NPL

Technology and Measurement Foresighting

A vision of the 2030s shaped by metrology

Technology and Measurement Foresighting was developed by scientists, engineers and staff working at the National Physical Laboratory (NPL), the United Kingdom's National Metrology Institute. NPL is grateful for contributions from the UK National Measurement Laboratory for Chemical and Bio-measurement hosted at LGC (NML), TÜV SÜD National Engineering Laboratory (NEL), the UK National Gear Metrology Laboratory (NGML), the National Institute for Biological Standards and Control (NIBSC), and the UK Office for Product Safety & Standards (OPSS).

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About NPL

NPL is the United Kingdom's National Metrology Institute, providing the measurement capability that underpins the UK's prosperity and quality of life.

From new antibiotics to tackle resistance and more effective cancer treatments, to secure quantum communications and superfast 5G, technological advances must be built on a foundation of reliable measurement to succeed. Building on over a century's worth of expertise, our science, engineering and technology provides this foundation. We save lives, protect the environment and enable citizens to feel safe and secure, as well as support international trade and commercial innovation. As a national laboratory, our advice is always impartial and independent, meaning consumers, investors, policymakers and entrepreneurs can always rely on the work we do.

Based in Teddington, south-west London, NPL employs over 600 scientists. NPL also has regional bases across the UK, including at the University of Surrey, the University of Strathclyde, the University of Cambridge and the University of Huddersfield's 3M Buckley Innovation Centre.

www.npl.co.uk/foresighting

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Contents

Executive summary

NPL has run a Foresighting project to explore the implications of new technologies and trends which may change why and how we perform measurements in the future. Using a well-established set of tools to gather information on emerging trends, detailed input was collected from industry and technology experts and carefully analysed. The key trends and technological advances which will impact measurement and society all over the world were identified. The findings are presented through six example industries, and overarching, game-changing technologies are highlighted.

Technology and Measurement Foresighting has concluded that metrology in the 2030s will have three key priorities:

1. Metrology will support a digitally enabled global measurement infrastructure
2. Metrology will improve understanding of complex systems
3. Metrology will give confidence in decision making

The outcomes of this work will help determine future research priorities for NPL and, in collaboration with our partner laboratories, national and international partners, to set the agenda for future metrology research.

A word from our CEO

These are challenging times, perhaps unprecedented in living memory.

Our Technology and Measurement Foresighting project started before the COVID-19 pandemic and concluded while we were still working in new and unexpected ways. The last few months of 2020 have left us all feeling some uncertainty, but I hope that sharing our Foresighting work will demonstrate how NPL, as the UK's National Metrology Institute (NMI), is looking to the future.

NPL has a national mission and a responsibility to ensure that new and emerging technologies are backed up by reliable and robust measurements, and that decisions are made based on accurate data which we fully understand – its provenance, timeliness and source.

Our Foresighting work will, therefore, influence how NPL develops over the next decade and beyond. As a leading NMI we are keen to prompt the international debate about which disruptive technologies will enhance and impact measurement and metrology.

The work highlights how a 'metrology mindset' will help us be confident in understanding the complexities of our world – from biological systems and the human body to transport systems and the electricity grid.

I am delighted to present our vision of the 2030s and invite you to come and talk to us as we collectively meet the challenges of the future.

Dr Peter Thompson FREng FInstP FRSC

Chief Executive Officer, National Physical Laboratory

"We need to continue blue-sky research and it needs to be clear that's what it is, not impact-driven. But it is also very important to implement accelerated translation of research into useable applications"

Sir Patrick Vallance

Government Chief Scientific Adviser

An introduction from our Chief Scientist

Many organisations publish their thinking about potential futures but NPL, as the UK's National Metrology Institute, has a unique perspective on technology changes and a key role to play in enabling them.

Our previous foresighting report, Metrology in the 2020s, was published in 2013. It was instrumental in framing the need to perform measurements which are beyond our immediate capabilities, exploit networked information, make use of the 'internet of things' and embed metrology at the heart of products and systems.

