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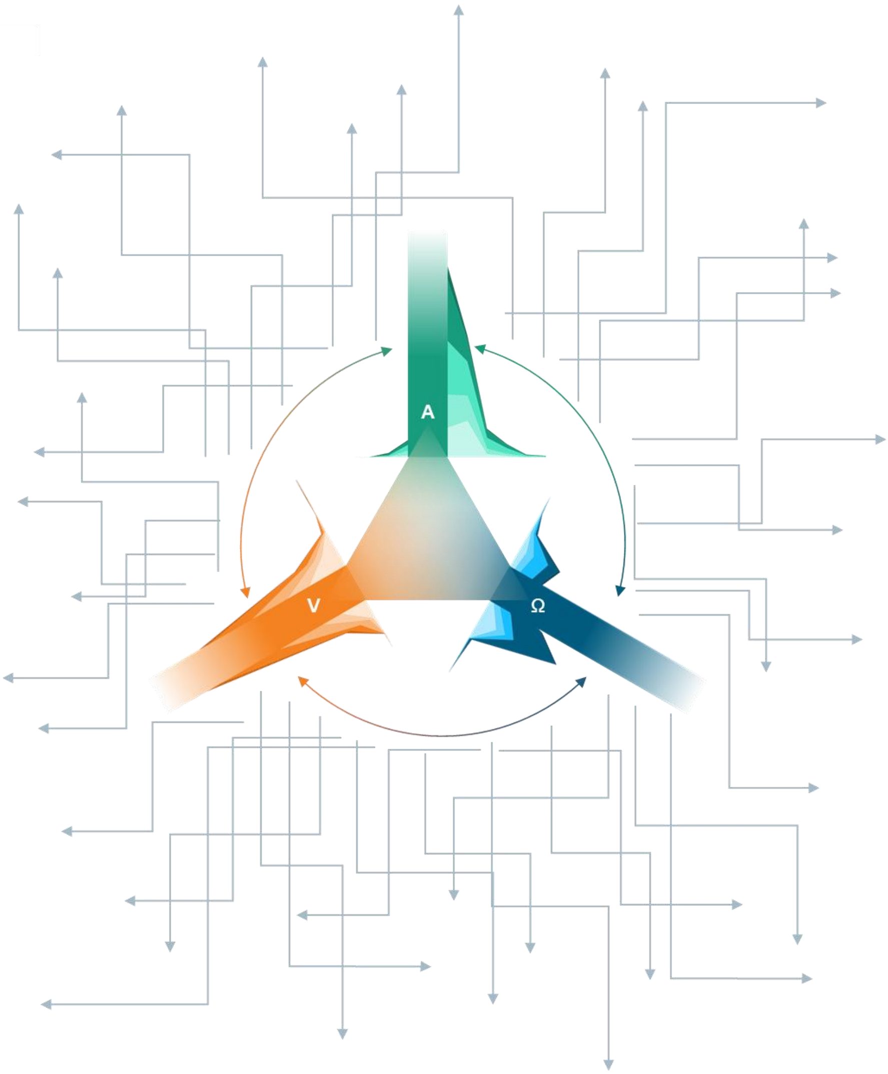

Economic Impact of Quantum Electrical Metrology

Study on the effects from innovative Quantum Electrical Metrology on Economy and Society

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Economic Impact of QEM

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1 Introduction and Goals

The British national measurement standards laboratory – the National Physical Laboratory (NPL) – plays a pivotal role in setting and maintaining physical standards. NPL's Quantum Electrical Metrology (QEM) Group develops primary standards for electrical units, in particular, voltage, resistance, and current, which are fundamental to a wide range of instrumentation, devices and technologies generating an impact on the economy and broader society. Significant impacts from Quantum Electrical Metrology (QEM) are expected on several high potential industries that have strategic relevance for economies and societies. Accurate standards and measurements in these and other application areas enable relevant companies to generate higher efficiency, design and produce new advanced technologies and realise better quality of their products. Moreover, NPL provides highly specialised know-how in the field of metrological applications. However, the broad benefits that result from the application of QEM technologies are largely unknown for the wide public.

Although there have been some attempts to examine the economic role of metrology and even some seminal research of the effects of metrology and standards in particular on the economic development[1], the topic is still not well studied yet. Especially the effects from R&D activities that are undertaken at national metrology institutes and mechanisms through which they impact the economy are still largely unknown.

Against this background, the goal of this study is to explore and assess the potential economic implications that arise from the utilisation of QEM innovations and technical expertise in the field and also to shed light on how metrology and QEM in particular contributes to the achievement of the strategic goals set out by the government of the United Kingdom. These involve the goal of an outstanding research and innovation system, global leadership in advanced technologies and innovation, economic growth and support of new industries based on advanced and emerging technologies, and enhancing the capabilities to tackle grand and environmental challenges. The study will also discuss the role of QEM technology in current and emerging technological developments and analyse trends that shape the market for precision electrical measurements and standards.

More specifically, the study intends to examine the impact of QEM on the economy and its players, its role in the National Innovation System through analysing the pathways through which it impacts its stakeholders and industrial players.

Therefore, an important part of this study concentrates on the investigation of the effects of innovations in electrical metrology and improvements in the realisation of electrical primary standards in technology intensive industries. This also involves the definition of specific industrial segments or sectors the QEM technology relates to, market definition, and identification of high potential application areas where QEM is of critical importance and where a significant economic impact from QEM is expected.

While the focus of this report in on the investigation of economic effects and especially on benefits for industry, other aspects, such as social and environmental need to be taken into account to demonstrate the relevance of metrology for the society. Specifically, the study undertakes an effort to identify and assess the value from recent scientific and technological progress that resulted from the R&D activities at NPL and other metrology scientific communities.

More generally, the analysis shall contribute to a better understanding, how science and technology in the field of QEM benefit the economy and society. More specifically, the scientific assessment of

[1] To the fundamental works that contributed to the understanding of the role of metrology belong, for example: Tassey 2008; Swann 2009.

the overall effects and value of QEM, will provide essential information for policymakers and support the NPL and the QEM Group in particular in their strategic planning processes. To capture all major effects and impacts that the activities of the NPL and the QEM group specifically entail and to demonstrate how the innovative QEM creates value to the economy and the innovation system, the Impact Pathway Model is developed and presented in this report.

The report is structured as follows: Chapter 2 describes the overall methodological approach applied in the study, Chapter 3 discusses the role of science-based metrology for the National Innovation System; Chapter 4 presents more specifically the relevance and impact of innovative electric metrology for economy and society focusing on the calibration and instrument technologies and their use in the downstream sectors. Chapter 5 provides the description of case studies delineating some specific applications with potentially large socio-economic impacts, where QEM has an important contributing role. Chapter 6 critically summarises the major impacts from QEM by presenting impact pathways and Chapter 7 sums up the generated insights, provides an outlook on expected developments and presents recommendations for increasing the socio-economic impact.

2 Methods and Approach

The goal of the project is to assess economic impacts from innovative Quantum Electrical Metrology (QEM). While the study focuses on the economic effects that activities and scientific and technological advances within QEM enable or support, it also considers technological, social and other effects to provide a whole picture of the relevance that QEM has on economy and society. By doing this, the study focus on some major application areas and technologies without making claim to be exhaustive.

The impact assessment of innovative metrology and of Quantum Electrical Metrology in particular requires a deep understanding of processes and mechanisms that generate or contribute to impacts. This understanding is essential to establish the causal relation between R&D activities in the field of QEM and their effects. Therefore, different methodologies were applied to obtain and analyse information that would allow to reach conclusions on the broad impact of QEM. To develop a comprehensive understanding of the impact and increase validity of findings, we used the triangulation technique that combines different research methods to arrive at meaningful insights. The methodolgical framework used for this study comprises: literature review, patent and scientific publication analysis, structured interviews, survey, and case studies. They were used complementarily, considering and combining different information sources and means for collecting data to ensure the objectivity of the study and to compensate for shortcomings of each individual method.

The originally proposed methodology with a strong focus on quantitative indicators and data analysis needed to be modified and adjusted to consider the nature of effects of QEM and the limitations to obtain quantitative data. In particular, during the study it became evident that the impacts from metrology are very much context specific, i.e. they do not apply equally across companies and industries. Further, it proved to be very difficult to obtain specific contextual information about utilising knowledge generated at NMIs. In the light of the aforementioned specifics of metrology effects on the economy, case studies is a methodology frequently used in other related and renowned studies (see, for example (Link 2021; Swann 2009; Dias and King 2022; King et al. 2022). The objective of case studies is to present the added value and contribution from innovative electrical metrology in one specific application context to different technologies and assess potential impacts from innovative quantum electrical metrology. For case studies, data from different sources, primarily in-depth interviews and literature review were used to demonstrate the contribution and economic impact of QEM in different application fields. The coverage of application fields in the selected case studies is not exhaustive, but represents some major applications, where significant impacts have been identified to demonstrate how innovative electrical metrology contributes to them.

To collect evidence on the real impact of electrical calibration and measurement technologies on industries and businesses, over 40 interviews with metrology experts and business representatives representing some advanced instrumentation companies in Europe and one large calibration lab, were conducted. In addition, an online survey was prepared and carried out to provide data on a broader basis, targeting three major groups: 1) commercial calibration labs, 2) providers of measurement instruments and tools and 3) commercial end users of measurement & testing technologies.

On the basis on collective findings and insights generated in the study, an impact pathway model and impact pathway for major contributions from QEM to economy are derived, outlining how innovative QEM creates value to the economy and society. Impact pathways connect activities and outputs from those with the identifiable economic, societal and environmental effects that eventually contribute to the broader long term impacts. They reflect the key dimensions, in which impacts are expected. The approach of impact pathways enables to gain insights and provide a systematic overview of all major effects. This approach is also useful to define corresponding KPIs in order to capture and track the achievement of short-term and long-term goals along the impact pathways.

Despite the comprehensive research performed combining different methods and strategies to generate data, there are some limitations that were difficult to overcome. Difficulties related to appropriate identification and quantification of the economic effects of metrology are broadly recognised (see for example: (CRISTAUDO et al. 2018; Gonçalves and Peuckert 2011)). The reasons for these difficulties are manifold: general challenge to capture the effects of metrology as a public good and the associated externalities, indirect/derivative effects that metrology has on economy, and difficulties to isolate the individual effects of specific metrological parameters. Modern technology driven industries rely on high quality metrology/measurement infrastructure characterised by considerable complementarities and interdependencies between its individual elements. This imposes a particular challenge to figure out, which impacts result from the integration of various activities and which are a consequence of a single effect (Gonçalves and Peuckert 2011). Therefore, it is very difficult to assess the overall scale and exact magnitude of impacts from QEM. Due to the difficulties to quantify and assign figures to different direct and indirect effects, the study focus on qualitative assessment of the effects of QEM, which is also better suited to provide the whole picture and to account for the total value generated by innovative QEM.

