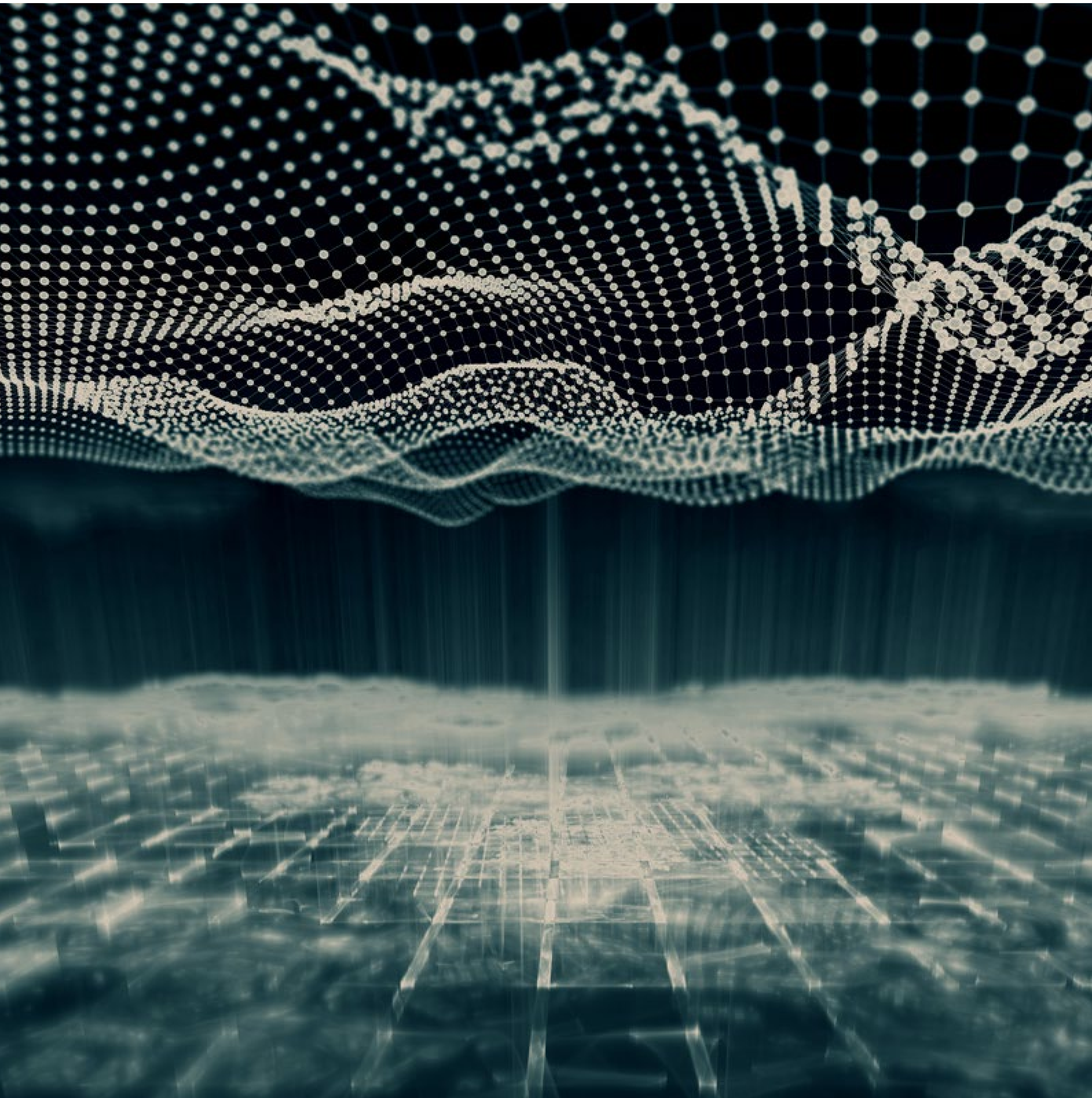
National Physical Laboratory

Advanced materials metrology strategy

March 2024



The National Physical Laboratory (NPL)

The National Physical Laboratory (NPL) is a National Laboratory spanning science, innovation, and technology. As the UK's National Metrology Institute (NMI), NPL develops and maintains the national primary measurement standards and collaborates with other NMIs to maintain the international system of measurement. As a public sector research establishment, NPL delivers extraordinary impact by providing the measurement capability that underpins the UK's prosperity and quality of life. NPL develops the metrology required to ensure the timely and successful deployment of new technologies and work with organisations as they develop and test new products and processes.

In this digital age, NPL's world-leading measurement science provides confidence in data, which enables innovation and international trade to flourish. NPL aligns our capabilities with the most important national challenges like energy, health, security, net-zero and the prosperity of the nation, and leads major national programmes that deliver impact across the UK. As a national laboratory, NPL's advice is always impartial and independent, meaning consumers, investors, policymakers and entrepreneurs can always rely on the work NPL does.

NPL is a Public Corporation owned by the Department for Science, Innovation and Technology (DSIT). NPL has a partnering agreement with DSIT, the University of Strathclyde and the University of Surrey. NPL is part of the National Measurement System (NMS) which provides the UK with a national measurement infrastructure and delivers the UK Measurement Strategy on behalf of DSIT. As a national and independent authority on metrology, NPL is therefore perfectly placed to disseminate strategy in the area of advanced materials in support of other overlapping strategies in this important sector.

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Foreword by Dr Emma Haynes

Measurements are fundamentally important for our everyday lives, even if we do not actually see their applications every day. These hidden mechanisms may vary from enabling a type of technology we use through to allowing international trade and regulation. Metrology, which ensures we are measuring these many different aspects accurately, is crucial in supporting both the quality of life of the general public as well as the economies of countries around the world.

Indeed, metrology accelerates the innovation of emerging technologies by providing confidence in new materials, manufacturing processes and products, ultimately leading to growth in GDP. Although there are many types of materials often classed as 'advanced materials' and these are disrupting many different technological sectors, they all have the same need - confidence in their ability to provide an improvement, whether that is in performance, cost, and/or sustainability. Without novel ways of measuring these new types of materials, that can be standardised so measurements are repeatable wherever they are performed, there will be no confidence in their claimed improvements.

As the Partnerships Director for the UK's National Metrology Institute (NMI), I get to see first hand how important it is to engage with stakeholders to better understand the metrology needs of industry if we are to best support them. NPL, with more than 120 years of experience performing this role, is perfectly placed to work with many different entities and communities and to disseminate the future metrological needs, as we have in this Advanced Materials Metrology Strategy. This then allows these communities, in partnership with many different companies, Institutes and Universities, to solve these grand challenges, leading us to a more prosperous future.

I hope that this document will help inform and guide you, as much as it will us, and motivate discussions that will help us all achieve these outcomes.

Dr Emma Haynes

Partnerships Director,
National Physical Laboratory

Foreword by Prof David Knowles

Materials are everywhere and critical to almost every aspect of our lives; the everyday products we use in our home or the infrastructure that supports sectors ranging from energy to healthcare. Innovation is intrinsically linked to the development and application of materials, through incremental improvements using new additives or step-changes in technology.

Our lives have been transformed with the introduction of silicon, for example, ushering in the 'silicon age,' which has led to wholesale changes in the way we live through personal computers and communication, to enabling the development of new medicines. For this reason, the research and development of new advanced materials that deliver improved properties and allow novel technologies are crucial, as recognised in the UK by establishing the Henry Royce Institute, the UK's national institute for advanced materials research and innovation.