Whether it's driving the green recovery or ensuring intelligent use of data, the UK's position as a science superpower depends on looking to the future and being one step ahead. Metrology, the science of measurement, continues to play a key role in innovation and has already enabled many new technologies to come to fruition, such as hydrogen fuel cells, radiotherapy, global satellite navigation and wireless communications.

The aim of this work was to explore the implications of new technologies and trends on the future of measurement, which will help us set future research priorities for NPL. Therefore, we asked ourselves two questions:

1. Which new trends will change **why** we perform measurements?
2. Which new technologies will change **how** we perform measurements?

As the Foresighting project drew to a close, the coronavirus caused drastic change in our society. At NPL, we advised and informed government, companies and research organisations on a wide range of topics to meet the unprecedented challenge. The impact of the pandemic accelerated some of the changes which were identified for the 2030s in Technology and Measurement Foresighting, and slowed others down.

Our Foresighting work has determined that metrology in the 2030s will have three key priorities. Firstly, building on the 2019 redefinition of the international measurement system, we will develop a global measurement infrastructure which takes full advantage of the digital revolution. Secondly, global challenges are getting more complex and multidisciplinary, requiring metrology to support a systems-based understanding of the world. And finally, trust in decision making is key to enable new technologies like machine learning and artificial intelligence to flourish, which requires accurate and reliable measurements.

I hope that this Foresighting work will motivate discussions with colleagues, collaborators and stakeholders about the future of measurement and I invite you to contact us at *foresighting@npl.co.uk* so that we may work together to realise this vision.

Prof Jan-Theodoor (JT) Janssen CPhys CEng FInstP FIET

Chief Scientist, National Physical Laboratory

"We seem to be focusing on the future workforce rather than upskilling those already here. This is especially important considering the technological disruption that has already happened and will likely continue"

Dr Hayaatun Sillem CBE

CEO, Royal Academy of Engineering

Technology and Measurement Foresighting

NPL has undertaken a wide-ranging review of society and technology in order to identify major trends in the future of society and industry, analyse which technologies will be vital to enable them and explore their implications on metrology – the science of measurement.

Drivers of change

Drivers of change are the pressures that make society evolve or industry develop. They may include legislation, environmental considerations, changes in human behaviour, cultural differences or financial factors. Technology and Measurement Foresighting identified three drivers of change:

Wellbeing

The health, security and safety of a growing population with evolving social attitudes and values

Enterprise

Digital innovation to increase prosperity, productivity and growth and also to enable equality and fairness

Sustainability

Reduced human impact on the climate and management of natural resources

These three drivers are seen in every industry and country, and will impact all of us. NPL used these drivers to analyse industries and highlight which technologies are key for the future.

COVID-19 has also had a profound and immediate impact on society and technology. It has accelerated some of the changes identified by this Foresighting work and slowed others down. It has emphasised how critical quality measurements are for informing policy and supporting industry.

Metrology enables technology

Changes in technology, society and industry make constant demands on metrology and measurement systems. In order to have confidence in emerging technology, encourage widespread adoption and safe roll out, the measurement infrastructure must be developed in parallel with these advances.

To present the Foresighting findings, NPL has developed visions for six example industries: **Built environment, Energy, Food production, Healthcare, Manufacturing and Transport** (pages 7–12). These will give an insight into possible developments in technology and measurement in the 2030s but are not exhaustive or exclusive. Many technical advances highlighted could have multiple applications across different industries.

Key trends and technological advances (page 13) covers the overarching findings that are vital to one or more industries, and investigates the measurements required for society to adopt new technology with confidence.

The future of metrology (page 14) explores the developments in technologies or industries which will enable, or make new demands of, metrology. Foresighting concludes that there are three key areas for metrology to prioritise in order to ensure the safe, reliable and robust new technology, as well as support the trends and demands of society and industry.

