacitors are not yet harmonised, and minimum qualification standards need to be established for suppliers. Some *de facto* standards are gaining popularity (*e.g.* AQG 342 Guidelines for Power Modules in Electric Vehicles [21]), yet these lag behind the latest technology trends and also need adaptation if they are to be adopted for aerospace applications. As with magnetic materials, it is important to be able to characterise the statistical variations between and within batches of power devices and modules.

5.3 Thermal properties

Thermal management is key to enabling high power densities in power electronics and electrical machines. Good designs rely on the ability to measure the thermal properties of a range of materials and interfaces (coolants, magnets, banding, die-attach, conductive pastes, *etc.*) across a wide range of conditions (stress, high and low pressures, extreme temperatures). Measurements both before and after ageing are needed to understand how stress-induced thermal faults may propagate to failures of entire modules or machines. Especially valuable would be the ability to infer such properties *in-situ* by combining sensor data with validated models of thermal transients.

5.4 Ageing and corrosion

Issues surrounding reliability of materials, components and systems have dominated discussions of measurement challenges in electric and hybrid propulsion. This is especially the case when applied to innovations that drive increases in operating power, power-density, voltage and temperature. For aerospace applications, the challenges are similar to automotive, but the conditions are more extreme and requirements even stricter.

Harmonised test cycles: Standards often define overly simple lifetime testing for qualification, such as repetition of identical cycles of a single stress component while all other stresses are held constant. These tend to be useful for recreating well-known failure mechanisms. To identify hidden failure mechanisms, there is a need to apply complex test cycles that combine multiple stresses in combinations that reflect expected real-world behaviour. Such tests also generate useful data for failure prognosis (see 7.2). Currently different organisations operate different test-cycles, making it difficult to compare results and more challenging for suppliers to validate their products.

There is demand in both the aerospace and automotive sectors for the development of harmonised test-cycles for both electrical machines and power systems. Test-cycles need to be cascaded from system to component and material levels to ensure that the entire supply chain can operate to the same tests. Appropriate test-cycles could be determined from analysis of big-data from real-world operations. Despite potential IPR issues, there is willingness to achieve this. It is likely that test-cycles would be initially developed as shared good-practice that is later standardised internationally. There are commercial benefits to companies that are the originators and first-adopters of such harmonised tests.

Corrosion of insulators and coatings: Winding insulation and other coatings used inside electrical machines are attacked by coolants/ lubricants while operating at high temperature. This has the potential to lead to catastrophic failure of an electrical machine. There is a need to define accelerated test conditions, including features such as the composition of the oil, that can be used to optimise the compatibility of different coatings for reliable operation. For insulators, rapid voltage changes, such as those caused by partial discharges, trigger failures. For this reason, breakdowns are more likely to occur in the first few coils of a winding. Measurements should include inspection of insulation for defects, contamination of oils with degradation products and insulation resistance and breakdown voltage.

Reliability testing and fault diagnosis for reducing failures in wide-bandgap semiconductor power modules for high-temperature operation: SiC chips are thinner and more brittle than conventional chips, creating new reliability issues. Similarly, GaN-on-Si technology can suffer from high defect densities and thermal-mismatch induced stress, while degradation and instability due to defects in gate oxides is also a concern. An ability to detect, diagnose and predict faults is needed. Higher power densities and junction temperatures enabled by wide bandgap semiconductors will require new materials, processes and architectures for back-end components. To enable their development, reliability testing needs to evolve for higher temperatures and more rapid thermal cycling. Current qualification tests do not extend to the more extreme operating conditions that these devices are capable of and are not tailored to the new package types that enable them. For adoption in safety-critical aircraft applications, rigorous qualification standards are crucial for certification.

Key Challenge - Reliability of power electronics in harsh environments: As with magnetic materials, it is necessary to simulate harsh environments with combined stresses. A multi-scale approach is needed to include screening tests on materials, but also upscaling to components and entire modules. Stress conditions include high-voltages, high temperatures, extreme thermal cycling, power cycling, thermal shock, corrosives, high humidity, and vibration. For aerospace applications, low-pressure is also important as this affects creepage and clearance tolerances and the frequency of damaging partial discharges.

As technology progresses, new packaging methods and materials are being introduced to cope with higher power densities and operating temperatures. While these eliminate some failure modes, diagnostic capability is required to identify new modes. Test methods need to adapt accordingly.

6 Manufacture

6.1 Inspection and data analysis

For most manufacturers, large-scale production or integration of electric powertrains is still a relatively new activity. The industry has decades of know-how to deploy in metrology for manufacture of thermal propulsion, but this doesn't necessarily translate to electric powertrains. Quality control for high-volume manufacture is underdeveloped: There is limited long-term field test data for new topologies and the critical manufacturing features that need to be screened have not yet been determined. The adoption of electric powertrains also coincides with the increasing digitalisation of manufacturing; electric powertrain manufacture will be highly data driven involving large numbers of in-process sensors, but expertise needs to be developed on how to validate and use these data streams.