3 Role of science-based Metrology within the National Innovation System

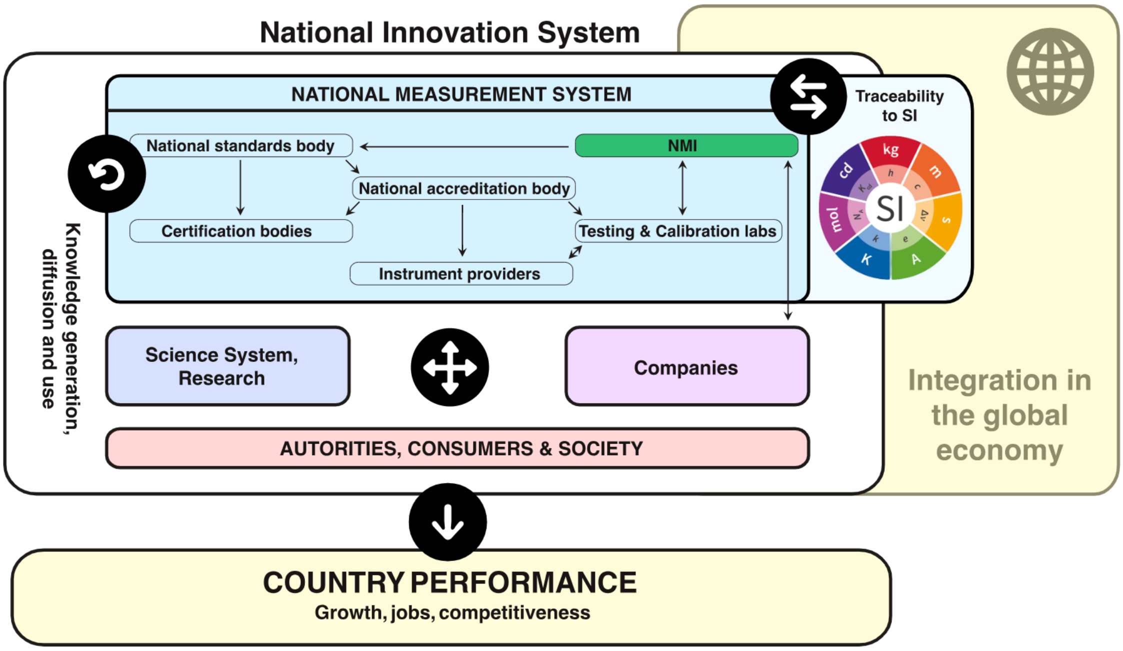
Today's technological development is increasingly characterised by rising complexity, accelerated pace of innovation and escalating R&D costs. Complexity relates to both the breadth and rapid change of technology and the underlying knowledge to which companies and other players of the innovation system need access. The speed of innovation is one of the major competitive advantage factors, so that the ability to accelerate the speed of innovation became essential to sustain in the global competition.

The increasing complexity of technologies implies increasing scope for product differentiation based on different combinations of performance characteristics of products (King et al. 2017). In order to specify such complex performance features, suitable measurement tools are required. Moreover, most advanced technologies are measurement intensive. With the advancement of existing technologies and the emergence of new technologies (e.g. recently quantum technologies) the nature of the measurement practices can change as well. Also the development of solutions to global challenges, such as climate change and energy supply, safety and security, environmental protection and the delivery of the high quality healthcare depend on a reliable and internationally agreed measurement infrastructure.

In the National Innovation System (NIS) the linkages and interactions among its actors – primarily companies, research and technology organisations, universities and other institutions involved in knowledge generation, – as well as the flow of knowledge and technology are key to innovation processes. It contains different leverage points that impact the innovative performance and competitiveness of a country. One of them represents the access to the high quality technical infrastructure. Fundamental research in metrology, development of measurement techniques and their incorporation into codified knowledge in the form of standards, as well as their application are referred to as National Measurement Infrastructure (King et al. 2017). It comprises various specialised players interacting with each other. **National Metrology Institutes (NMIs)** are its central players developing, maintaining and transferring measurement standards and related expertise to all other actors of the NIS and beyond. Thereby they provide a fundamental basis for the necessary conformity assessment activities, such as calibration, testing and accreditation within an economy and support the development of science based regulation. Through operation, maintenance and further development of primary standards as well as calibration against primary standards, the **NMIs guarantee the accuracy of measurements and traceability to SI standards**. Further important players of the Measurement System are: national standards bodies, certification bodies, the national accreditation body, calibration and testing laboratories and instrument providers that offer measurement instruments used in industry, science, development, and testing (Figure 1).

The application of metrology plays a key role in the adoption of technological innovations. It supports safety and monitoring of conformity along with ensuring quality in manufactured goods and processes through accurate and reliable measurement. Among others, this provides an important basis for the integration of the national economy in the global economy and international trading (Figure 1). Moreover, metrology contributes to meeting societal needs, such as protection of buyers and sellers, health and food security, and environmental protection. In summary, the impacts from the National Measurement Infrastructure and metrology in particular extend far beyond the effects on economy. Consequently, metrology and the national measurement system are central for the effective functioning of the economy and the innovation system. As such, metrology has a truly systemic function with many effects both direct and indirect on different spheres of economy and social life.

Figure 1 Role of the National Measurement System within a National Innovation System



Source: Fraunhofer ISI

There are different mechanisms through which advancements in the measurement science driven by NMIs are transferred to and impact the economy. These include dissemination of measurement standards by providing calibration services, the development of standard reference materials, test methods, skill developments and trainings, joint R&D activities with businesses and academia, scientific publications, licensing, consultancy and other professional services (see: Activities of the QEM group at NPL).

Metrology has a strong public good character. As such it is characterised by high fixed costs and positive externalities, allowing "third parties" (private and public players) to benefit from metrology, while the marginal costs are relatively low, which makes underinvestment in metrology by private players most likely. This justifies public support and investment in the metrology infrastructure and R&D. Positive externalities are very much linked to knowledge spillovers to different third parties. More specifically, the knowledge in the context of the measurement infrastructure is defined as "measurement and test methods, process and quality control techniques, evaluated scientific and engineering data, and the technical basis for product interfaces" (Tassey 2008). **Knowledge embedded in the standards, is applied throughout the innovation system**. Considerable positive externalities and knowledge spillovers make it difficult to evaluate the whole scale of impacts from metrology. However, it can be rightly reasoned that the more complex and differentiated the technology is getting, the more important metrology and resulting impacts are becoming including overall spill-over effects thereof.

3.1 Literature review on economic relevance of metrology

A number of studies were conducted examining the general relevance and value of metrology. The goal of this section is to provide an overview of key economic arguments for the relevance of metrology and measurement infrastructure provided in the literature so far.

There is a lot of evidence that metrology is one essential driver of economic development and innovation, as measurements are ubiquitous in research, development, production, and application of technologies (see for example (Tassey 2008; Gonçalves and Peuckert 2011; Robertson and Swanepoel 2015; King et al. 2017; Link 2021; Swann 2009). Accurate, traceable measurements are needed to demonstrate the quality and reliability of products for consumer and businesses, thus reducing uncertainty and promoting trade. This highlights the fundamental relevance of metrology for economic transactions (Robertson and Swanepoel 2015). Moreover, improved measurement capabilities enhance chances for product and process innovation enabling the development of new instruments and techniques, which result in productivity gains (Fennelly 2021). The stability of the outcomes, resulting from accurate measurements, improves trust between firms and other organisations, which facilitates new partnerships, products and processes (Gonçalves and Peuckert 2011).

The main effects of metrology (both as science and imbedded in the measurement infrastructure and technologies) on economy indicated in the major literature sources[2] are:

- **Efficient functioning of markets and reducing the risk of market failure**: provision of measurements and standards help to verify product quality and reliably inform the buyer about it. This helps the buyer to avoid the risk of adverse selection buying an inferior product which does not meet the necessary specification and quality standards, On the whole, the access to the science based conformity assessment framework reduces the risk of information asymmetry, which may lead to market failure and contributes to the efficient functioning of markets.
- **Lowering the transaction cost**: by meeting an agreed standard of measurement, cost associated with an inferior quality of products would be avoided for both the buyer (e.g. searching a product with higher quality or double testing checking whether the product meets the specifications) and the product provider (correcting defects to meet specifications).
- **Opening markets and enhancing competition**: higher transparency and compliance with standards help firms to enter new markets. Through certification and accreditation, firms obtain more easily access to external markets and trust from foreign consumers as it guarantees that their products meet the required specifications and norms. It allows firms to better differentiate their products in terms of quality or improve their internal processes, which helps them to sustain competition.
- **Facilitating and driving innovation**: provision of the state-of-the-art metrological infrastructure and measurement capabilities provides an important platform for the development, fabrication and application of new technologies. Accurate measurements traceable to common references make R&D activities more effective guaranteeing the compatibility of methods, instruments, or properties of products employed in the R&D activities.
- **Supporting regulation and regulatory compliance** by providing measurement references for policy advice, directives, conformity assessment, and verification to protect consumers and businesses. Metrological techniques determine and help enforce accurate measurement of different parameters within economic transactions and support their functioning within an economy and supports trade with other economies. Moreover, metrology and measurement infrastructure are essential for assuring compliance to achieve environmental, safety, security and other social goals. The cost of complying with regulations is high for both the regulator and industries, so compliance efficiency is key.

[2] Based on insights generated through previous research by: Tassey 2008; Gonçalves and Peuckert 2011; Robertson and Swanepoel 2015; King et al. 2017; Link 2021; Swann 2009.

3.2 Relevance of R&D in QEM for the Innovation System and Economy

There is a continuous need for the R&D in metrology, including electrical metrology, as modern economies and underlying technologies are constantly changing and developing. Consequently, metrology systems also need to change and adapt in order to better meet the needs of new technologies and industries using or providing them. This holds true in particular for QEM which is a novel and highly research intensive metrology approach (see: R&D in QEM and their relevance).

3.2.1 Activities of the QEM group at NPL

The Quantum Electrical Metrology (QEM) Group at the NPL[3] develops primary standards for electrical units, in particular, voltage, resistance, and current and conducts world-class research in this area. Through their R&D activities, the QEM group advances the existing electrical standards, prepares the next generation of standards, develops technologies for their efficient dissemination and exploitation. An examples of most prominent achievements and R&D activities with huge potential and fundamental importance is the development of a simplified Quantum Hall device for the realisation of SI unit of resistance using a Quantum Hall Effect.[4]

Research at the QEM group is also focusing on single-electron transport and the development of nano-scale devices for moving electrons one-by-one. This work has a potential to form the foundation of a future redefinition of the SI base unit for current, the ampere. Single electron devices may also be a building block in future quantum circuitry and can be used to test our understanding of the fundamental laws of quantum mechanics.[5]

The QEM group is currently developing the next generation primary voltage standard based on programmable Josephson arrays and a cryogen-free system (without the need for liquid helium). This new system is expected to replace the existing old primary voltage standard.[6]

As was mentioned before, metrology plays a key role in supporting the regulation and regulatory compliance by providing measurement references and necessary technologies and technique to undertake measurements and verify the compliance. However, the cost of compliance is high, so that R&D activities that lead to improvements in the realisation of primary standards in terms of better usability, reduction of complexity and cost reduction are critical. Also there is a need for continuous improvement of measurement technologies which are more efficient and easier to use and better meet the demands of new or advanced technologies. On the whole, this contributes to the overall cost reduction and efficiency improvements within the entire Innovation System.

Much of the work of the QEM group is linked to fundamental QEM research with a large impact on metrology and related sciences, supporting research and technological progress in metrology. However, the scope of activities and their impacts of the QEM group goes far beyond the R&D. NPL actively engages and exchanges knowledge in the international metrology community through joint R&D and other activities, which is disseminated within the country. Of particular importance in terms of impact is the knowledge and technology transfer that takes place through different channels. Knowledge transfer between the NPL's research groups and external partners occurs

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[3] The NPL is one of the world's leading National Measurement Institutes (NMIs) which plays a key role in the international metrology system defining, realising and disseminating the primary standards. The mission of NPL is "... [to] develop 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."