Built environment **Energy** **Food production** **Healthcare** **Manufacturing** **Transport**

Built environment

The built environment is undergoing a dramatic change impacted by the fourth industrial revolution, climate change, resource scarcity, population changes and urbanisation.

Homes of the future will be embedded within smart sustainable buildings and structures, interconnected by sophisticated intelligent infrastructure systems designed to support environmental sustainability and the quality of life of users.

Future buildings will evolve from places of living and working to intelligent, efficient and sustainable environments that enhance human health and wellbeing.

The built environment will be connected, robust, secure, adaptable and constructed sustainably, and will have the needs of the user at its heart.

What does this mean for the built environment?

Sustainable - The built environment will be constructed, operated and maintained in a sustainable way.

Examples include: recycled and recyclable materials; energy and building management systems; local and renewable energy production, storage and use, upgrading and retrofitting.

Measurement will ensure the reduction of waste and the continual use and re-use of resources - also known as the circular economy.

Infrastructure - The building and civil engineering infrastructure will be reliable, efficient and robust to support changes in living, working and population migration.

Measurement will help increase efficiency, reliability and robustness of infrastructure, such as water, gas, electricity, transport and logistics.

Resilience - The entire built environment, homes, buildings, structures and infrastructures, will be resilient to climate change.

Examples include: floating homes, space or extra-terrestrial colonies, geoengineering projects, space-based geo-monitoring, indoor air quality monitoring and active control.

Measurement will enable buildings and structures to optimise their own operation or configuration and adapt to the external environment.

Digital - Homes will be connected and smart to allow integration of living, relaxation and other activities, and support the more vulnerable in society.

Examples include: robots to help the elderly live and work independently, technology for health assessment at home.

Measurement will support the increase in wireless and communication technology, assistive devices and the needs of individuals.

Foresighting has highlighted technological trends for metrology based on our vision for the built environment:

- **Embedded, digitally interconnected and secure sensors** will harvest real-time information and allow the prediction of infrastructure demand, use and condition.
- **Wireless technology and quantum cryptography** will facilitate the seamless and secure sharing of data.

Energy

The demand for energy will continue to increase as our society becomes more digitally connected and integrated, which will put pressure on resources and security of supply, increasing global tensions and economic pressure for innovation.

The energy production infrastructure will become increasingly resilient, robust and efficient, as well as more decentralised and operating under new business models.

Energy systems and energy use will change significantly in response to climate change targets, supported by proactive, evidence-based legislation and education to help change consumer behaviour.

What does this mean for energy?

Supply - There will be increasing demands on our energy supply due to the accelerated electrification of transport and the increase in data and communication infrastructure.

Examples include: the next generation of nuclear fission plant, nuclear fusion, combined biomethane power and carbon sequestration plants.

Measurement will enable new, innovative and low-carbon energy generation technologies.

Demand - Pressures on our energy supply will be reduced through more efficient equipment, new generation methods and more sustainable systems.

Measurement will enable the next generation of low-power, low-loss electronics, communication technologies and computer systems.

Measurement will underpin the development of evidence-based energy policies and regulations and support the evolution of social values on energy use.

Decentralisation - Electricity generation will become widely distributed and a smart, secure and resilient network will be needed to exploit and smooth fluctuations in supply and demand.

Examples include: small, portable and modular nuclear reactors, development of a diverse gas system infrastructure, increased use of hydrogen as a fuel or blended with natural gas, offshore wind and large-scale solar development, the use of networked batteries, microgeneration, hydrogen as a storage mechanism, portable power sources, supercapacitors.

Measurement will enable decentralisation, maximise efficiency and ensure an AI-enabled, smart grid infrastructure.

Commercial - New business models for grid operation will emerge to balance supply and demand between consumers and a growing number of producer/consumers.

Examples include: modelling and predicting of intermittent and distributed energy supply, improved conversion and storage management through smart grid technologies, new business models for energy sale and purchase.