As these issues are common to many organisations across the automotive and aerospace supply chains, there is a clear case for a collaborative approach to solving these challenges. For example, development of in-process/in-line metrology, non-destructive testing (NDT) and quality-control processes could be tackled by multi-partner projects in national laboratories and centres of excellence or else via open-innovation platforms.

Data-driven tools for early identification of manufacture issues: A consequence of digitalisation is increasing amounts of data available from all stages of manufacture, testing and in operation. In principle, they can be used to provide early detection of manufacturing problems before they become too costly, but there is a lack of know-how in what to look for and how to filter the data. Machine learning can be used, but this ideally requires large amounts of historical data for training. This is a problem that can be tackled by a collaborative approach with agreements on data sharing. There is also significant interest in virtual design and testing to reduce costs and accelerate innovation. These, however, rely on validated models and high-quality data of materials and systems under realistic conditions.

Developing /sharing best practice on what needs to be measured for manufacture: As with the above challenge, the relative lack of experience in integration of electric powertrains is reflected in a lack of awareness of what needs to be measured, and how frequently and how accurately. Best practice needs to be developed collaboratively and shared to move towards harmonised procedures for manufacturing measurements.

NDT of a range of properties to diagnose component failures: Non-destructive testing (NDT) is an essential element of the manufacturing process. With the switch to electric powertrains, there are new requirements for non-destructive tests. These include:

- Welds on copper joints,
- Coverage of insulation on windings,
- Locating faults in windings,
- Assessing the quality of cable termination,
- Assessing the quality of magnet segmentation adhesives and coatings.

6.2 Wide bandgap semiconductors

Wide bandgap semiconductors (SiC, GaN, Ga_2O_3) have had limited adoption so far in electric vehicles. As an emerging technology, they have the potential to improve thermal efficiency and power density of power modules and to operate reliably at higher temperatures. However, to realise these benefits fully, challenges need to be addressed around high-volume manufacture, reliability and capable packaging.

Key Challenge - Characterisation and inspection tools for upscaling manufacture: Cost and volume currently limit uptake of wide bandgap devices in automotive applications, though it is likely that the industry will undergo rapid upscaling of manufacture and cost-reductions. Obtaining good, large wafers at low-cost is an issue. To maintain quality, it is necessary to develop new characterisation and inspection tools for high-volumes and large areas, or else to translate existing low-volume high-accuracy tools to the high-volume manufacturing environment. It is also important to be able to trace reliability issues back to wafer properties.

6.3 Flexible manufacturing

Electric powertrain manufacture will experience rapid scale-up in parallel with rapid innovation of both the product and manufacturing processes as manufacturers work to reduce costs while simultaneously improving range-limiting performance. The rapid pace of change needs to be complemented by a more flexible approach to manufacturing to reduce the risk of being financially tied to a particular process - manufacturing facilities need to adapt rapidly to changing markets and customers' demands. Flexible inspection and measurement tools will be a critical element here.

Inspection tools that can adapt rapidly to changes in manufacture process: In-line, low "Takt-time" inspection systems are required to verify each stage of production. In the flexible manufacturing environment, configurability is critical. There is a need to develop solutions that can be rapidly changed to a new process, with minimal time lost in recalibration and verification. Thus, quality control can be maintained from the outset of a new production run with minimum time lost.

Standards and procedures to verify and validate changes of the manufacturing process. To align with the above, product verification needs to be able to cope with flexible manufacture. This involves the creation of digital verification tools and the creation of suitable standards.

Open innovation platform for developing metrology for new processes. Setting up manufacturing facilities is costly and ties users to a technology. Several platforms already exist in the UK to enable piloting of innovative designs and manufacturing processes. There is a need, however, for such facilities to include open-innovation capacity specifically for the development of process metrology and quality control measures. Consideration needs to be given to sensitive handling of IP issues that may hinder participation in multi-partner projects.

7 In-service and end-of-life

7.1 *In-situ* test and measurement

A range of *in situ* measurements are required to understand operation of machines and electronics and their associated faults fully. These include specific measurements targeted at particular aspects of electrical machines, or more generic challenges around the flexible use of sensors to generate *in situ* test data. Some examples of these challenges are highlighted below:

Winding hot-spot measurement. Hot spots can occur in windings due to defects or as artefacts of a manufacturing process. They are likely to be a significant cause of premature failure of an electrical machine. Hot spots lead to degradation of winding insulation, and therefore ultimately limit the maximum power density that can safely be achieved in a machine. To characterise hot spots properly and therefore eliminate issues with the winding process or else with materials ideally requires the ability to locate and measure hot spots in operating machines.