[4] https://www.npl.co.uk/products-services/quantum-technologies/the-table-top-quantum-hall

[5] https://www.npl.co.uk/quantum-technologies/electrical-si

[6] https://www.npl.co.uk/products-services/quantum-technologies/josephson-voltage-standard

through collaborative R&D, contractual R&D, publications and licensing, testing and consultancy services or through employment of experts that built their broad expertise at NPL.

Scientific publications: in the last 10 years (from 2014 up to July 2023) the QEM group published 91 articles in scientific journals.

Collaborative R&D: Due to the growing complexity of technologies and acceleration of innovation dynamics, cooperation with specialised research organisations is becoming increasingly important for the technological leadership. Therefore, in a dynamic innovation environment, firms need to seek a variety of technological inputs. The cooperation with NMIs is highly important for companies – especially device designers and manufacturers, measurement equipment providers, calibration labs and instrument manufacturer rely on the expertise provided by QEM group. In the interviews it was repeatedly stressed that access to the specialised expertise provided by the NMIs is of high significance to companies, both large firms and SMEs. Previous research has shown that collaborating with NMIs helps companies reduce time-to-market, minimise costs, develop innovations that they would not be able to develop on their own, improve the quality and efficiency of technologies and processes. The QEM group is continuously involved in a number of projects on advanced technological developments together with industrial and academic players. Apart from regular large R&D projects with industrial and other partners, the QEM group has been involved in a number of projects with companies to solve specific quantum related measurement challenges as part of the UK's Quantum program.

Consulting services: A quite significant part of QEM group activities aims at solving problems of industrial companies. Companies and other stakeholders can receive bespoke consultancy and professional support in the form of a consulting service from experts within NPL that helps resolve specific problems.

Access to cutting-edge infrastructure: the NPL enables access to modern technology and cutting-edge equipment for external partners (universities and companies), which compensates them for the lack of cost-intensive technological infrastructure. This enables companies – especially SMEs – to develop and test novel technologies otherwise not possible to do, supporting innovations, business opportunities and competitiveness. To simplify the access to NPL's facilities for short term/responsive projects, 20 day access to NPL facilities at no cost has been offered to the companies as part of the UK Quantum program.

Training and continuous development of expertise: Both technological progress and the introduction of new methods require up-dated metrology skills and competencies in all parts of the Innovation System. The NPL ensures both formal training (within PhD programmes) and continuing professional development of its scientists and experts. In addition, it provides online training courses and other training activities to external organisations. With this, NPL and the QEM groups performs an important function in the Innovation System by training electrical metrology specialists at high qualification levels and disseminating competencies in electrical metrology to various industrial sectors, scientific and other areas.

Knowledge and technology transfer to other countries: The international transfer of technology and technical know-how promotes economic development in poorer regions, while also helping to open new markets. NMIs in advanced countries participate in programmes that support the metrology related advanced knowledge and technology transfer (e.g. transfer of technological infrastructure and equipment, knowledge sharing and provision of training activities) to less developed countries. As electrical metrology addresses quantities that are ubiquitous, the establishment of the national metrology infrastructure with traceability to primary standards is essential in order to support economic activities and social development in these countries. The ability to provide their own measurement and calibration services offers new economic and technological opportunities, contributes to wellbeing and living standards of the people and supports measurement based regulations. Overall, it improves the capabilities of the National Innovation System and helps integrate the country in the international trade. Smaller NMIs or NMIs from less advanced countries also benefit from the procurement of more cost efficient and less complex equipment for the realisation of primary and secondary standards, developed by the NMIs in advanced countries.

3.2.2 R&D in QEM and their relevance

In the following, we will illustrate the significance of advanced metrology and the relevance of the R&D in the field of Quantum Electrical Metrology in supporting innovations, industries and technologies using some important examples.

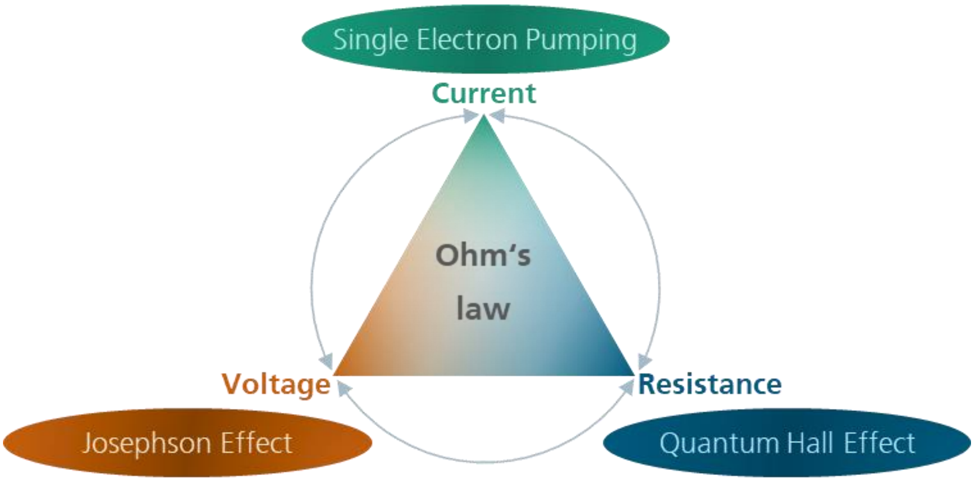
Quantum metrology is driven by the goal of defining and realising physical units with an absolute precision by basing them on fundamental physical constants. The accurate realization is a technological challenge, which is achieved with a high precision for many units already. For quantum electrical metrology, the three electrical units volts (V), ampere (A) and ohm (Ω) are crucial. The quantum metrological realisation of volts and ohm was achieved with the Josephson voltage standard and the Quantum Hall Effect (see below), respectively.

The Josephson voltage standard is based on two superconductors connected by a thin isolator. If an AC voltage is applied to this so-called Josephson junction, measuring the current reveals frequency dependent steps, so-called Shapiro steps. If an AC voltage is applied to this so-called Josephson junction and the current is measured, frequency dependent steps emerge in the current-voltage diagram. The position of these Shapiro steps is based on the Planck constant and the elementary charge – two natural constants. If a well-defined frequency is applied, the voltage can be calibrated accordingly.

The Quantum Hall resistance standard is based on another quantum effect that emerges in conductors in a magnetic field: If the magnetic field is applied perpendicular to the travelling direction of the electrons, the so-called Hall resistance is induced, which depends on the strength of the magnetic field. At low temperatures, steps emerge in the resistance-magnetic-flux diagram, which are again based on the Planck constant and the elementary charge.

With these two standards, the unit for the electrical current (ampere) can be realised directly via Ohm's law. However, developing a quantum electrical standard for the realisation of the ampere could bring further advantage. Obviously, this could pose a path for achieving higher precisions for the realisation of ampere, especially at low orders of magnitude. And furthermore, the combination of three quantum electrical standards will enable fundamental research on the quantum metrology electrical triangle (see Figure 2). Since all three units are based on the two same fundamental physical constants, an experimental verification of the underlying foundations of the SI unit system could be pursued. And finally, this realisation could have positive impacts on the measurement precision of the volt and the ohm as well.

Figure 2 The Quantum Metrological Triangle or the Quantum Electrical Triangle



Source: Fraunhofer ISI

In the following sections, we highlight the impacts from advancements of QEM. The first is the improvement of the Quantum Hall Effect and the realisation of the ohm, while the following two sections outline how QEM impacts other metrology disciplines, using examples of optical measurements and the measurement of ionising radiation.

3.2.2.1 Quantum metrology breakthrough: Using graphene's potential for resistance standard

Fundamental importance

Realising quantum primary standards for resistance based on the Quantum Hall Effect (QHE) had boosted the accuracy level of measurements considerably. However, the practical use of the QHE remained restricted mostly to high-level NMIs, due to demanding QHE operation environment requiring very low temperatures and high magnetic fields. For these reasons, no providers of calibration services or end users, and often not even national metrology institutes (NMIs), could take direct advantage from the QHE based standards.

The possibility of implementing the QHE and the resistance standard based on graphene was opened after discovery of graphene in 2004. NPL demonstrated for the first time the use of epitaxial graphene as the resistance standard. The first graphene-based standard of resistance was demonstrated at NPL (published 2015). In this case, the quantum resistance on graphene could be realised at a significantly lower magnetic field (5T) and higher temperatures (~ 4K) than existing resistance standards.

Its breakthrough character lies in the fact that it **considerably simplifies the realisation of the QHE** having the potential to disseminate it and be used by a wider group of users. This will help shorten the calibration chain and **improve the measurement accuracy bringing it closer to users**. This is going to considerably advance the ability to utilise the quantum based representation of resistance and impedance measurement units.

The reason for its fundamental importance lies also in the revised International System of Units, SI that came into effect in 2019. With the new definitions, the graphene-based QHE devices can be used not only to disseminate the electrical units, but also other standards that rely on electrical measurements, such as the unit of mass, the kilogram. The importance of the QHE for the mass unit (kg) is based on the fact that the redefinition of the kilogram is based on the Planck constant h in the revised SI. Through tying to the Planck constant, the new definition of the kilogram has no systematic drift and is inherently stable. The connection to h, as realised in a so-called Kibble-balance requires the use of the Josephson and Quantum Hall Effects. Therefore, the simplification and better availability of the **graphene-based resistance standard will have also huge impact on the primary mass standards** (Ahlers 2016). From highly accurate mass measurements with even higher resolution based on fundamental constants can benefit application fields, such as forensics, pharmaceuticals and experimental physics, just to name a few. And since mass is an integral for the definition of other quantities, such as force, energy and power, a higher-resolution kilogram will have an impact on a whole range of measurements beyond just mass.[7]

3.2.2.1.1 Economic impact

Electrical resistance is an important measurement parameter in an advanced economy. The availability and wide distribution of the graphene based resistance technology and the fundamental constant based QHE reference entails therefore significant economic impacts. The high economic relevance of electrical resistance results not least because of the essential role it plays for electronics, as the development and manufacturing of any kind of electronics requires accurate measurements of the resistance of electronics components. Strategic position of electronics in the modern economy makes resistance measurements even more important (see the section on Semiconductors: Semiconductor Industry).

First, the availability of **QHE based on graphene considerably facilitates calibration services of resistance** by shortening the calibration chains, improving their productivity (e.g. through increasing the throughputs and considerably shortening the turnarounds time) and making them more efficient and cost effective. **Significant benefits will arise** not only for calibration laboratories and their customers within national economies, but also **for NMIs through reducing cost** compared to the traditional approach for the operation of primary resistance standard (see Box 1). Furthermore, it enables NMIs in other countries, which until now have not been able to afford to operate the complex quantum resistance standard. It also opens up quite new opportunities for the industrial and science players in these countries, which go far beyond the provision of QHE based calibration services. New technological areas highly dependent on accurate measurements of resistance, such as advanced semiconductors, could be better exploited by businesses and R&D players offering new and high value development opportunities.