Measurement will be needed to ensure accurate and fair energy sale and purchase and enable demand-side response programmes.

Foresighting has highlighted technological trends for metrology based on our vision for energy:

- **Computationally intensive modelling and simulation** of the whole energy grid will benefit from the increased computing power, such as quantum, neuromorphic and spin-based computation.
- **Low-power, wireless devices and sensors** will be enabled by bio-inspired systems and electronics, energy harvesting from the environment, wireless electricity and long-distance wireless charging.

Food production

The rising global population is increasing demand for food and water, and everyone expects more choice about their food.

More efficient and automated food production, both through agriculture and the manufacture of food substitutes, will be required to meet demand.

Food retail will be primarily online, benefitting from automated and zero-carbon delivery methods, with food safety guaranteed by sustainable and smart packaging.

The increased need for the nutrients and functional foods to support diverse demographics and improve health will require engineered biology.

What does this mean for food production?

Substitutes - There will be a rise in the consumption of food substitutes, reducing the cost and environmental impact of farming and increasing food security.

Examples include: 3D printing of food, insect protein, laboratory grown meat and vegan protein substitutes.

Measurement will be needed to enable the development of food safety standards and regulations, while also ensuring palatability for the consumer and cost-effective mass production.

Commercial - Continued growth in online food shopping, smart ordering systems in the home, economically viable on-demand deliveries and autonomous delivery systems.

Measurement will enable tracking throughout the food production and distribution system.

Waste reduction - There will be a push to reduce food waste and the use of plastic packaging waste in response to consumers' values and behaviours with respect to environmental sustainability.

Examples include: conversion to bio-fuel or other resources, regulated sustainable packaging materials, intelligent packaging to preserve food and monitor safety.

Measurement will help eliminate unnecessary disposal of food, increase the sustainability of packaging to support the circular economy and enable sustainable and efficient distribution.

Innovation - Novel forms of automated food production will become widespread due to increased pressures on land use, and demand for food and resource efficiency.

Examples include: hydroponics, LED lighting, 3D farming, urban agriculture, cellular agriculture.

Measurement will provide confidence in automation and p rocess engineering.

Engineered biology - Genetic engineering will be applied to modify crops to feed an increasing population, cope with climate changes and enable food to be tailored for the personal dietary requirements of different demographics.

Examples include: production systems for genetically modified organisms, proteins, cells and nucleic acids, food additives and supplements for enhanced performance diets, interventions to support a healthy human microbiome.

Measurement will ensure food safety and crop resilience.

Measurement will be needed to control nutrition and function, and design food to tackle diseases.

Foresighting has highlighted technological trends for metrology based on our vision for food production:

- **Monitoring of food production** will be enabled by machine learning and AI-controlled logistics, hyperspectral imaging systems, real-time monitoring of livestock and quantum sensing and measurement for mapping underground features, including different soil types and water resources.
- **Traceability of ingredients and allergens**, from production to point-of-sale, will be enabled by smart packaging and smart labelling technologies and plasmonic-based toxin and allergen detection.
- **Determination of individual food and nutritional requirements** will benefit from advances in genetic testing, and the understanding and modelling of biological systems.

Healthcare

An increasingly ageing population will create new demands on our healthcare systems for technologies, products and services to promote independent, quality lives.

There will be a significant increase in the use of wearable and implantable sensors to generate continuous, reliable and high-quality data, which will support data-driven models and AI systems to make health-related decisions.

There will be a shift towards proactive healthcare with a focus on predictive, preventative and personalised medicine which will be enabled by a detailed understanding of health and disease.

Educated and empowered citizens will take an active role in managing their health, supported by a more decentralised healthcare system.

Technological advances and the digital revolution will support both physical and mental health in co-ordinated and innovative ways.

What does this mean for healthcare?

Decentralisation - Healthcare systems will be decentralised as citizens take a more active role in their health and wellbeing.