Understanding how these materials' properties link to the ultimate performance of the final real-world products enables more rapid innovation and growth in exciting new areas of research and business. However, without the ability to accurately and reliably measure the properties of advanced materials, both researchers and industry alike cannot progress either the materials or their applications with confidence. A lack of robust materials metrology will therefore stifle the innovation process and adds a level of risk for any investment which is necessary to support technology translation in a commercial environment. It is therefore essential to undertake metrology research, both for technological advancement and economic growth.

I welcome this metrology strategy for the UK's advanced materials community, one which supports and coincides with development of the UK's Materials Innovation Strategy, both providing academia, national laboratories and companies with the challenges that must be addressed to provide a thriving advanced materials sector.

Prof David Knowles

Chief Executive Officer,
Henry Royce Institute

Executive summary

Advanced materials are a cross-cutting technology that impacts all aspects of our lives, such as green energy, advanced medicines, quantum technologies and the future of telecommunications. The manufacturing of raw advanced materials contributes approximately £14.4 billion in GVA to the UK economy and is critical for innovation in all manufacturing sectors.

Despite the increasing global investment in advanced materials, the pace of innovation across a supply chain is often limited by confidence in a material's technology readiness level. For instance, this may be in the reproducibility of the enhanced performance of an advanced material measured in an academic research environment, or in the measurement data that demonstrates safety to consumers and to the environment.

Robust metrology provides that confidence, reducing investment risk and enabling innovation and commercialisation of advanced materials. As the pace of innovation accelerates and new and more complex materials become available, there is a growing need to develop the materials metrology capability required to accelerate the uptake of advanced materials and provide competitive advantage to UK companies in the global market.

This Advanced Materials Metrology Strategy has been developed through in-depth review of UK and international strategies for advanced materials and metrology, and a comprehensive series of stakeholder interviews. It identifies how critical drivers of change, including the energy and the digital transitions, require innovation in measurement capability and a new approach to delivering the UK materials metrology infrastructure.

Major trends in materials metrology have been identified and categorised under two broad themes:

- Measurements at the Frontiers: As materials become more complex and are used in different and challenging conditions, metrology needs to adapt to allow measurements at multiple scales (from the very small to the very large, from ultra-fast processes to long term changes) and under complex conditions that mimic those in real-world applications
- Smart and Interconnected Metrology: Single measurement methods are often insufficient to fully characterise advanced materials. Measurements will need to become smarter and more interconnected through the concept of hybrid metrology, combining multiple measurement techniques and advanced data fusion to extract more information and with higher confidence than can be currently achieved using individual methods.

These trends will allow efficient implementation of digital and virtual testing, fast materials informatics innovation and robust selection of advanced materials. All of this will support disruptive innovation across multiple industries, all the while reducing environmental impact.

This document also provides three key recommendations to enable UK competitiveness in this important area and to both underpin the UK's science superpower status and enable economic growth in a sector requiring a highly skilled workforce. These are that the UK should establish:

- a national centre for materials verification and assurance, bringing together materials metrology, materials science, and industry expertise
- a nationwide materials database to empower innovation through materials informatics and the digitally driven design-make-test-use cycle
- a strategy and funding framework to maintain UK leadership in international materials metrology with the aim to target and influence the development of standards, codes and regulation of emerging technologies based on advanced materials.

Why advanced materials?

Advanced materials are a cross-cutting technology platform that enable innovators to move from incremental improvements to creating truly disruptive technologies. The innovation and uptake of advanced materials impacts all aspects of our lives. They make airplanes more fuel-efficient, smartphones more powerful, food and medication safe to use for longer and a wide variety of sectors more environmentally sustainable.

> **"This is a truly revolutionary time in advanced materials development. Materials are being manipulated at an atomic level to elicit new properties and vastly improved performance."**
>
> UK Innovation Strategy 2021[1]

The UK has world-leading academic research in advanced materials and a strong industrial base. Commercialisation of advanced materials provides a significant opportunity for the UK economy and is key to achieving UK Government priorities, including meeting environmental targets, improving the sustainable use of materials, protecting against global shocks in supply chain shortages and transforming industries to secure jobs in new and existing industrial clusters. The manufacture of materials in their primary form is a major UK industry in its own right, contributing approximately £14.4bn of GVA to the UK economy.[2] In addition, advanced materials are of critical importance to all manufacturing sectors, which contribute £203bn every year to GVA and support 5m jobs.[3]

Globally, the importance of advanced materials to major economies has been implicit across multiple national, regional and industrial strategies for decades. More recently, advanced materials have been more explicitly identified as critical enabling technologies both in the UK and in international strategy documents. However, the number of recent materials-specific national strategies remains limited. Exceptions to this rule include the Netherland's "National Materials Agenda, Accelerating Materials Technologies", South Korea's "Advanced Materials Plan", and Japan's "Materials Innovation Strategy".

In addition to the clear multi-sectoral impact, the strategic importance of materials for security of supply in key sectors has been increasingly recognised both in the UK, with the inclusion of advanced materials in the "National Security and Investment Act", as well as internationally, with the USA's Department of Energy "Critical Minerals and Materials Strategy" and the EU's "Critical Raw Materials Act". In parallel, the need to invest in materials testing methodologies to support development and enforcement of safety and environmental legislation has been a key topic of international discussion, building on the role that OECD Test Guidelines play for assessment of traditional chemicals with a view to measure/test the safety and environmental impact of advanced materials.

Materials-focused national interventions, such as the "Materials Genome Initiative" in the USA, and the "Strategy for Strengthening Materials Innovation" in Japan, have focused on the need to bring together multidisciplinary teams, including academia, metrology institutes and industry to accelerate materials discovery and innovation. Japan's Advanced Materials Strategy also identifies the promotion of initiatives to make trustworthy analysis and measurement data become international standards as key to supporting innovation capabilities.

1. Department for Science, Innovation and Technology. (2021, July 22). *UK Innovation Strategy: Leading the future by creating it*. GOV.UK. https://www.gov.uk/government/publications/uk-innovation-strategy-leading-the-future-by-creating-it
2. Department for Business Energy & Industrial Strategy – A Study to Assess UK Strategic Advantage in Advanced Materials https://www.royce.ac.uk/news/royce-welcomes-study-to-assess-uk-strategic-advantage-in-advanced-materials/
3. https://www.royce.ac.uk/collaborate/innovationstrategy/

Despite the increasing global support for advanced materials, a major challenge to accelerating the pace of their innovation is confidence by critical adopters throughout a supply chain in their performance as they advance through the technology readiness levels. This lack of confidence typically stems from three areas:

- Reproducibility of the enhanced performance of an advanced material measured in an academic research environment.
- Provenance and quality of measurement data provided through the supply chain when selecting the best materials for manufacturing.
- Availability of measurement data that demonstrate both improved reliability and safety to consumers and to the environment.

Metrology provides confidence in each of these areas, acting as a key enabler of innovation and commercialisation of advanced materials.