Box 1

Economic benefits from graphene-based QHE compared to the traditional approach

Since 1990 the Quantum Hall Effect (QHE) has been used as the primary reference for the electrical resistance. Before the introduction of graphene-based (table top) systems, the realisation of the QHE was quite expensive. High cost are linked to the demanding experimental setup needed, which requires low temperatures, high magnetic fields and a specialised equipment and materials to run the experiment. This involves liquid helium – a limited natural resource, the price of which has continuously increased in recent years. Presently (as of 2023), helium prices range between $30-$50 per liter or more. Up to hundred liters can be necessary to run the experiment. To maintain the ultra low temperature cryostats, special refrigerators and other equipment is needed. For strong magnetic fields, powerful superconducting magnets are necessary, for which costs are substantial. The experiment takes long times (few days and even weeks in case problems occur and need to be fixed) and require a large number of skilled personnel to control and operate the processes. The further limiting factor are safety concerns. The total cost of experiments involving QHE with liquid helium can reach the level of up to $ 10,000 and higher, resulting in annual cost that can amount to several hundred thousand US$ and more. Therefore, the Quantum Hall Resistance standards were mostly out of reach for

[7] https://www.nist.gov/si-redefinition/kilogram/kilogram-disseminating-new-kilogram

smaller NMIs, calibration laboratories and companies. The consequence of the limited access to the primary resistance standard was a loss of accuracy at each step of the calibration chain culminating in various negative economic effects and other disadvantages. High economic costs are also associated with considerable loss of time and money due to the need to send the equipment to remote NMIs for regular recalibration of secondary standards, which can be avoided now due to the availability of innovative primary resistance technology. Thus, the new quantum resistance standard systems eliminates these high costs and efforts. Moreover, it enables further considerable savings and other benefits due to the operation of primary standards much closer to the actual users, making the processes more efficient and saving the players involved a lot of money and time. Further simplification of resistance primary standard are expected to bring further benefits to end users.

Second, **instrument providers can exploit the new technological opportunities through providing new instrumentation and tools**. UK based Oxford Instruments[8] created in close collaboration with NPL and launched in 2018 the first commercial graphene-based primary standard of resistance (QHR), based on a mechanical refrigerator. The long-term collaboration of NPL, Chalmers and Graphensic[9] has resulted in commercially viable Quantum Hall Effect devices offered by Graphensic for use as primary standards for research purposes.[10] The Canadian company Measurement International (MI)[11], the world-leading manufacturer of instrumentation and systems for resistance metrology, has recently introduced a graphene based Quantum Hall System.

Third, the simplification and better usability allow a **more widespread use of the primary resistance standard leading to the reduction of uncertainty down the calibration chain**. Hence, a broader user base can take advantage from the highly accurate and traceable to primary resistance standard. The broader availability of a better and simpler resistance standard supports the development of materials and technologies with improved stability and accuracy across various technological and application fields, where resistive properties of materials are important. Further, resistance is strongly dependent on material properties and temperature which is exploited in resistive sensors, temperature sensors, capacitive sensors, to name just a few (Ahlers 2016). The following boxes provide summaries of economic impact of graphene-based resistance standard on resistance based thermometry (Box 2) and on impedance (Box 3).

Box 2

Economic relevance of resistance based thermometry

Resistance thermometers are widely used across industries. In Europe, more than 60 % of processes used by the manufacturing industry depend on accurate measurements of temperature and thermal properties of the materials (Filtz 2015). Determination of these properties is most commonly done by the resistance thermometers. Resistance thermometers are widely used across industries, such as food and beverage, consumer electronics, automotive, chemicals, aerospace & defense, healthcare, and others. Moreover, resistance thermometers can help mitigate the environmental impact of a large share of industrial processes, as measurement of temperature is in many instances necessary to minimise releases of harmful emissions.[12] Resistance thermometer sensors (RTD sensors) enable highly accurate and stable temperature measurement, which makes them indispensable in various industrial operations, HVAC systems, and scientific research. The need

[8] https://www.oxinst.com/

[9] https://graphensic.com/

[10] https://graphensic.com/quantum-metrology-breakthrough-using-graphene/

[11] https://mintl.com/

[12] https://www.euramet.org/research-innovation/search-research-projects/details?tx_eurametctcp_project%5Bproject%5D=1346&cHash=3a1b60e35db403d520d1ae85a8391439

to optimise processes, maintain quality, and ensure safety drives the demand for the precise, reliable and repeatable temperature sensor solutions. This ongoing trend puts the global resistance thermometer sensors market for significant growth. It is expected to a CAGR of 10.5% from 2023 to 2030, reaching a market size of USD 1.2 billion.[13]

The measurement principle of resistance thermometers is fairly simple: The key process is the temperature induced change of resistance in a well-known material (such as platinum), which is measured by applying a fixed current through the material and measuring the emerging voltage. The driving force of technology development of resistance thermometry is the search for new materials with resistances that exhibit a strong temperature dependency at specific and preferably wide temperature ranges. This material dependence results in a varying temperature accuracy that can be achieved over the whole temperature range. Furthermore, measuring at a large temperature range could require the combination of different materials to cover the required temperatures – this could lead to discontinuities in the measurements. The calibration of thermal sensors require temperature standards, which are not available at all temperatures. Furthermore, maintaining measurement accuracy requires industrial thermal sensors to be calibrated against primary resistance standards. The availability of less complex and cost efficient graphene-based resistance standards can help overcome shortfalls in the provision of calibration services and allowing more industrial users benefit from accurate measurements leading to higher production quality.

Box 3

Impedance: Economic and environmental importance

Furthermore, the use of the QHE at AC frequencies provides the key foundations for the wider use of QHE devices also as a standard of impedance (Ahlers 2016). Graphene based QHE impedance enables an economically efficient traceability of impedance to the defined constants of the revised SI. Electrical impedance is a quantity of high practical importance. Especially modern electronics applied in different application fields, as well as many medical and scientific measurements rely on impedance.

Apart from the economic impact, the proliferation of the QHE for the use as a standard of impedance is going to have a strong long-term environmental impact. Many environmental measurement techniques are based on capacitance. Improving the traceability to capacitance helps improve the sensitivity and reproducibility of such measurement techniques, enabling higher data quality which in turn leads to further benefits: more efficient engines, a reduction in exhaust gases, the measurement of polluting particulates, and to an improvement in electrical impedance spectroscopy for geophysics, just to name only some (Pierz 2021).

3.2.2.2 Avalanche Photodiodes: contribution of electrical metrology

Optical metrology has a large variety of application fields, due to the versatility of optical sensors and optical sources. Quite commonly light detectors are used in spectroscopic technologies in which a predefined light is altered by the object of interest and the difference of outgoing and incoming light is analysed. One major challenge to enable the development of new technologies and to open up new application fields is the detection of faint (optical) signals or – in its ultimate form – the detection of single photons. Therefore, accurate, quick and sensitive photon detectors are being developed. One approach are avalanche photodiodes (APDs). In APDs the central internal process is the amplification of an incoming photon: the incoming photon triggers the emission of two or more photons, which subsequently trigger further photon emissions, hence the name "avalanche", which can be translated into an electrical signal, which can again be amplified and measured. APDs are used for their high responsivity (enabling the detection of faint signals), low noise

[13] https://www.digitaljournal.com/pr/news/newsmantraa/resistance-thermometer-sensors-market-is-expected-to-witness-incredible-growth-forecast-2030-senmatic-unipi-jsp

(low number of false counts) and a short dead time (enabling the photon detection at high rates) in a wide range of commercial, military and research applications (Campbell 2007). Their quantum efficiency is moderate compared to other single photon detectors (e. g. PIN detectors and in many cases not well-defined, i.e. the ratio of incoming photons that trigger a signal at the counter. APDs are being calibrated by measuring an accurately defined incoming signal. However, generating this signal is not a straight-forward process. The common approach is the (well-known) attenuation of a laser beam with a well-known intensity. The accuracy of this process is limited by the attenuation of the beam, which is usually achieved by the combination of different attenuators, which could give rise to interferences or other effects, which could alter the intensity of the light beam. To account for such effects during the calibration of an APD, the combination with an additional approach is helpful – this is where QEM comes into play.

By using an electrical primary standard for calibrating the output current (in the order of 100 fA) the quantum efficiency can be determined with a significantly higher accuracy. This results finally in a better knowledge of the sensitivity of the APD. This order of magnitude can be achieved by good primary standards already today. However, applying this calibration to a large number of APDs still requires significant effort and cost.

Economic impact

Deducing the technological and potential economic impact of this technique is again not straight forward. APDs are used in a wide range of applications: thermal imaging cameras resolving spatial variations across the target, which can indicate problems within the manufacturing process (Hobbs et al. 2018), can benefit from APDs especially at low target temperatures; single-photon APDs can be used for fluorescence lifetime imaging, which is used for drug discovery or minimally-invasive optical biopsy, due to their low dead-times (Palubiak et al. 2011), the detection of low visible near infrared light is required in high energy physics caliometry, which could benefit not only from the APDs high responsivity, but also from their insensitivity to magnetic fields (Anzivino et al. 1999; Renker 2002; Karar et al. 1999). This immunity to magnetic fields comes in handy for various medical imaging applications, such as positron-emission tomography (Renker 2002) and X-ray imaging (Moszyński et al. 2000) and are especially well suited for morpho-functional imaging (PET/CT, SPECT/MRI) (Britvitch et al. 2007); another medical application of APDs is laser velocimetry, allowing for a non-contact measurement to determine the velocity of fluids, such as blood flow in human tissues (Cova et al. 1996). Some light-scattering-based techniques for measuring the distribution and concentration of molecules in a solution rely on APDs (e.g. the investigation of interactions of proteins in solutions (Yadav et al. 2011); further applications of APDs rely on the direct detection of faint light, such as the remote sensing of toxic chemical agents, vegetation and geological monitoring (Krishna et al. 2005) or short-wave infrared detection systems demanded for surveillance, reconnaissance and remote sensing applications (night vision) (Rutz et al. 2019), as well as other low power detection applications (e. g. in military applications or in space (Singh et al. 2011). Various communication application depend on faint light detection as potentially provided by APDs: they are not only used as optical receivers in fiber optic based telecommunication, but also in potential quantum communication technologies which require accurate and rapid measurements of single photons; APDs can support laser communication with satellites by supporting their laser tracking system (Toyoda 2002). Another wide application field is the use of APDs for light detection and ranging sensors (LiDAR / LADAR), also known as reflextometry – LiDAR sensors are a crucial for emerging technologies, such as advanced driver assistance systems, autonomous vehicles and robotics (Zhao et al. 2019). This list gives an overview about the different nature of (potential) APD-based applications. The further development of sensitive and achievable APDs impacts a range of technology fields.

The example of APDs perfectly illustrates the challenge of estimating the technological impact of advances in QEM. As pointed out, electrical metrology could directly impact the calibration of the APDs sensitivity. However, it is hard to assess the need for the accurate knowledge of an APDs quantum efficiency and responsivity. In quantum communication, for example, the knowledge of how many photons were not detected has no direct value in the communication, as only the detected photons are used in the further process. So in this case, no obvious direct benefit can be seen from improving the calibration of an APDs sensitivity, since the comparison of APDs is still equally possible with a not-optimal defined laser beam. Nevertheless, it should not be underestimated, how the improved knowledge of the APDs parameter can drive the further development and improvement of APDs, which again would benefit all applications.

The example of the technological impact of QEM on APDs is a perfect example for indicating the total impact that QEM has on technology development. Only in rare cases a "direct technological impact path" becomes visible for QEM. In most cases, the technology developers have more urgent challenges to face than those that can be addressed by improvements in QEM. However, even though in most cases no additional requirements considering the calibration of electrical instruments are formulated in technology developments, indirect technological paths can still play a significant role.