Examples include: advances in wearable and implantable bioelectronics, informed citizens collecting and securely sharing personal data to improve health.

Measurement will enable remote consultation and intervention through AI-assisted diagnosis, telemedicine and remote treatment, and also to support responsive medical regulation.

Complex systems - Predictive and preventative medicine will become a reality as the effects, risks and contributions from environmental, behavioural, biological and genetic factors are unravelled.

Examples include: analysis of large, complex and complementary datasets for decision-making, in-situ validation and calibration of sensors.

Measurement will be needed of many factors to support healthcare decisions, the development of early warning and real-time systems for emerging health risks.

Regenerative medicine - Simulations of the activities, mechanics and physiological response of entire organs will enable regenerative medicine and transplants.

Examples include: replacing animals for research, data to study the effects of pharmaceuticals.

Measurement will be needed to understand biological functions and processes.

Personalisation - Therapies, treatments and drugs will be individually designed as personalised medical interventions become the primary method of treating diseases.

Examples include: cell and gene therapies developed through engineered biology, advances in '-omics' technologies and nanotechnology-based sensors and drug delivery systems.

Measurement will be needed to design and evaluate individualised interventions.

Innovation - Advanced technologies will be used to treat, cure and prevent genetic and acquired diseases to revolutionise quality of life.

Examples include: 3D biomaterial printers, advanced radiotherapies, combined diagnostic and treatment solutions, machine-brain interfacing.

Measurement will be needed to develop new regulations and regulatory processes to build confidence in new technologies.

Foresighting has highlighted technological trends for metrology based on our vision for healthcare:

- **Continuous data collection for health monitoring** will benefit from advances in the quantification and processing of multimodal and multiscale data as well as improved wireless and sensor technology.
- **Internet linked, self-powered, self-calibrating, wearable or implantable bioelectronic devices** will require traceable and innovative measurement techniques.
- **Quantification and analysis of complex data sets** will enable the understanding of influences on health and disease.

Manufacturing

Manufacturing will become more complex as supply chains become interdependent, digital and international.

Future manufacturing systems will be enabled by a large variety of digital solutions and intelligent data driven tools, which will result in the full digitisation of manufacture and sustainable resource management.

Responsive and agile manufacturing systems will emerge, which use innovative production techniques and rely on continuous measurement and product verification through digital or virtual methods.

Consumers will expect products and services to be personalised to their own needs and preferences.

What does this mean for manufacturing?

Digital design - All manufacturing will rely on digital design as product function, user requirements, material properties, and processing and fabrication strategies flow from a single source.

Measurement will enable development of materials by design, virtualisation and product innovation through modelling.

Measurement will allow new parts and products to enter service safely without being subjected to a physical test.

Smart - Intelligent data driven tools will manage responsive, productive and efficient manufacturing systems, supporting the circular economy as resources become scarce.

Examples include: smart contracts and distributed ledgers, autonomous and co-operative robotics, exoskeletons, human enhancement.

Measurement will enable process analytics, help control manufacturing processes, enable rapid demand forecasting, and provide trusted data through digital certification.

Materials - New materials will be adopted as advanced functionalities are realised and alternative sources become available.

Examples include: materials for biomanufacturing, metamaterials, alternative sources (such as deep sea or asteroids), reprocessing of plastics and natural replacements.

Measurement will enable a deeper understanding of complex material behaviour, ensure safety regulations are in place and allow confidence in their widespread adoption.

Personalisation - Products and services will be tailored to individual requirement as consumers come to expect more choice and bespoke products at no extra cost.

Measurement will enable flexible manufacturing facilities that allow multiple variations of products without loss of throughput.

Measurement will support AI-enabled data analytics to extract value from securely shared customer data.

Business models - A new paradigm in value creation will emerge as consumers consider the environmental and social impact of their choices, not just financial metrics.

Measurement will provide trusted information and confidence in its source.