Advanced materials metrology

Materials metrology is the science of measurement applied to materials or technologies where materials have a significant influence on the overall performance of components and products. This improves the understanding of the sources of variability through a rigorous approach and provides confidence in measurements and materials data by improving reproducibility, reliability and comparability, therefore enabling discovery, scale-up, industry adoption and reducing investment risk. Materials metrology is key to providing assured data needed to develop an understanding of how the properties and performance of materials can be defined and how they are linked to the structure and processing of those materials **(Figure 1).**

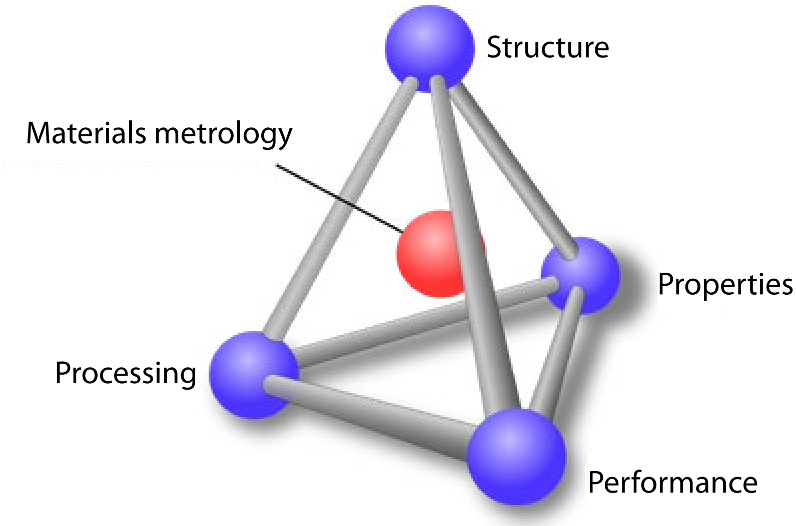


Figure 1: Materials metrology at the centre of advanced materials development.

Confidence in assured data is important throughout the R&D process. This ranges from 1) supporting materials scientists who strive to improve performance and materials engineers who develop new products, to 2) industrialists who need to have confidence in the lifetime of their goods and services and 3) government agencies who ensure the safety and sustainability of products through regulatory enforcement. Assured data provides trustworthy information which can improve both yield and quality, as well as productivity.

The key stages of materials metrology, from the discovery of new measurement methods to the development of these methods and establishment of international test standards, are described in **Figure 2**. Firstly, academia, together with research and technology organisations, National Metrology Institutes (NMIs) and industry all contribute to the development of novel and improved measurement methods, often driven by the need to better understand materials' properties.

The second stage, pre-normative research, is focused on developing the measurement methods to a point that they can be widely used in a reliable way to obtain reproducible and comparable results. This is key to support reproducibility of science and critical to support innovation in industry and regulations, as well as to accelerate uptake of new materials. This second stage is led by NMIs (such as NPL in the UK), in collaboration with academia and industry, and is focused on the science of the measurement itself to establish reliable technical procedures and understanding of measurement uncertainty, leading to delivery of robust, calibrated measurement facilities, reference materials, best practice guides, and, where relevant, draft documentary standards.

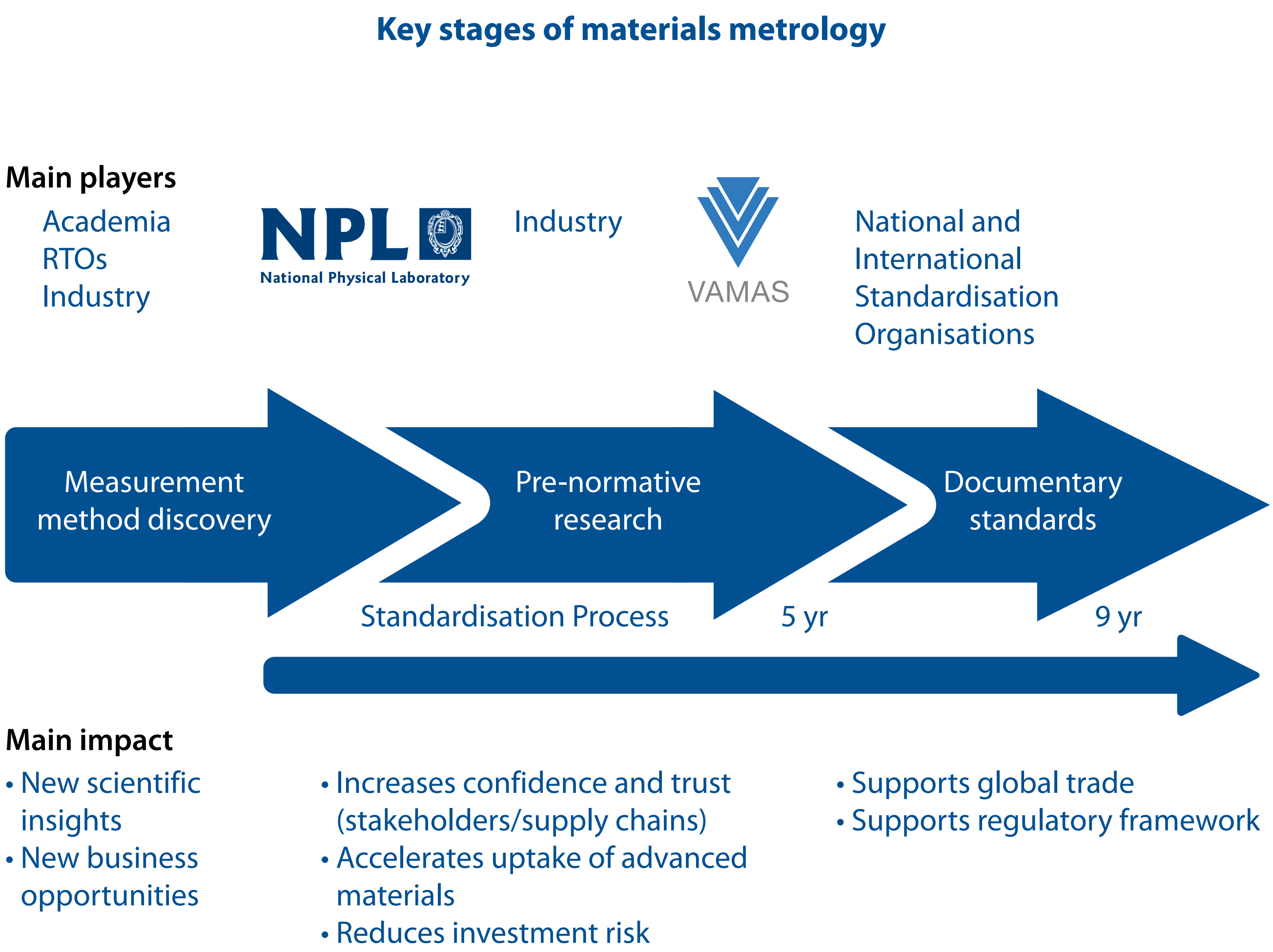
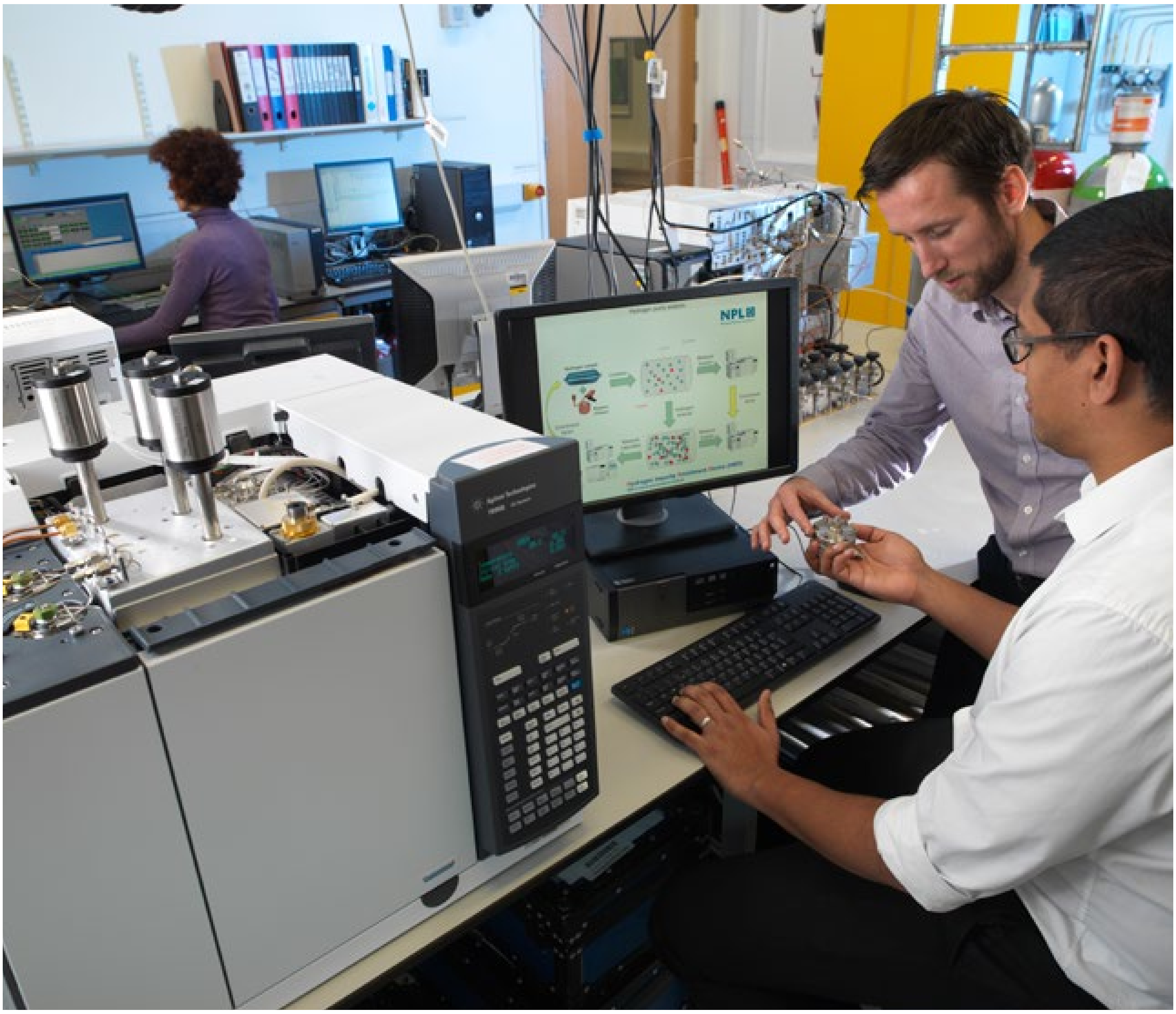