The previous discussion illustrates the technological impact path that advancements in QEM can have on other metrological disciplines. As developments of photodetectors impact a wide range of applications that are based on photonics, which is considered as one of the key enabling technologies of large economic and societal relevance.[14] Its global market was valued at ca. £650 billion in 2022.[15] Photonics deliver solutions to address some key societal challenges. Photonics industry is one of the most productive manufacturing sector in UK and motor for innovation and growth contributing £15.2bn to the economy per year and employing 80,000 people. UK's photonics industry is the second largest in Europe after Germany and the ninth largest globally (Innovate UK 2023).

3.2.2.3 Current-based measurement of ionising radiation

Measuring radioactive or other (electromagnetic or particle) radiation with energies large enough to ionize atoms or molecules is required to provide and control safety standards for certain technologies (e. g. nuclear power plants) or enabling (new) technologies, especially for medical applications (e. g. radio therapy or diagnostics). (See Case Study on Ionising Radiation for Treating Cancer).

Technological improvements of dosimeters for the measurements required in nuclear power plants show no significant demand. Safety regulations and certifications for nuclear power plants are well defined and the dosimeters to control and ensure these specifications are commercially available. Similar, the dosimeters to ensure the safety of patients and medical staff do not seem to be developed towards higher accuracies currently. Both fields show a rather slow innovation speed, even though they have strict regulations and requirements for certifications. The more innovative technology fields (besides research) are diagnostics and treatment based on ionizing radiation and potential applications of detectors in space. The measurement principle is usually based on an electronic detection of the ionized particles: in the commonly used ionization chamber based dosimeters, for example, an electrical field is induced across a gas-filled volume by an applied voltage. When the radiation enters the volume, charge carriers are released (ionization of gas) and acceler-

[14] https://digital-strategy.ec.europa.eu/en/policies/photonics

[15] https://www.precedenceresearch.com/photonics-market

ated towards the electrodes, where they are measured by inducing an electrical current. The absolute and relative precision of the electrical measurement instruments are crucial for a high precision measurements of the radiation dose. However, only in rare cases (e. g. research at the LHC CERN) the highest precision of the dose measurement is required. Usually the distorting side effects that influence the measurement are large, which puts the need for measurement uncertainties in the order of 1 % into perspective. The precision of the electrical measurement equipment is, therefore, not of the highest relevance, since it is only one of the three main steps in the measurement principle: generation of the charge carrier in chamber, transport of charge carrier over cable (especially relevant since a close-to-signal measurement is not possible in radiation environments to prevent measurement distortions or damages to the measurement equipment), measurement of charge carrier in electrometer. The precision is mainly limited by the step with the lowest accuracy. Nevertheless, advances in quantum electrical metrology could have a significant impact on the discussed technology fields. **Reducing the calibration cost or the calibration time of electrical measurement equipment brings obvious economic benefits**.

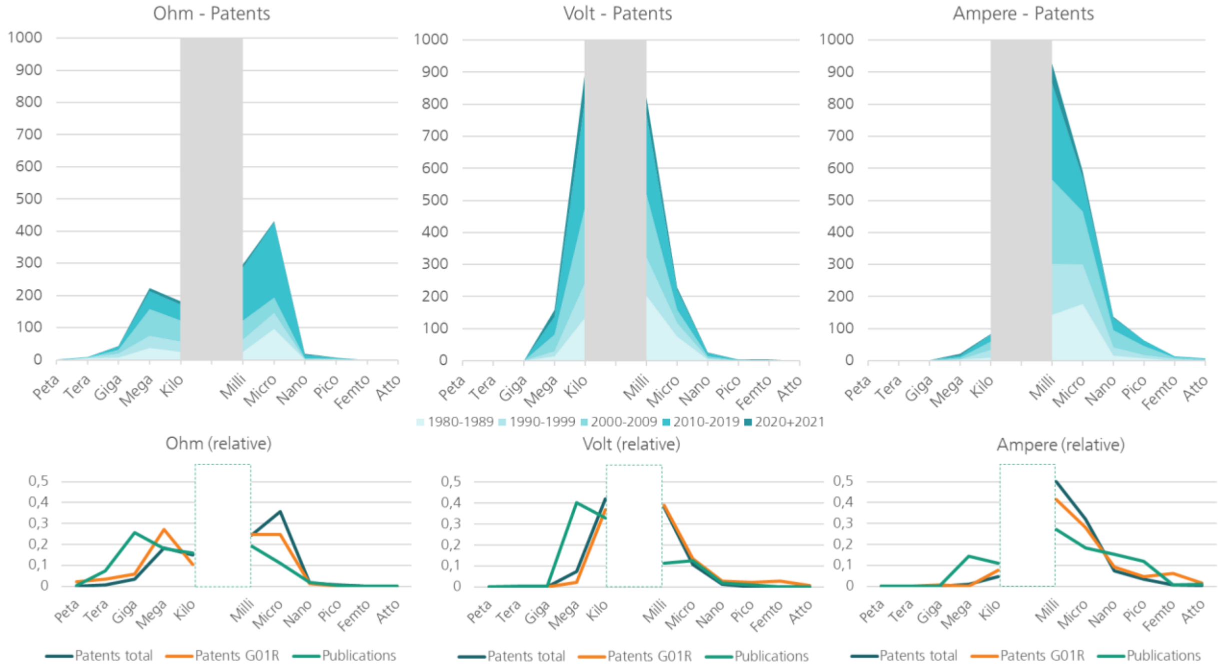
Improved dosimetry will also facilitate the study of effects from low levels of radiation exposure (Bordy 2022) and has an impact on environmental radioactive monitoring (soil, water, and atmosphere). They rely on precise measurement and reference systems. The measurement of ionizing radiation from space on satellites could provide information on radiation induced component failures. Even though measurement of ionizing radiation is performed by some satellites, mostly to investigate scientific questions, it is not part of the common equipment. If this will change in the near future remains unclear. The adoption of quantum electrical primary standards in space is a potential future technology that could provide calibration services to on-board instruments (e. g. to measure ionizing radiation).

3.2.3 Patent and publication statistics

Resolving the potential impact of advances in electrical metrology on science and technology, a patent and publication analysis was performed with various search strategies. For the publication analysis "Web of Science" was used. Counting the number of publications that contain different keywords in the abstract, indicate the development of the potential relevance of the respective topic in scientific disciplines over time. The Derwent Worlds Patents Index (WPI) database, hosted by the Scientific & Technical Information Network was used for the patent analysis. The search was restricted to transnational patents in the European Patent Office (EPO) or the World Intellectual Property Organization (WIPO) to account only for the most relevant patents. Furthermore, this allows for a fair comparison of country statistics, due to the different requirements in national patent offices.

The quantitative analysis of relevant patents and publications is based on the combination of a number of approaches. By analysing the different terms (milli-, micro-, nano-, …) for the main electrical units (volts, ohm, ampere) the relevant orders of magnitude for research and the development of new technologies could be resolved. By analysing the patent class **G01, in which all patents for measurement technologies are grouped**, further insights about the relevant metrological topics can be gained. The analysis of the **subclass G01R gives information about patents that belong to the measurement electrical variables**. By extracting patents with applicants from the UK, a comparison of national and global trends can be performed. To resolve potential impact paths of developments in (quantum) electrical metrology on technological applications, the further subclasses of the G01R patents were analysed. While the combination of these approaches give a multifaceted insight on the research questions of this study, it should be kept in mind that each of the presented approaches has its limitations and should, therefore, be taken with a grain of salt.

Figure 2 Number of transnational patents that mention electrical units in different orders of magnitude (top). Share of orders of magnitude for transnational patents and publications mentioning the order of magnitude in the abstract (bottom)



Note: Data base as specified in the text. The analysis was performed for patents from the subclass G01R.

Source: Fraunhofer ISI

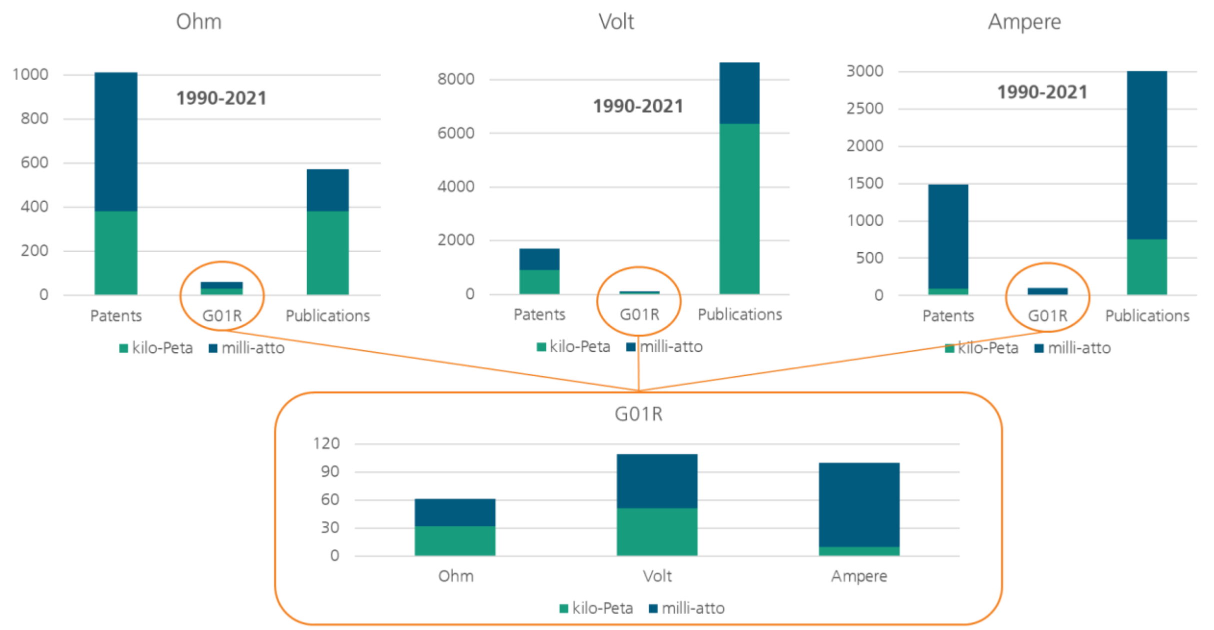
For resolving the most relevant prefixes for science and technology development, a quantitative analysis of patents was performed. Each combination of prefix and electrical unit was investigated, by counting the number of transnational patents that contains the key word(s) (e.g. picovolt, pico volt, pico-volt, picovolts, …) for every year since 1980. The prefix-free keyword (e.g. volt, volts, …) could not be included for the sake of comparability.[16] This quantitative analysis can obviously not resolve the nature of the use of the respective order of magnitude (e.g. is a measurement at this order of magnitude enabled by the patent?). The results are presented in the top row of Figure XY.