Foresighting has highlighted technological trends for metrology based on our vision for manufacturing:

- **Continuous measurement throughout the supply and manufacturing chain** will be enabled by advanced imaging, sensors and monitoring.
- **Digital calibration certificates** will be held on global distributed ledgers and, combined with digital and machine-readable standards and regulations, will enable virtual verification and calibration.
- **Digital product verification** methods will be enabled by dynamic propagation of measurement uncertainty through performance models.

Transport

A complex, dynamic and connected transport system will be critical for our economy and society, from moving people for work and leisure and goods as part of a supply chain.

Future transport solutions will be faster, safer, inclusive and convenient, and new mobility options will address the demands of an ageing population, rural areas and disabled people.

Sustainable propulsion methods will be needed to support the net-zero carbon target, with a significant infrastructure investment needed to encourage adoption of new technology.

Advances in artificial intelligence, digital and sensing technologies will transform the management and integration of the transport landscape.

What does this mean for transport

Mobility - Transport options will increase for all, especially for the ageing population and those living in rural areas, as public perceptions and attitudes towards personal travel change.

Examples include: micromobility, personal air transport, integrated information systems

Measurement will provide logistical and environmental data to influence consumer transport choices.

Automation - Personal and goods transport systems will be automated as safety, efficiency, convenience and speed become more important.

Examples include: location tracking and timestamping, road trains, airspace regulations for automated drones, validated and reliable multi-scale and multi-level models of transport systems.

Measurement will enable AI and machine learning algorithms to operate interconnected and interoperable modes of transport through seamless and secure transmission of data.

Innovation - Technology will enable new modes of sustainable transport to become mainstream.

Examples include: frictionless drive, evacuated tube-based mass transport and new materials for road surfaces.

Measurement will enable test and validation of products and materials, and the development of agile regulations.

Decarbonisation - The electrification of our transport will continue at a faster pace, driven by the need to achieve net-zero carbon emissions.

Examples include: rare-earth element recovery and recycling, novel electric propulsion technologies including those with no moving parts, hybrid-electric engines which can function with multiple fuel sources.

Measurement will help optimise the manufacture and recycling of batteries, and the adoption of alternative, less-polluting, natural and synthetic fuels and additives.

Ownership - Operating and ownership models of individual transport will become service-based (servitisation) which will significantly reduce running and maintenance costs.

Examples include: shared use of vehicles, battery-swapping points, regulations to overcome non-proprietary technology-sharing challenges.

Measurement will enable management of integrated energy storage and a smart national charging grid.

Measurement will support consumer choice and the economics of new operating models.

Foresighting has highlighted technological trends for metrology based on our vision for transport:

- **Open-access, traceable and verified environmental impact data** will influence customer choice.
- **Advanced, robust and connected sensors** will enable performance monitoring of safety critical components, even in extreme environments.
- **Analysis of complex systems** will enable truly smart transport systems and infrastructure.

Key trends

Technology and Measurement Foresighting used the drivers of change to investigate six industries. By drawing parallels and analysing the challenges, common themes and technologies emerged. These trends represent the overarching changes that will impact society and citizens all over the world. However in any vision of the future there are changes that cannot be anticipated or may turn out to be more influential than imagined.

> "We need to be able to measure thousands of parameters important to health, and analyse them in real time, away from a hospital or laboratory environment"
>
> Dr Tony Wood
>
> Senior Vice President, Medicinal Science & Technology, GSK

Sustainability It will become essential to manage limited global resources - land, energy, water and materials. Recycling, re-use and repurposing will become widespread, however rising consumption and resource limitation may lead to conflicting demands.

Automation Advances in machine learning, robotics, imaging and sensing will unlock the benefits of automation for society. Automated systems will do labour intensive tasks, increasing productivity, convenience, safety, quality and resource efficiency, but these technological advances may have negative effects on human wellbeing and skills.