Figure 2: Key stages of materials metrology including main UK contributors (top) and impact (bottom).

Such work often involves international inter-laboratory comparisons to ensure results can be reproduced and to deliver the required information with sufficient confidence to stakeholders. For advanced materials in particular, this pre-normative research is carried out at the international level through organisations such as Versailles Project on Advanced Materials and Standards (VAMAS).

The third and final stage is the development of documentary standards, which is led by national (such as BSI in the UK) and international standards organisations (e.g. ISO, IEC, ASTM) that convene experts from industry, NMIs, and academic/R&D organisations. At this stage, experts will use the existing science developed through the pre-normative research stage to agree on documents that standardise the process of measuring or testing materials. The process of defining documentary standards relies on developing a consensus between the experts of the relevant working groups. The final outcomes are national and international documentary standards which support global trade and the regulatory framework.

As the pace of innovation accelerates, it creates a growing gap between the time when industry requires confidence and measurement guidance and the time when published international measurements and test standards are available. For this reason, pre-normative research becomes increasingly important to provide early access to best practice and to accelerate the standardisation development process.



Classification of advanced materials

Materials have traditionally been classified by their atomic structure into metals, ceramics and polymers. As material properties become more complex, a range of additional sub-classes are used. For instance, the term "composites" has been used to describe materials formed of more than one component, to create a material with properties unlike the individual elements. Then, "functional materials", providing intrinsic functionality beyond the structural, became increasingly important in multiple sectors, such as energy, electronics, and space. In parallel, the understanding of the impact of dimensionality, shape and hierarchical structuring on functionality led to a revolution in materials for nanotechnology.

The major current trend can be classified under the term 'multi-functional materials', which encompasses materials with more than one functionality. Such a term is very broad, including relatively well-known materials, such as optoelectronic materials that can detect or control light often by transducing optical into electrical signals (or vice versa), all the way to animate materials that can react autonomously to their environment and change their properties, leading to new applications such as self-repairing paints or self-healing concrete.

This evolution in advanced materials is intrinsically linked to materials metrology. Advances are enabled by novel measurement capability (e.g., improved high quality structural imaging to support materials discovery and innovation), and, at the same time, challenge materials metrology to evolve (e.g., how to reproducibly characterise complex multifunctional materials where one property depends on another).