Direct measurement of magnet temperature in operation. For model validation and to gain a better understanding of how manufacturing processes and material choices impact on performance, it is important to be able to measure or infer the temperature of magnetic components during operation. This is particularly challenging as motor designs become more complex and include buried magnets with complex geometries.

Open test platform for sensors. There is a need to develop and deploy new sensors for *in situ* monitoring (see 7.2). Many new sensor technologies are developed by start-ups and SMEs who lack their own full-scale test facilities. It is difficult for them to prove these sensors for operation in the relevant conditions. An open-access test platform specifically for the testing of accuracy and reliability of sensors under realistic operating conditions would be a potential solution to this problem. The development of standards for qualification of new sensors would also help to reduce barriers.

7.2 Failure prognosis and analysis

Traditional preventive maintenance involves replacing components at regular fixed intervals, commonly based on a usage time or distance criteria. These are complemented by regular off-line inspections to detect unusual wear or tear. Such approaches are based on statistical descriptions of failures under typical or accelerated conditions. They fail to distinguish between well-made and poorly-made components and do not account fully for variations in the harshness of operating conditions. The use of integrated sensors with prognostic tools to monitor the condition of components and predict their remaining service life can improve the specificity of maintenance, both ensuring that components are not replaced before necessary, and reducing unexpected failures. However, accurate prognostics are reliant on:

- The availability of accurate and comprehensive reliability data (failure and degradation statistics across a broad range of conditions). relates to Ageing and Corrosion (5.4),
- Knowledge of failure modes (sensor conditions that distinguish failing components from good ones).
- The availability of accurate and robust sensor data.

The following measurement challenges relate to achieving these conditions:

Key Challenge - Data-driven approaches for early prediction of failures and estimation of remaining component lifetime (at component level): The cost of adding sensors to high-value components is relatively low, but the greatest challenge is how to handle and use the large quantity of data that they can generate. The use of intelligent sensors that include data processing at the sensor is an increasing trend. Also, the use of deep-learning tools applied to both in-service sensor data and laboratory test data provides a data-driven approach to predicting failures before they occur. Many such techniques are available at a research level, but need validation followed by harmonisation and development of best practice.

Use of sensor networks for data-driven failure analysis - understanding how components interact normally and abnormally (at system level). The abnormal behaviour of one component may propagate to cause failure of another system. For example, partial discharge in an inverter may cause voltage spikes that lead to a breakdown of winding insulation. A complete systems picture is needed to link sensor data from multiple components. Retrospective analysis of data can help to understand why a failure occurred, improving the next generation of systems. The challenge follows on from the above, but also includes accurate modelling of a complete system to understand how failure may propagate. Success also depends on coordination across the supply chain, resolving ownership and connectivity issues for sharing data from individual components to the system level.

Key Challenge - Accurate, robust sensors: The development and validation of sensors that provide accurate data for the entire service life of components is critical to achieving accurate prognostics and model validation. For example, temperature sensors located on the substrates of power modules measure temperatures away from the chip. They suffer from slow response and require modelling to infer on-chip temperatures. On-chip sensors can solve some of these problems but are costly and have poor accuracy (*e.g.* for temperature ± 15 K) without calibration. Development of methods for self-calibration of sensors is critical.

Testing and validation of sensors under a range of conditions in terms of both accuracy and reliability is important too. For high-performance electrical machines, sensors are required to operate in ever harsher environments including extreme temperature gradients and electromagnetic interference. This requires the development of new types of sensors, such as fibre-optic based systems. Thought must also be given to cabling, volume and weight. Start-ups developing new types of sensors will benefit from standards and test facilities that can be used to build confidence in their products.

7.3 Recycling and reuse

The future of manufacturing will embrace the circular economy. Recycling of materials and components, particularly of scarce materials such as rare-earth metal permanent magnets, will become an essential element of design, manufacture and business models. However, during periods of initial rapid growth in adoption of a technology (as now with electric vehicles), demand outstrips supply. For this reason, industrial stakeholders do not see recycling as an urgent priority. It is likely, though, that this will become increasingly important in the long-term as the market matures and legislation develops to move environmental costs onto manufacturers. In the meantime, active research will be needed in preparation for a circular economy focussing on:

1. Reduction in the use or rare and polluting materials through the development of substitute materials.
2. Development of designs and manufacturing methods that facilitate material recovery at the end of components' life.
3. Use of recovered and recycled materials in new machines to displace consumption of virgin materials.

Of these, the third category raises a specific measurement challenge:

Tests and standards for reusing materials: Recycling and reprocessing of machines and components requires a deep understanding of how performance and reliability are affected by the history and quality of the used components. In particular, re-qualification standards and accompanying screening tests are needed to de-risk the market.

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9 Workshop Participants

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