For electrical voltage, most patents were registered with the prefix kilo- and milli-, steeply decreasing for higher and lower order of magnitudes, respectively. For resistance, the picture is more diverse with a peak at micro-ohm (for below ohm units) and Mega-ohm (for above ohm units). This shape was stable over the past decades. Not surprisingly, the results are shifted to lower order of magnitudes for electrical current (ampere). Patents containing milli- and micro-ampere are dominating. The very low orders of magnitude (pico-, femto-, atto-) are considerably more pronounced than for volt and ohm. In the bottom row of Figure Figure 2, a comparison of the relative number of patents (total and G01R) and publications is shown. The patents of the subclass G01R demonstrate in general a similar distribution over the order of magnitudes as the complete number of transnational patents. The only considerable deviations are at Mega- and micro-ohm (even more pronounced peak at Mega- in G01R, while the micro-ohm are at the same level as milli-ohm), as well as at femto-ampere (peak in G01R), indicating a potential focus of measurement related technologies at this order of magnitude. Quite naturally, publications are expected to show stronger

[16] Note that only patents were counted that use the word written out. While this might neglect a large number of patents (using for example pV) – potentially in a non-systematic way – it proved to be the best way to prevent false hits.

deviations, for example due to the potential discussion of physical effects at these order of magnitude, which are not connected to their realisation within electrical technologies. These deviations are realized by the (relatively) large number of publications at Giga-ohm, Mega-volt and Mega-ampere, as well as pico-ampere. Whether these "hot-topics" could lead to an intensified development of technologies covering these order of magnitudes cannot be concluded straight-forwardly.

Figure XY-2: Number of transnational patents (total and in subclass G01R) and publications mentioning electrical units in the denoted orders of magnitude (top). Comparison of class G01R (bottom) for better visibility

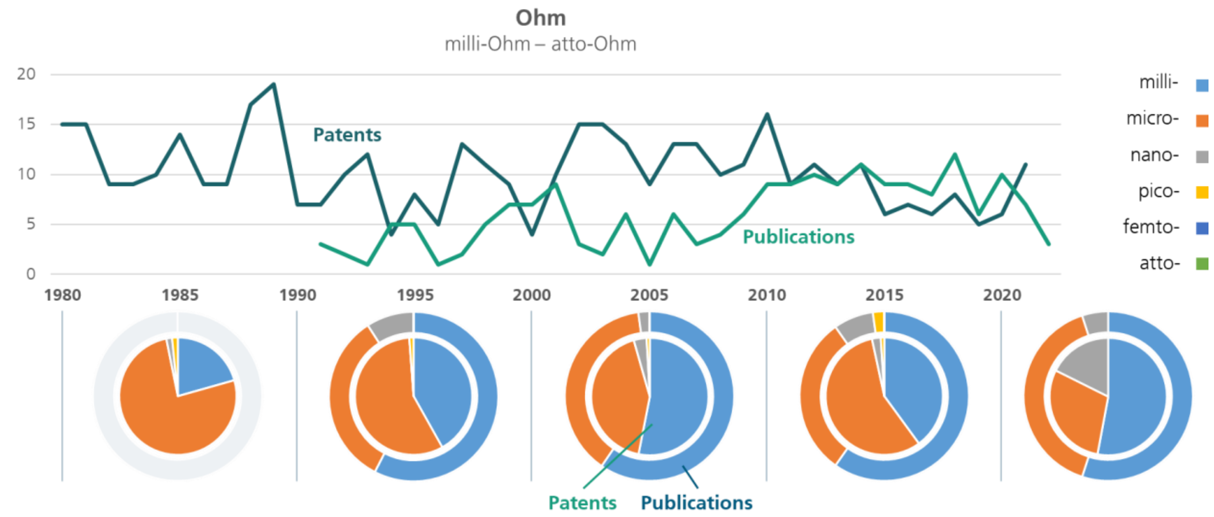


Note: Data base as specified in the text.

Source: Fraunhofer ISI

The absolute number of patents (total and in the subclass G01R) and publications is shown in Figure XY-2. Note the different scales at the y-axis (number of patents/publications). The colour code indicates the share of patents/publications at the above (kilo-, ...) and below (milli-, ...) 1 prefixes. While for volt and ampere the number of publications is significantly larger than the number of transnational patents, it is the other way for ohm. As seen above, the number of "milli- and below" patents and publications are dominating for ampere (at G01R only at a few percent). For volt, the publications are dominated from "kilo- and above", while the total patents are rather balanced. For G01R, again, the number of "milli- and below" patents are larger. For ohm, a large number of "kilo- and above" patents were observed.

Figure 3 Number of yearly patents and publications that mention sub-Ohm electrical units (top). Comparison of share of prefixes for patents (inner circle) and publications (outer circle) for the respective decades (bottom)

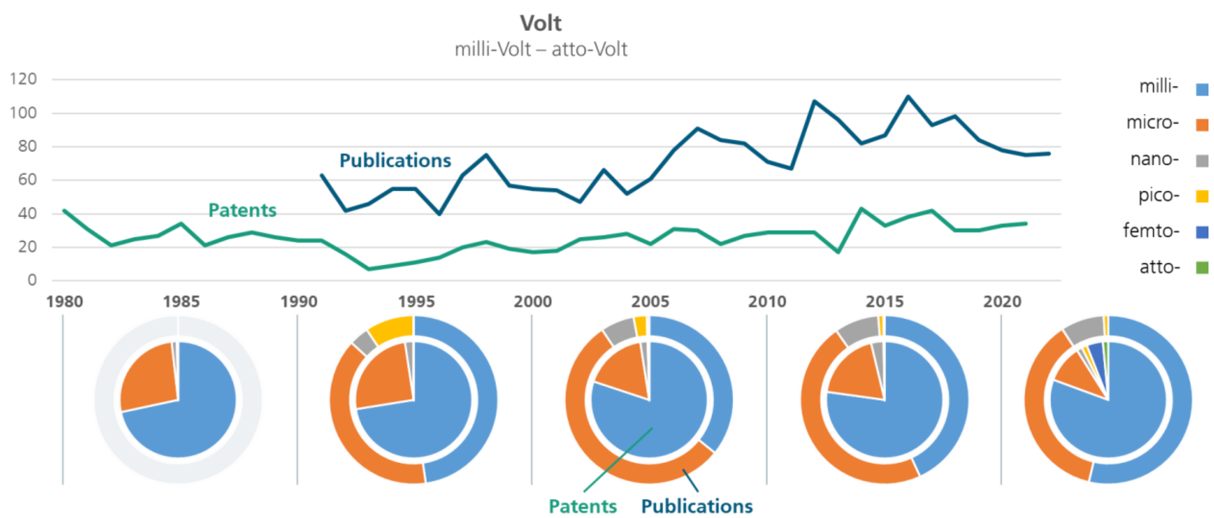


Note: Data base as specified in the text.

Source: Fraunhofer ISI

Since for this study, the lower orders of magnitude are of specific interest, an additional analysis of the temporal development of the sub-ohm, -volt, and -ampere patents and publications was performed. As presented in Figure 3, no significant trend of the absolute number of patents and publications can be observed for ohm. In the past decade the share of publications containing "milli- and below" ohm was larger than the respective share of transnational patents containing these keywords. Before the 2000s and during 2010-2020, patents containing micro-ohm were dominating. In the last two available years (2020+2021) an increasing role of nano-ohm can be observed, which was already visible in earlier publications – as presented in the bottom row (relative number of patents / publications).

Figure 4 Number of yearly patents and publications that mention sub-Volt electrical units (top). Comparison of share of prefixes for patents (inner circle) and publications (outer circle) for the respective decades (bottom)

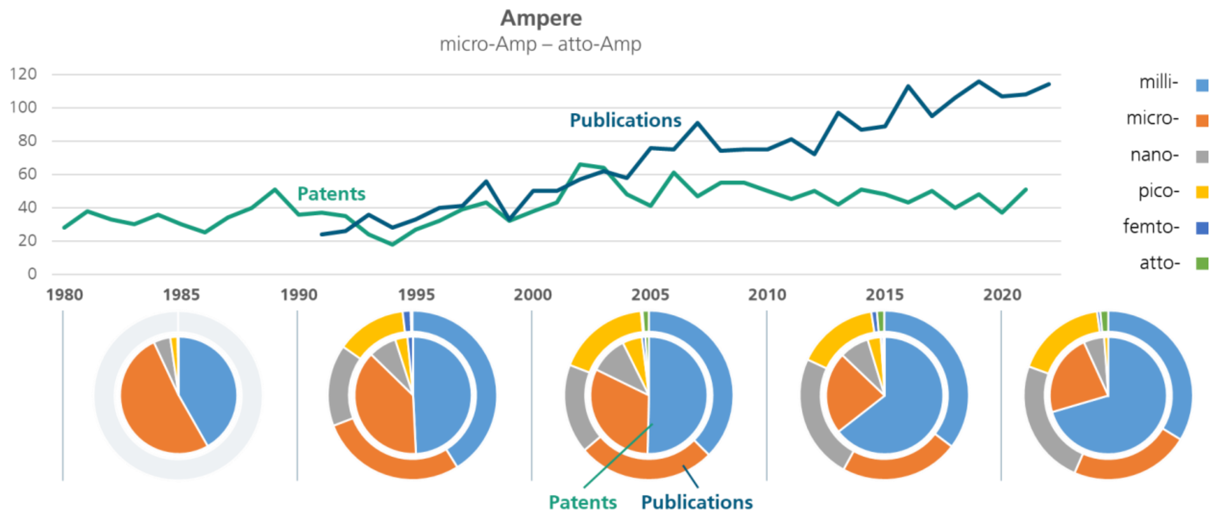


Note: Data base as specified in the text.

Source: Fraunhofer ISI

A clear increase of the number of patents and publication with sub-volt keywords can be observed since 1990, both having an equal rate of increase (roughly doubling since 1990) (Figure 4). While this is dominated by the prefix milli- for patents, micro-volts play an equal role in publications. Pico- and nano-volt play a pronounced role in publications as well. While no significant number of sub-nano patents were observed before 2020, in recent years, a significiant number of patents contained femto-volts.

Figure 5 Number of yearly patents and publications that mention sub-Ampere electrical units (top). Comparison of share of prefixes for patents (inner circle) and publications (outer circle) for the respective decades (bottom)

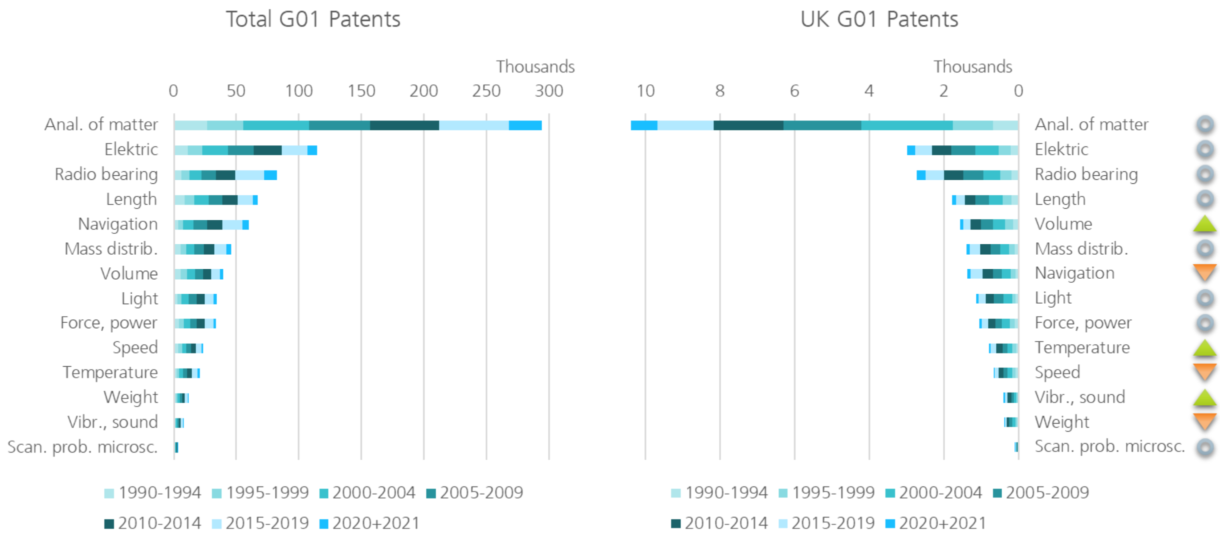


Note: Data base as specified in the text.