Examples of classes of advanced materials

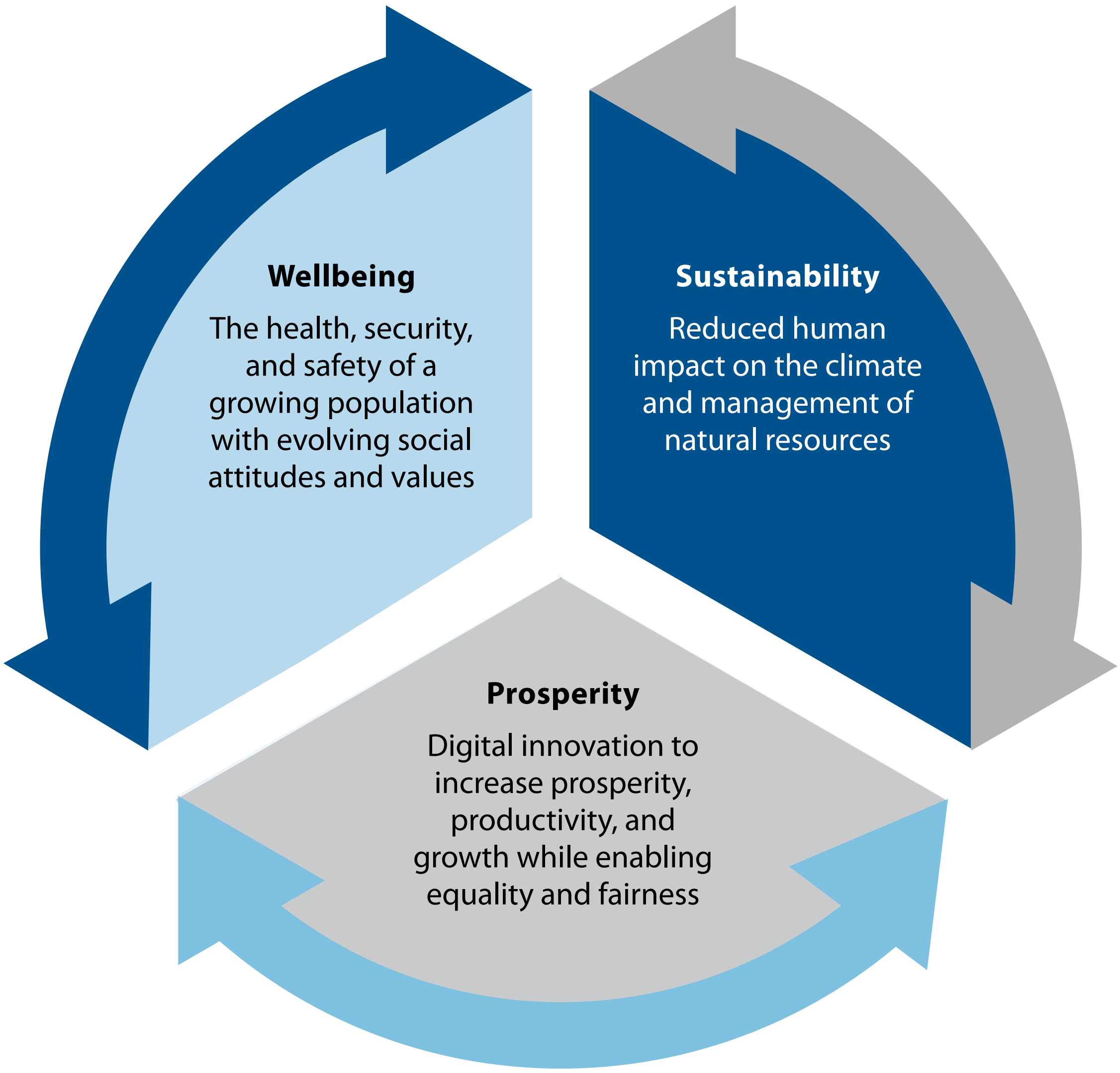
Advanced alloys and metallic additively manufactured (AM) materials offer advantages in high value applications particularly when operating in extreme environments. In addition to improved corrosion resistance, lighter weight, greater thermal resistance, and lower costs of the advanced alloys, AM also offers the capability of producing very complex geometries and structures optimised for a particular function.	**Multi-functional materials** combine multiple properties into one complex material and include animate, smart, and meta-materials, with multiple application areas, ranging from implants to photonics. They can exist in nature or be specially engineered and include materials capable of responding to and interacting with external stimuli by reconfiguring or changing their properties either on demand or autonomously.
Advanced coatings and engineered surfaces can provide step changes in the functionality and long-term performance of components in challenging environments and also contribute to sustainability by enabling substitution of expensive rare materials with cheaper alternatives.	**Energy materials** are designed to store, convert, or harvest energy. They are crucial for renewable energy technologies, energy conversion and storage systems, and energy-efficient devices. Example applications include lithium-ion batteries, solar cells, fuel cells, electrolysers, nuclear energy and thermoelectric materials.
Biomaterials are intended to interface with biological systems to evaluate, treat, augment or replace any tissue, organ or function of the body, to support novel approaches to sustain and improve human health and wellbeing. These materials could be for a range of applications ranging from wound healing and gene therapy to biosensors.	**Electronic and electromagnetic materials** are the basis of modern electronics, telecommunications, electric motors, sensors, lasers, and quantum devices. They include quantum materials, soft and hard magnetic materials, semiconductors, optical materials, dielectrics, and 2D materials.
Composite materials may refer to fibre reinforced-polymer composites, which are crucial in many applications where structural strength, durability and light weighting are required, or composites based on metals and ceramics, such as hardmetals, which form the bedrock of efficient manufacturing, or new materials reinforced with graphene for enhanced performance and multifunctionality.	**Nanomaterials** are a variety of materials that have dimensions on the nanoscale, with different chemistries that may improve the properties of, or add additional functionalities to, macroscopic systems. Used either as an additive or to enable a new type of system not otherwise possible, these materials may be used in different sectors ranging from medicines to sensors to automotive.

Table 1: Examples of key materials classes that underpin progress towards addressing UK priority challenges, such as the drive for net-zero carbon emissions and sustainability.

Metrology challenges for advanced materials

Metrology is critically important for the innovation and commercialisation of advanced materials; however, the challenges are complex and intertwined within many sectors and across the different classes of advanced materials. To identify the key cross-cutting challenges and main metrology trends for advanced materials, an in-depth review of UK and international strategies for advanced materials and their applications has been performed, supplemented by a series of stakeholder interviews conducted for NPL in 2022, and by the NPL foresighting project 'A vision of the 2030s shaped by metrology'.[4]

The metrology challenges have been identified through different lenses provided by key societal drivers of change:



4. https://www.npl.co.uk/foresighting

There were two drivers that stakeholders consistently referred to and are discussed in more detail below. These both require and directly impact the development and uptake of advanced materials.

The energy transition

The transition to sustainable energy represents the largest set of technical challenges to industry globally.

The future of energy will see an increasing decentralisation of supply and a growing shift to electricity-based energy systems.

Environmental concerns over the impact of a growing energy demand will continue to change consumer behaviour and drive changes in legislation.

In parallel, the growing demand will continue to put pressure on world resources and security of supply, increasing economic pressure for the implementation of disruptive materials innovation at pace.

The digital transition

An increasing digitalisation across industry is causing the merging of the physical and the virtual, and will begin to blur the distinction between human, machine, and nature.

Widespread adoption of intelligent embedded sensors, step-changes in computing power, and access to ultra-fast digital connection will provide the tools to create, process, analyse and act on vast amounts of data about everything including the environment, healthcare, manufacturing processes, transport systems, among others.

In response to these predominant drivers, two major trends in materials metrology were identified as having the biggest impact.

Measurements at frontiers

- At multiple scales (from very large to very small, ultra-fast to long term changes)
- In harsh environments
- In real-world applications
- In complex environments (e.g., presence of interference, rapidly changing)

Smart and interconnected

- Hybrid metrology (multi-method)
- Materials informatics
- Digital/Virtual testing (validated multi-scale modelling)
- Self-sensing, self-calibrating

Driver: The energy transition

Clean energy generation is the fastest growing source of electricity globally, in part fuelled by the sharp decrease in price, which makes **solar energy** and **wind** the cheapest sources of electricity in the majority of countries. In parallel, the importance of **nuclear** power is becoming more appreciated as the difficulties of the transition away from fossil fuels becomes more apparent.

Energy storage demand is accelerating due to the shift towards electricity-based energy systems, demanding innovation in advanced battery systems, carbon capture and hydrogen, which are seen as an essential part of the plan to achieve net-zero. To be competitive, there is an urgent need to reduce costs, extend lifetime and improve energy density, while ensuring safety.

Energy distribution, conversion and consumption needs to be more efficient to reduce demand and wastage. Advances in low-loss electronics, power electronics and electric motors are key to delivering reliable, higher power densities at reduced costs. Electric motors account for approximately 45% of all global electricity usage and around 70% in industry.[5] In parallel, it is estimated that 80% of all electricity in the USA will pass through a power electronic component by 2030, which leads to demands for efficient and reliable power conversion and distribution. Underpinning data and test methodologies to ensure safe use of materials in the transport of hydrogen have not yet been established. Fuel cells and electrolysers have complex materials challenges, and their performance efficiencies are sensitive to both their manufacturing quality and the purity of input gas and water.

Advanced materials are critical enablers of innovation for all of these technologies, and their implementation and uptake require advances in metrology. Detailed evaluation of materials metrology challenges for electric and hybrid propulsion, hydrogen industry, battery industry, and carbon capture, usage and storage, have been published recently[5] in close consultation with stakeholders.