Infrastructure Utilities, transport and logistics will become increasingly interdependent and interconnected. All our infrastructure will become more secure, efficient, resilient and safe, but these complex systems may not benefit everyone equally.

Personalisation Products and services will become personalised and bespoke - from medical interventions to consumer products. However, people may not be willing to share their personal data if they do not trust it to be used ethically.

Business New business models will emerge which increasingly wrap services around products and are focused on personalisation, sustainability and cost-reduction. However, inequality of access to technological advances may disadvantage sections of the population.

People Informed citizens will take a more proactive role in tackling society's challenges and change their behaviours regarding the environment and health. Social attitudes may reflect mistrust of the use of personal data.

Complex problems Unravelling the complexity of interconnected and dependent systems - such as disease, weather, climate - will revolutionise our ability to assess risks and contributions, and benefit individuals and society. However, controlling complex systems may increase the risk of unintended or irreversible consequences.

Technological advances

Foresighting has highlighted key technological advances which will require or enable metrology:

- **Advanced nano- and biotechnology** for medical application and human enhancement.
- **Hyperspectral imaging** for sensing and automation.
- **Novel and meta-materials** for sustainability and low-loss, low noise and low-power electronics.
- **Quantum communication and cryptography** for seamless and secure sharing of data.
- **Quantum, photonic, neuromorphic and spin-based computers** for low power, high performance computation.
- **Quantification and processing of multi-scale, multimodal data** for automated, model-based, decision-making.
- **Quantitative biology** for the application of precise engineering discipline in medicine and pharmaceutical sciences.
- **Wireless electricity, energy harvesting from the environment and micro-generation** for self-powered devices.

These trends and technologies represent the changes that will impact why and how we perform measurements, and therefore the implications for the future of metrology and NPL's future research priorities.

Future of metrology

The role of metrology is to ensure that measurements are useful and accurate. It is about more than the routine making of measurements, it concerns the infrastructure that ensures we have confidence in the accuracy of the measurement or the adoption of technology.

NPL works to provide the measurement infrastructure that meets the needs of industry and society. Whether it is improving trust in scientific reporting, reducing waste in manufacturing or accelerating technological progress, metrology is the common theme that underpins our work.

The International System of Units ('the SI') is the only globally agreed system of measurement units. The SI defines units for many types of measurement and is necessary to ensure that our everyday measurements remain comparable and consistent worldwide.

Technology and Measurement Foresighting explored the implications of new technologies and trends on the future of measurement. There were three key conclusions for metrology:

1. Metrology will support a digitally enabled global measurement infrastructure

- Traceability chains will be shortened, therefore reducing uncertainty
- Traceability to the SI will be embedded directly into measuring instruments
- In-situ calibration of sensors and local standards will be commonplace

The definitions of the SI base units are now designed to enable easier access for end users. New digital knowledge management and dissemination tools will bring primary standards closer to the end of the measurement chain and deliver lower measurement uncertainty for end users. Digital and machine-readable calibration certificates held on global distributed ledgers will enable in-situ calibration of sensors and local standards, improving the provenance of measurements and simplifying traceability chains.

2. Metrology will improve understanding of complex systems

- Metrology will support a systems-based understanding of the world
- Metrology will support the growing prevalence of indirect, hybrid and proxy measurements
- Metrology will help combine data of different quality, provenance and time periods

Understanding complex systems is becoming more important as we try and manage and control climate change, biological processes and our ever growing, interconnected and interdependent infrastructure. In order to develop and operate large, multi-scale and multi-level models of complex systems, we will need data quality frameworks to combine multimodal and multi-scale data. By using a 'metrology mindset', complex systems can be analysed and uncertainties assigned, even though many of the measurements involved sit outside the SI.