Source: Fraunhofer ISI

The analysis shows a different result for ampere, whereas a strong linear increase is visible in the number of sub-amp publications (five-fold increase since 1990) which cannot be observed for patents (Figure 5). This increase is clearly present in milli-, micro-, nano- and pico-ampere, with a slightly increasing relevance of below-micro ampere orders of magnitude. However, this increasing relevance is not visible for patents. Instead the relative number of milli-amp patents was increasing in the past decade. If the increase in publications can trigger further patents in the future, as often seen with a delay of about 15 years, has to be seen (Schmoch 2007).

Figure 6 Number of transnational patents in the G01 class (total – right, with applicants from the UK – left) over time. The symbols on the right indicate which subclasses rank higher or lower for the UK statistics compared to the global statistics

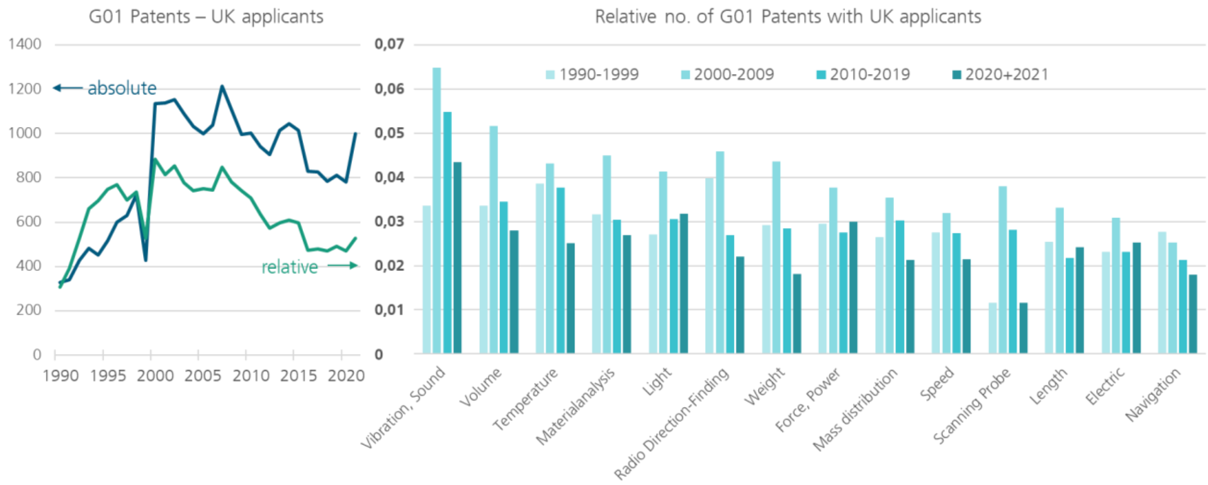


Note: Data base as specified in the text.

Source: Fraunhofer ISI

In the following, we will have a closer look into the patent class G01, which groups different subclasses that address "measuring and testing". By analyzing the number of patents in these subclasses, a first straight-forward insight of the relevance of the different measurement-related technology fields can be deduced. The by far largest subclass contains patents for the analysis of materials. Considering the wide range of topics covered by this title, this seems to be not surprising. Based on the number of patents since 1980, the measurement of electric variables ranks second. However, the subclass radio direction-finding is growing with an equal speed in recent years. With more than 100,000 patents, the subclass G01R consists more patents than the subclasses for measuring light, temperature and weight combined. On the right side of Figure 6, the patents with applicants from the UK are shown (about 3,000 patents in G01R). The ranking of subclasses is similar to the global ranking (analysis of matter on the first, electric measurements on the second rank). To get more detailed insights in the strengths and weaknesses of the UK patent applications a further analysis of the share of transnational patents with UK-applicants was performed (Figure 7).

Figure 7 Number of transnational patents of patent class G01 with UK applicants. On the left: the total number of these patents is compared with the share of these patents (UK / global). On the right: share of patents with UK applicants on the total number of transnational patents for G01

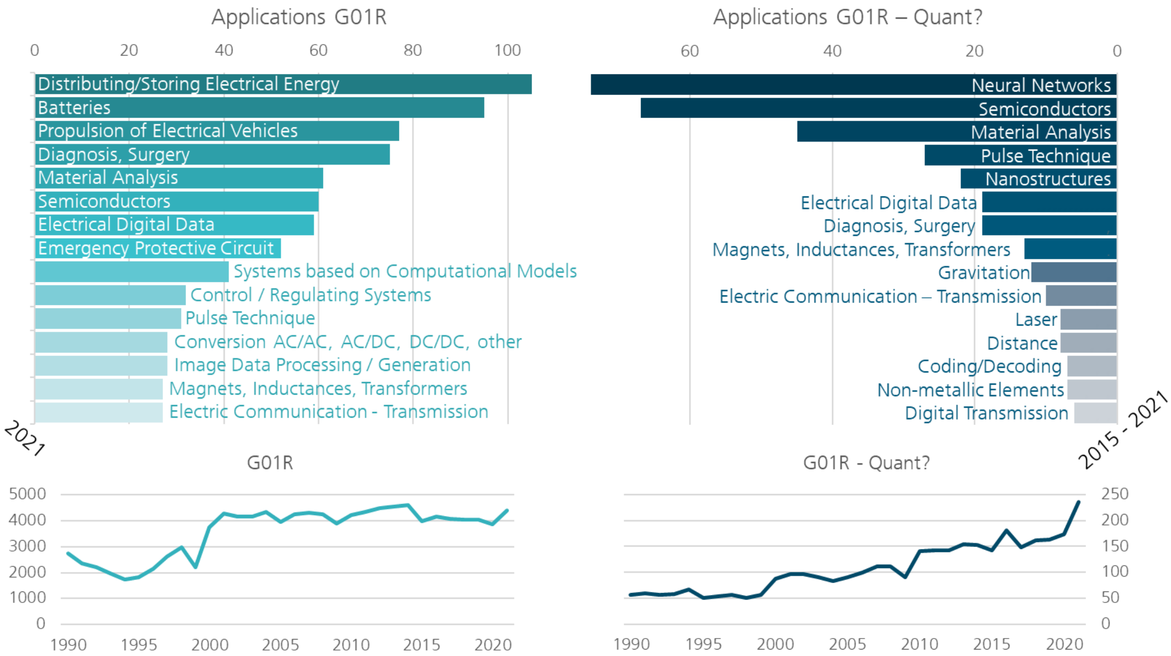


Note: Data base as specified in the text.

Source: Fraunhofer ISI

The absolute number of transnational patents with UK-applicants in the patent class G01 was (non-monotonously) decreasing since the 2000s, leading to a significant decrease of the share in this patent class, which can be connected to the increasing patent activities in other world regions. This decrease is visible throughout all the G01 subclasses, but with varying degrees of significance. The subclasses on the right side in Figure 6 are ordered by the share of patents with UK-applicants compared to the total number of patents in these subclasses since 1990. The measurement of electric variables (G01R) is after G01C (navigation) the subclass with the smallest share of patents with UK-applicants (even though it is the second largest subclass of UK-applicants when accounting the total number of patents!).

Figure 8 Patent subclasses of transnational patents that are also registered in the G01R subclass. Left: Total in 2021, right: patents that contain "quant" from 2015-2021. Bottom: total number of these patents over time



Note: Data base as specified in the text.

Source: Fraunhofer ISI

Finally, the applications of the subclass G01R will be discussed, as presented in Figure XY-8. By analyzing the subclasses that patents in G01R share in most cases, an indication of relevant fields of application for electrical measurements can be gained. Unsurprisingly, considering the transformations of the energy systems and the mobility worldwide, the distribution and storage of electrical energy, batteries, and the propulsion of electrical vehicles ranked the highest in 2021. More interestingly might be the relevance of medical diagnosis and surgery patents. In order to get a glimpse into the relevant fields for QEM a simple variation of the search strategy was performed, which included keywords that start with "quant". The first take-away of this approach is a sharp increase of patents in G01R that contain these keywords (fourfold since the late 1990s). In 2021, more than 5% of the patents in G01R contained keywords that start with "quant". The most relevant shared subclasses in the past six years are neural networks, semiconductors and material analysis. The results are shown in Figure XY-8 on the right side.

Conclusions

The patent and publication analysis reveals a **significant relevance of small orders of magnitudes of the three main electrical units**. Smaller orders of magnitude could be tapped in recent years. However, this cannot be equated with a shift to smaller orders of magnitude, but rather an **increasing activity in all sub-volt and sub-ampere regimes** (not visible for sub-ohm). Patent activities in these regimes could be driven by the large number of publications (volt and ampere). The measurement of electric variables is one of the most relevant subclasses of the patent class G01 (measuring, testing). Even though is also true for patents with UK-applicants, the share of patents registered by actors from the UK is one of the smallest in the subclass G01R. **Globally, the relevance of quantum related technologies seems to become rapidly more relevant for the measurement of electrical units** (either as application or element of the technology, as in QEM).

4 Role of Electric Metrology for Economy and Society

The impact of metrology on the modern economy of UK is significant, as technology driven economy largely depends on measurement infrastructure. With the GDP of £2,491 billion in 2022[17] and a population of more than 67 million, the United Kingdom is the sixth largest economy in the world after the US, China, Japan, Germany and India. The technology sectors are the main drivers of the British economy and technological innovation. Their contribution to the UK's economy grew by 26.5% between 2010 and 2019. Over 3 million people work in UK tech companies. The UK tech industry reached £0.8 trillion in the market value in 2022, making it the third country after the US and China.[18] The digital sector alone added £138 billion in 2021 (7% of the total Gross Value Added).[19]

The Great Britain's goal is to position itself and maintain its role as a technology leader in the global economy. This shall be achieved through securing strategic advantage in science and technology and focusing on critical technologies set out in the UK's Science and Technology Framework (S&T) (Department for Science, Innovation & Technology 2023a). Priority technologies that drive the British economy and innovation are quantum technologies, semiconductors, engineering biology, AI and future telecommunication technologies.

4.1 Direct economic impact of the Quantum Electrical Metrology

The NPL maintains and develops national standards and delivers quality services at a national level and provides direct impact to customers/partners with whom it closely collaborates. A large direct economic impact is expected from calibration, measurement and consultancy services it provides to third parties and the overall knowledge and technology transfer that take place through different channels.

The following section outlines the market development supported by QEM. Specifically, the trends of electrical calibration and electrical instruments & tools as well as impacts of innovative QEM on these segments will be discussed. In addition, section 5.1.4 provides an overview of the relevance of QEM on various end users, zooming in on the semiconductor and Quantum Computing technology. This chapter also summarises the results of the survey conducted by the project team.