The key cross-cutting metrology challenges identified by researchers and industrialists include:

- Methods for measurements of materials properties and performance under realistic operational conditions.
- Best practice in materials and device testing to ensure reproducibility and comparability of results.
- Evaluation of performance and assessment methods to understand reliability of materials and devices, including accelerated test methods and durability in harsh environments.
- Evaluation of recyclability and biodegradability to support a circular economy.

5. Measurement challenges for electrification (npl.co.uk)

Case Study: Energy transition

Improving yield estimates in bifacial photovoltaics[6]

A key challenge to enabling the transition to green energy sources is the optimisation of new technologies such as bifacial photovoltaics (BFPV).

Solar panels are critical to reducing carbon emissions related to energy generation, with the global solar panel market worth more than £100bn a year.

BFPVs are a new type of solar panel that can harvest light on both sides of the panel, utilising additional light reflected from the ground. They can generate 5-15% more energy than conventional panels.

The advanced passivation materials used in BFPV technology affect their response to different colours of light. Accurate measurement of the BFPV's optoelectrical properties is used to model their interaction with reflected light and enable more accurate energy rating of modules. Pre-standards research helped accelerate the publication of the IEC 61853 standards series defining energy rating metrics for PV systems and the revision of the IEC 61724-1 Ed.2 standard to improve the accuracy in monitoring BFPV systems. This means technology providers and users have greater confidence in the energy yield that the systems will provide. Methods for BFPV yield modelling can reduce the cost of BFPV systems by almost £1 per MWh, corresponding to approximately £100,000 per year for a medium-sized 50 MWp solar farm.

Industry has estimated that it could facilitate up to £1bn of new PV investments in BFPV systems, helping to achieve up to 40% of new installations to be bifacial by 2025. Indeed, methods developed through pre-standards research have been used by a UK company to reduce risk in a new £100m BIPV solar farm. The increased energy production of BFPV could reduce costs of electricity and bring a step-change in this multi-billion pound market.

6. https://www.npl.co.uk/case-studies/improving-yield-estimates-in-bifacial-photovoltaic

Driver:
The digital transition

The digitalisation of industry is accelerating innovation and reducing development costs through virtual design, and virtual testing. It optimises process and production leading to more competitive manufacturing with reduced environmental impact.

Cyber-physical integration is providing opportunity for human and productivity enhancement, through advances in robotics, brain-computer interfaces and bionic implants, while the increased use of embedded intelligent sensors provides innovations across industries, including more competitive manufacturing. These require the use of advanced materials in unexpected and complex environments.

Advances in new computing technologies (e.g., quantum computing, neuromorphic) and fast wireless interconnectivity (e.g. advanced telecommunications) will allow highly complex data handling and models to make use of vast amounts of data to tackle increasingly complex and previously intractable problems.

Advanced materials are critical to enable the required innovation that supports the digital transition, from advances in semiconductors and quantum materials to multi-sensorial interfaces and multi-functional materials.

Advanced materials are also beneficiaries of the digital transition. For instance, materials informatics is accelerating the discovery and deployment of new materials by combining advanced modelling and computational tools with the understanding of materials processing and properties. However, the trustworthy data and information generated through materials metrology is key to enabling successful technology convergence with artificial intelligence – with any system the quality of the output is limited by the quality of the input. Successful technology convergence will lead to truly transformative materials development, where materials discovery will be fundamentally changed, with development of the material led by the properties required for an application.

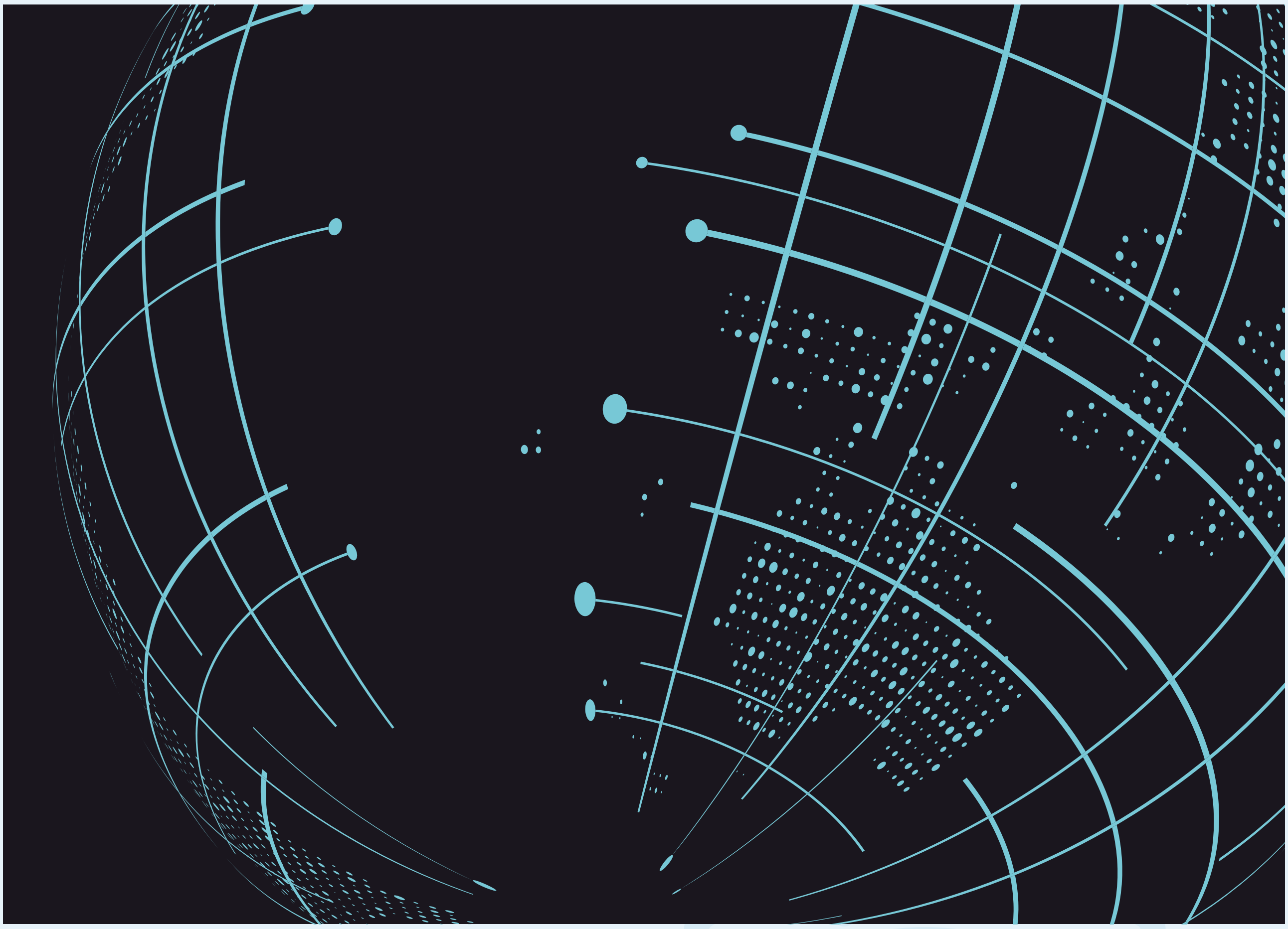
In a world becoming driven by data, how trustworthy the data (and equally important, the metadata) on materials really are becomes a key consideration for businesses, particularly when that data will then be used in machine learning or artificial intelligence algorithms that are not entirely transparent. This means the traceability of the actual data and the instrumentation used to generate that data will be crucial to enable industry to manufacture novel devices with higher quality and productivity.