3. Metrology will give confidence in decision making

- Metrology will support decisions made by machine learning algorithms and explainable artificial intelligence
- Agile and responsive regulation will enable automated decisions to be made, even in safety critical situations
- Measurement scientists will have a responsibility to ensure that data is being used with integrity and impartiality

Confidence in decision-making will be reliant on the dynamic propagation of uncertainty through computationally intensive models or algorithms. Taking advantage of increased measurement sensitivity, the seamless and secure sharing of data and increased computation power, needs to be combined with a sound metrological framework and understanding. This will lead to better decision making and the application of artificial intelligence and machine learning to new areas therefore accelerating the process of discovery.

Working together

Measurement and metrology will be essential to maintain and enhance global wellbeing, sustainability and enterprise. Metrology concerns the infrastructure that ensures we have confidence in the accuracy of measurement and the adoption of technology.

As society responds to the challenges of resource limitations, increased automation and digitalisation, key technological advances will require and facilitate new ways of measuring. Metrology will support better understanding of complex systems and decisions made by machine learning algorithms, artificial intelligence or based on large quantities of data. A digitally enabled global measurement infrastructure should be a key priority as industry responds to the changes in society.

NPL works with partners nationally and internationally, and we invite you to collaborate with us so that we may realise this vision together. NPL will use the findings of this work to set its future research priorities. Working with national and international partners, NPL will set the agenda for metrology research over the coming decades. We invite you to collaborate with us so that we may realise this vision together.

Please contact us: **foresighting@npl.co.uk**

"We need to reduce emissions, we need to capture CO_2, but also we need to find better ways to deal with the consequences of climate change, such as shifting weather patterns and shifting habitable areas"

Dame Frances Saunders CB

Past President, IoP;
past-Chief Executive, DSTL

"We need a holistic understanding of our interconnected world. We can no longer think in silos"

Sir Jim McDonald

Principal & Vice-Chancellor, University of Strathclyde and President of the Royal Academy of Engineering

"We need a vision for a viable AI-driven digital world"

Dr Elizabeth Donley

Head of Time and Frequency, NIST

"There are already places on earth where solar energy is the lowest cost energy source. This will become so across the whole world within 5 to 10 years"

Dr Hermann Hauser

Entrepreneur and co-founder, Amadeus Capital Partners Ltd

"AI will be fantastic tool of future, but the software solutions are developing faster than hardware. Computer hardware must be revolutionised or it will continue to suck in more and more resources"

Prof. Sir Ian Boyd

Immediate Past Chief Scientific Adviser for UK Department for Environment, Food & Rural Affairs (2012-2019)

"Self-care is key, and this can only be achieved with education and technological advances in personal health monitoring"

Brigadier Tim Hodgetts CBE QHS

Head of Army Medical Services and Senior Health Adviser to the British Army

Our approach

NPL has undertaken a wide-ranging review of society and technology in order to:

- identify major trends in the future of society and industry
- analyse which technologies will be vital to enable them
- explore their implications on metrology – the science of measurement

The Technology and Measurement Foresighting project was delivered by a diverse team of 26 people from NPL and its partner measurement laboratories in the UK using a set of tools developed by the UK Government Office for Science:

- Horizon scanning - gathering information on emerging trends and their impact
- Structured interviews - detailed input from 27 industry and technology experts
- Analysis - extensive discussion and analysis
- Validation - workshops for feedback and guidance from more than 70 experts

NPL worked closely with the University of Surrey and the University of Strathclyde, NPL's Science and Technology Advisory Council and the expert advisors for the UK's National Measurement System.

Many thanks to all those who were interviewed in depth

Prof. Grahame Blair, Executive Director, Programmes, STFC

Emma Howard Boyd, Chair, Environment Agency

Prof. Sir Ian Boyd, Immediate Past Chief Scientific Adviser for UK Department for Environment, Food & Rural Affairs (2012-2019)

Paul Bramley, Founder and Technical Director, Metrosol

Prof. David Brettle, Chief Scientific Officer, Leeds Teaching Hospitals NHS Trust

Prof. Richard Craster, Dean of Natural Sciences, Imperial College London

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