As the complexity of the gathered data increases, it also becomes more important to have reliable data processing approaches and associated methods for uncertainty propagation through those approaches. Meanwhile the development of "translation dictionaries" for metadata will enable the exchange of data between experts in different fields. Achieving these milestones will truly provide confidence in data, which will then allow industry to accelerate innovation and make more rapid and sound business decisions.

The drive towards product certification by analysis and the introduction of product passports to ensure regulatory compliance are dependent on novel and digitalised metrology. Investment in these new metrology techniques and technologies will be critical to the regulatory and certification authorities who will need to be able to trust the data to be able to certify safety-critical systems based on advanced materials.

Case Study:
Digital transition

Maximising the benefits of machine vision measurements and modelling software for optimal composites manufacturing



Detailed characterisation and optimisation of the process parameters for advanced liquid composites moulding (LCM) manufacturing results in high-quality, high-performance products with longer lifetimes. Standard measurement methods for the evaluation of in-plane, out-of-plane permeability, and compressibility are becoming available and often require measurement of the resin flow through the engineering fabric reinforcement. To this end, utilising machine vision allows the monitoring and accurate evolution of the resin flow front.

Camera images of the flow front across a calibration board are displayed alongside 3D geometrical modelling of the flow, to show the conformity between data and the model. The 3D numerical fitting process comprises multiple stages that progressively refine the model, while the software can compensate for effects such as camera lens and perspective distortion. Machine vision enabled measurements result in the fast, efficient, and more accurate measurement of resin flow and in turn increase the fidelity of composite materials manufacturing process optimisation, ultimately accelerating the development of new high-value products. The machine vision system offers a validated practical implementation of the newly published ISO 4410 and a pathway to reducing measurement uncertainty.

Trends: Measurements at the frontiers

Materials often operate in complex environments, which can include harsh and/or rapidly changing conditions. For example, turbine blades for aero engine gas turbines can operate at temperatures that exceed their melting point, with safe operation ensured by using protective thermal and environmental barrier coatings. They are also subjected to high static and variable stresses and often are required to operate in an aggressive chemical environment.

Understanding how materials properties link to the ultimate performance of real-world products enables more rapid innovation and growth in exciting new areas of research and industry. To achieve this goal, key metrology developments are required, including:

- Capability for accurate and reliable measurement of the properties of advanced materials under conditions that simulate real use. This requires close collaboration between metrology experts, materials scientists and industry.
- Reliable methods to allow understanding of failure mechanisms under complex environments so that representative accelerated tests can be developed for reliability evaluation. Advances in data analysis and hybrid metrology could play a significant role in reducing the test parameter space and facilitating implementation and uptake of multi-stress test methods.
- Advances in operando measurements to monitor performance. Combined with the previous advances, this will play a key role in increasing product and infrastructure lifetime, reducing costs, shortening the time to market, reducing environmental impact and supporting the transition to net-zero.

To address the needs for the provision of materials data under these complex environments, measurement strategies need to be carefully designed and conducted to achieve the required results. These include:

- Designing the measurements so that they can be used to develop an understanding of how the materials behaviour depends on their composition. This will be essential to develop models for how materials perform in the complex environments that they are operating in, facilitating material selection.
- Robust and validated measurements and data analysis methods across the length scales to allow consideration of the impact and interactions between nanoscale and macroscale that directly impact performance and reliability.
- Advances in measurements that push the limits of time scales, from ultra-fast to long-term changes. This will require improved resolution, sensitivity, and long-term measurement stability.

Case Study:
Measurement at frontiers

Reducing erosion on wind turbine blades

Erosion of wind turbines can reduce performance and lead to 3-5% power losses. Repairs and replacements, in particular for offshore environments, can be costly. Therefore, it is important to characterise the durability of different materials to minimise the need for repair or replacement. Assessing the materials under testing currently involves stopping at discrete intervals for visual inspections and making mass loss measurements. This only shows what the damage is, but not how and when it occurred. It is a laborious and time-consuming process which can be compromised by stopping and starting the tests.

Industry wants to understand the erosion throughout the testing, which requires measurement of micrometre-level changes of blades moving at up to 150 metres per second. Through materials metrology, a new solution utilising an optical measurement method, for characterising material loss by volume whilst the material is being bombarded by particles, has been developed and adapted for use on wind turbine blades. This was combined with a high-speed camera, and software was created to interrogate the vast amounts of data generated by the camera images. The method was validated on blade sections with well-understood defects. The technology was shown to measure the known defects correctly, down to a couple of micrometres. This successfully demonstrated the possibility of making measurements of the size and shape of damage caused by erosion during testing, which will help to accelerate wind turbine blade development and deployment. This work has informed the development of metrology standards within ISO TC 35 SC9 WG32 on coatings for wind turbine blades.

Trends: Smart and interconnected metrology

Due to the increasing complexity of advanced materials, which can be related to porosity, nanostructure and/or multi-element and multi-phase characteristics, their functional performance is determined by many physical and chemical properties. This means that single measurement methods are often not sufficient to fully characterise these materials and multi-method approaches are required to fully understand and optimise materials' properties.

Traditionally, measurement techniques are developed individually, and even complementary methods are often used separately, failing to build on synergies to deliver robust metrology for complex materials. The current trend is to make measurements smarter and more interconnected through the concept of hybrid metrology, where multiple complementary measurement techniques are applied in combination, and advanced data fusion is used to extract more information and with higher confidence than can be achieved using each technique separately. Achieving this will:

- reduce measurement uncertainty for model-based measurements
- make optimal use of available data by understanding which measurements are more critical to the material property of interest
- reduce demand for data collection, by removing redundancy in information, which ultimately reduces costs and material/product development time
- allow translation of results between measurement methods, facilitating comparison and transfer of knowledge between laboratories and industry, where typically different measurement methods are available.

To support digitalisation, metrology needs to continue to evolve, for example by enabling the validation of modelling and virtual testing. Effort should be directed at:

- developing calibration and validation of materials test methods. These need to be carefully considered to ensure that the results of testing are traceable and have well-defined uncertainties
- generating accurate and precise experimental data on material properties under realistic conditions. These are needed to form the basis for models of material behaviour, which are critical to underpin the development of digital twins by ensuring seamless exchange of information and decision making between physical assets and digital replicas
- developing and providing relevant reference materials to allow calibration and comparability of measurement equipment. This becomes increasing challenging for more complex material systems, and would strongly benefit from closer collaboration between materials scientists, metrology experts and industry
- data and metadata generation and dissemination should be conducted in accordance with FAIR – Findable, Accessible, Interoperable, and Reusable – principles. Metadata needs to include not only a full description of the material but also details of measurement conditions
- creating a materials data repository framework and content to empower innovation through materials informatics and the digitally driven design-make-test-use cycle. A particular challenge will be to develop a robust and unbiased determination of materials data quality, particularly for emerging technologies where measurement standards are not yet available.

Case Study:
Smart and interconnected metrology

Developing in-line quality control of advanced materials for net-zero applications

To realise the potential for graphene nanoplatelets (GNPs) to enable reduced greenhouse gas emissions related to applications such as concrete reinforcement and battery performance, manufacturers need optimised, in-line quality control methods for more efficient production of GNPs. These methods must be verified against the highest point of reference – in this case documentary standards produced within ISO TC229, namely ISO/TS 21356-1:2021, which have undergone extensive pre-normalisation research and interlaboratory comparisons.

Although Raman spectroscopy has been demonstrated as an in-line tool, the sources of measurement uncertainty must be addressed to achieve increased confidence in deploying these techniques in production facilities for quality control, as well as partnering this technique with other complementary measurements that can be performed in-line, such as nuclear magnetic resonance (NMR) proton relaxation. This work can then itself lead to new international standards for quality control methods that are complementary to the current standardised methods. This will provide manufacturers with rapid, in-line characterisation of materials, and will help to lower costs, reduce wastage and improve product quality.
This, in turn, offers a solution to companies producing a range of advanced materials for net-zero applications, accelerating innovation and helping the UK to meet net-zero carbon emissions targets.

Materials metrology in the UK advanced materials ecosystem

The UK has a well-developed and globally recognised strong scientific knowledge base in advanced materials, with a significant investment in lower TRL (1-3) areas within universities (Figure 3)[7,8], and a strong and innovative industrial base. Accelerating the uptake of advanced materials is crucial for UK economic growth and to maintain global competitiveness. Materials metrology provides the confidence required to accelerate innovation and the UK is globally recognised as a leader in this area.

However, a key challenge to keep the UK at the forefront of advanced materials is the lack of co-ordination joining the fundamental and applied knowledge in both advanced materials and metrology, across academia, national laboratories, Catapult centres and industry, which are in dispersed locations across the regions and nations of the UK.

In the UK, there is no co-ordinated approach to couple materials experts with metrology experts, which is out of step with world-leading economies where materials metrology is a focussed and often co-located activity. Furthermore, in other countries such as the USA, Japan and Germany, these sets of experts collaborate across the TRL scale, thus developing measurement best practice early on to increase confidence and trust, focusing innovative science development into underpinning the needs of industry and providing insights into what is possible with the next generation of materials.

There is a significant and impactful opportunity to accelerate progress to meet critical UK priorities and de-risk commercialisation of innovation through the strengthening of clusters of excellence via a co-ordinated approach, bringing together materials and metrology experts.

7. Department for Business Energy & Industrial Strategy – A Study to Assess UK Strategic Advantage in Advanced Materials

8. https://www.royce.ac.uk/news/royce-welcomes-study-to-assess-uk-strategic-advantage-in-advanced-materials/

Vision

Our vision is that the UK develops the highest point of reference worldwide for advanced materials measurement, via a digitally integrated infrastructure. This will provide physical measurement capabilities connected to predictive digital twins, through the provision of assured data.

As materials become more complex and the pace of innovation accelerates, the role of pre-normative research that establishes the science for measurement for materials becomes increasing more important. A lack of robust materials metrology stifles the innovation process and increases risk to investors. Therefore, it is essential to initiate metrology research early and when advanced materials are at low technology readiness levels, to ensure the measurement infrastructure is in place at the right time, both for technological advancement and economic growth.

The future of materials metrology will focus on "measurements at the frontiers" and "smart and interconnected metrology". This will allow efficient implementation of digital and virtual testing, fast materials informatics innovation, and robust selection of the right material for the right application, all the while reducing environmental impact and supporting disruptive innovation across multiple industries, from green energy to quantum technologies and future telecommunications.

To deliver that vision, the UK will need to develop a more cohesive and interconnected advanced materials innovation framework where materials metrology, materials scientists and industry expertise are co-located, collaborating closely to keep the UK at the forefront of advanced materials development, commercialisation, and uptake. This will be critical to support the energy and digital transitions with direct impact to our wellbeing, prosperity, and sustainability.

Metrology innovation is the key to unlocking the full potential for all advanced materials. This potential will help realise greater productivity, economic growth, and increased prosperity, across the UK. Investment in measurement science will be as important as the materials discoveries themselves if we are to take full advantage of the opportunities they offer, ultimately decreasing the time to market for new, innovative products and reducing the development costs required.

To deliver the vision for advanced materials there are three key elements that must be considered:

Collaboration

Advanced materials innovation is a truly international affair. Trading relationships are built upon, amongst other things, an important structure of international standards, agreements, codes, and regulations designed to ensure that when businesses and consumers buy something, they get exactly what they expect. Without experts across industry, national laboratories and academia working with their national standardisation institutes, accreditation and regulation bodies, such as the British Standards Institution (BSI), the United Kingdom Accreditation Service (UKAS) and the Office for Product Safety and Standards (OPSS) in the UK, these international standards cannot be achieved through the equivalent international bodies. Standards must be written with representation from affected parties and implemented rigorously and consistently in ways that give everyone involved a high level of confidence in the outcome.

It is significant that VAMAS was established by the G7 group of nations in the 1980s to promote world trade by innovation and adoption of advanced materials through international collaborations that provide the technical basis for harmonisation of measurement methods, leading to best practices and standards. The list of VAMAS member countries has grown, but it is notable that the UK has maintained strong leadership for over 40 years, with many scientists from the UK's National Metrology Institute, NPL, acting as Chair and Secretary of VAMAS.

Clusters

The co-location of metrology innovation, alongside ground-breaking advanced materials research and its industrial applications will be critical to accelerating innovation and reducing the time to market for new technologies. Indeed, within the "Advanced Materials: Call for evidence" for the Department for Business, Energy & Industrial Strategy (BEIS) in 2022, UK stakeholders from both academia and industry recommended the need for a national centre focused on materials verification and assurance that would co-locate both sets of expertise.

Investment in and maintenance of world-class facilities across the UK, that deliver the measurement innovation and services needed, can be realised in regional clusters that support industrial and academic areas of excellence.

Using and growing the existing UK materials research infrastructure and creating the partnerships needed to embed the necessary metrology innovation will require co-ordination and leadership.

Co-ordination

Metrology for advanced materials innovation is an important and cross-sectoral subject. To realise the full potential, a national, independent co-ordinating programme is required. This will need to be delivered in partnership with the researchers, scientists, and engineers from across multiple government laboratories and agencies, academic institutions, and industrialists.

To realise the maximum impact, policymakers will need support to develop the appropriate regulations, standards, and guidance on the best investments to make in national infrastructure. This will have to be done in new and agile ways, keeping pace with the increasing use of data and machine learning, the introduction of novel materials and the machines needed to manufacture them, whilst also being mindful of the full lifecycle to ensure they are both sustainable and recyclable, to have a minimal carbon footprint.

Recommendations

- The UK should create a dedicated centre for materials verification and assurance that brings together the innovative and enabling metrology research needed to realise the full range of opportunities identified, known and unknown. This will require co-ordination across the network of UK science assets, whether through a virtual centre or a centrally located centre with a hub-and-spoke model across the UK.
- The UK should create a nationwide materials database. A materials data repository framework would empower innovation through materials informatics and the digitally driven design-make-test-use cycle. It will require robust and unbiased determination of materials data quality, particularly for emerging technologies where measurement standards are not yet available.
- The UK should establish a clear strategy and funding framework to maintain its leadership in international materials metrology with the aim to target and influence development of standards, codes and regulation of emerging technologies based on advanced materials. This will require concerted effort in pre-normative research to provide the UK with a competitive advantage ahead of publication of international standards.

We hope you will engage with this vision and consider these drivers, trends and recommendations within your own strategies and plans, to help shape and drive the future of metrology for advanced materials.

Appendix A

'Advanced materials metrology strategy' NPL authors

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Table 2. List of stakeholders engaged as part of producing this strategy.

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