4.1.1 Electrical calibration market

One important route through which advancements in measurement science, standards and technology are transferred to the public and private players is calibration testing. Industrial and other users across different sectors must regularly calibrate and recalibrate their equipment to ensure error-free operation of their facilities. Calibration testing conducted at NMIs is a measurement science-based activity that has the potential to affect the productivity of the country (Link 2021). This happens not only as a result of primary measurement-based calibration services performed at the NMIs. Firms do not only calibrate their measurement standards at NMIs, they internally use these standards many times within their R&D, manufacturing and quality assurance activities. Thus,

[17] https://commonslibrary.parliament.uk/research-briefings/sn02783/

[18] https://www.gov.uk/government/news/uk-tech-sector-retains-1-spot-in-europe-and-3-in-world-as-sector-resilience-brings-continued-growth

[19] https://www.gov.uk/government/statistics/dcms-sectors-economic-estimates-monthly-gva-to-june-2022/using-annual-estimates-from-summed-monthly-gva-data

through calibration services and the measurement science behind them, NMIs generate a much greater economic impact though multiple applications of standards across the economy. According to a recent study performed by Link 2021, a 10% increase in calibration tests at the National Institutes of Standards and Technology (NIST) is associated with an increase in the U.S. multifactor productivity index[20] of 0.32%-0.38%.

The electrical metrology has a fundamental relevance, since most measured quantities are converted into an electrical signal with a traceability of these electrical measurements – with a few exceptions (e.g. mass, force, length, HF/optics) – to primary electrical standards.

For advanced industries precision and accuracy are highly important quality aspects of operations. Therefore, the role of measurements and calibration is becoming more critical in maintaining product quality and safety. According to major market analysts, such as MarketsandMarkets[21] and imarc[22], the global calibration services market is going to reach a market size of US$ 5.6 - 5.7 billion in 2023 and is projected to grow at a CAGR of between 5.1% and 5.3% expanding its revenue to ca. US$ 8 billion by 2030. Electrical calibration services hold the largest market share. This is related to the widespread use of electrical equipment across various industries, including power generation, electronics, telecommunications, and automation, creating demand for calibration of electrical instruments. Additionally, constant advances of technologies necessitate advanced electrical equipment, which in turn also becomes more complex and sophisticated relying on precise calibration to maintain accuracy and functionality. The increasing adoption of automation throughout modern economies further stimulates the demand for highly accurate and reliable instruments and sensors used in automated machinery and control systems and their calibration, in order to enhance operational efficiency and productivity.[23] Moreover, stringent quality and safety standards in many industries like healthcare, aerospace, defense, and automotive drive the need for accurate electrical measurements. Accordingly, more than 40% of all calibration services provided in the European countries are electrical calibrations (Pierz 2021), which underpins their fundamental relevance for the European economies.

Various instruments and devices utilised across different sectors and activities need to be calibrated against primary standards, including instrument calibrations for radiation dosimetry, medical diagnostics and treatment, smoke detectors, devices for environmental monitoring, semiconductor wafer characterisation, etc. (Pierz 2021). Even relatively small improvements in the accuracy, which results in the shortening of the calibration chain, generates significant positive effects for end users, such as cost reduction, better efficiency and higher productivity (e.g. due to higher throughputs) of processes and higher quality of technologies based on them. These benefits are particular noticeable for the high technology sectors, where electrical measurements are widespread. Hence, the technological advancements and innovation are major factors driving the market of electrical calibration services and instrumentation.

According to the market analyst Fact.MR, the global electrical calibration equipment[24] market was valued at US$ 2.4 billion in 2022 and is projected to reach a market size of ca. US$ 4 billion in 2032 growing at a CAGR of 5.6%. In terms of portability, benched type of equipment accounted for 64.8%

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[20] Multifactor productivity index describes economic performance as a ratio between the amount of output to the amount of various inputs (capital, labour, purchased services, energy etc.).

[21] https://www.marketsandmarkets.com/Market-Reports/calibration-services-market-222898714.html

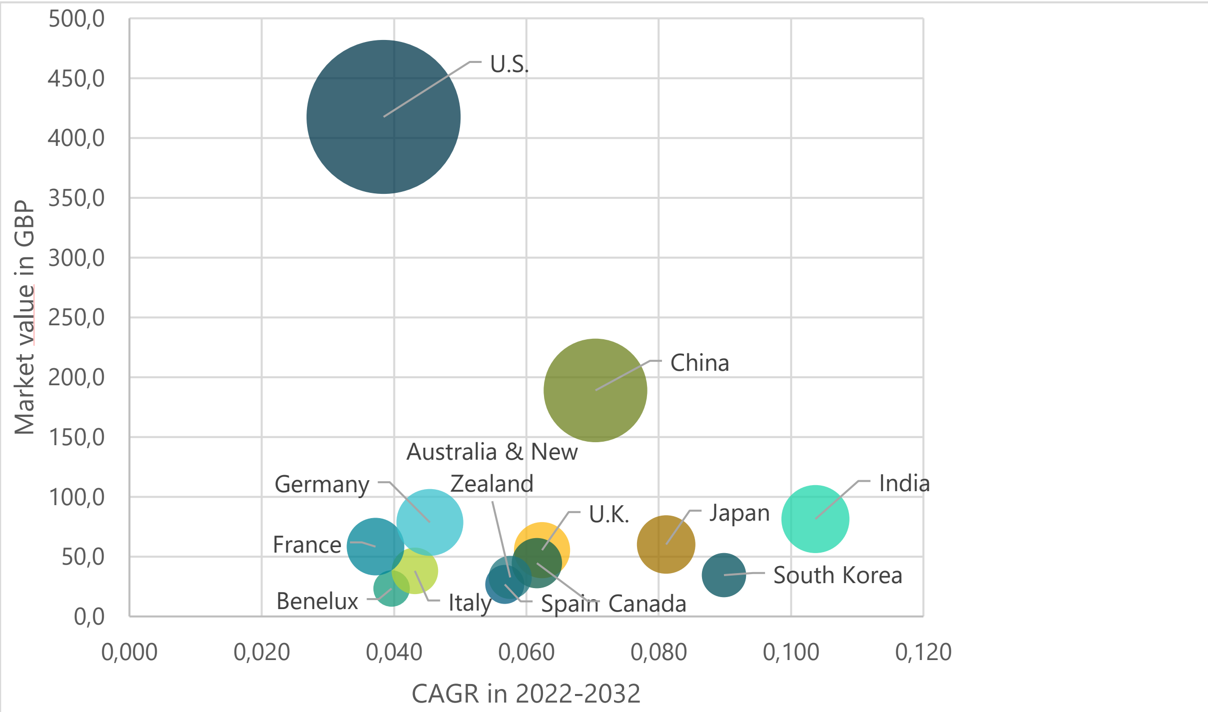
[22] https://www.imarcgroup.com/calibration-services-market

[23] https://www.finanznachrichten.de/nachrichten-2023-08/59831231-calibration-services-market-worth-dollar-8-1-billion-by-2030-exclusive-report-by-marketsandmarkets-008.htm

[24] As electrical calibration equipment the study subsumes instruments, devices and tools, which are used to perform the evaluation or modification of any equipment's performance that monitors or tests electrical qualities. In order to measure the performance of critical parameters for other equipment, or units being tested, electrical calibration necessitates employing precise equipment (Fact.MR 2022).

of the total revenue in 2022. North America and Europe hold the largest market share, while South Asia is going to reach the highest growth during 2022-2032 of 7.6% (compared to North America (4.1%) and Europe (4.6%)) (Fact.MR 2022). The major driving forces behind the market growth are enhanced focus on accurate measurements, especially in electronics, aerospace and defense industry, growing demand for maintenance and repair of systems and the need of customisation in electrical calibration equipment. High installation cost and the lack of skilled professionals along with the scarcity of raw materials for production of calibration equipment and high calibration costs are main aspects that impede the market growth.

Figure 9 Electrical calibration equipment market size and growth in 2022-2032 of countries



Note: the bubbles reflect the relative share of each country in the global market and their present absolute market value. The values were converted GBP using official exchange rate data provided by the Federal Reserve[25]. For GAGR in 2022-2032, the average exchange rates in 2017-2022 were calculated to account for possible exchange rate fluctuations.

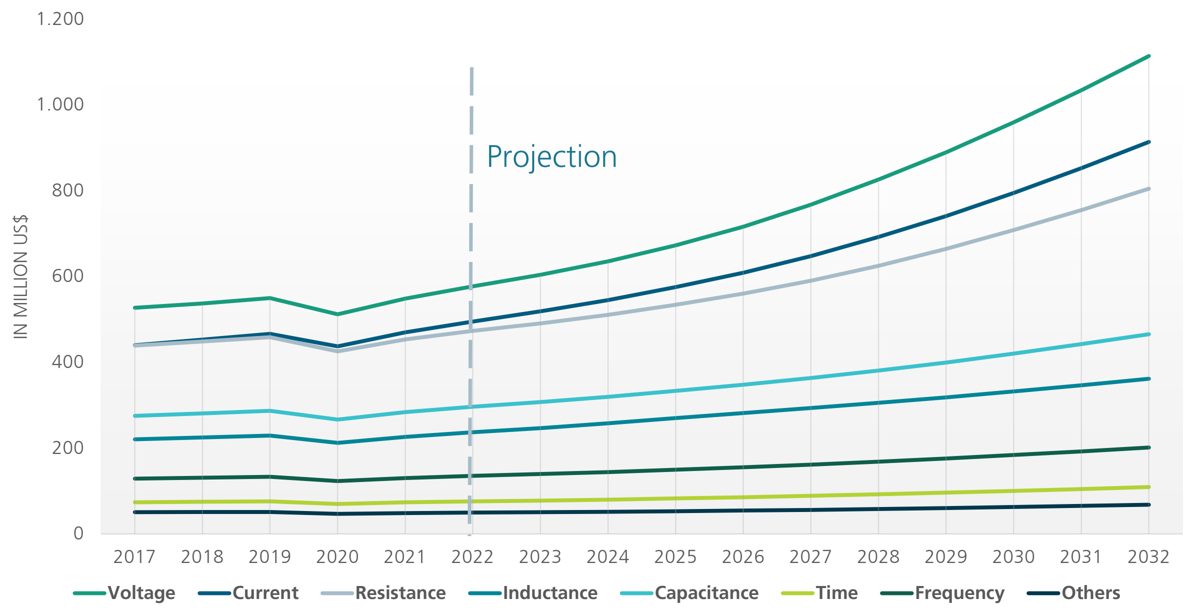
Source: own calculations based on (Fact.MR 2022).

The US has the largest electrical calibration market worldwide, accounting for ca. 30% of the total market share in 2021 (Figure 9Figure 9). China holds approx. 12% of the global market. Among further major markets are also Germany, India, Japan, UK, France and South Korea. Countries in East Asia (China, Japan, South Korea) India are projected to reach the highest market growth in the next decade.

Voltage type of principal parameter accounted for the maximum share (24.7%) in the electrical calibration equipment market in 2021, followed by current (21.2%) and resistance (20.2%) (Figure 10). They are expected to hold their market shares by the end of 2032.

[25] The Fed - Foreign Exchange Rates - G.5A Annual (federalreserve.gov)

Figure 10 Current and projected market value of electrical calibration equipment by principal parameters



Source: (Fact.MR 2022)

4.1.2 Impact of innovative QEM on calibration activities

According to the recent research presented by (Fennelly 2021), **measurement related activities are becoming increasingly important for the UK industries**. This is reflected by an increase in the number of employees by 13% between 2007 and 2017 to a total of 2 million in measurement related activities. In 2017, there were 162,000 employees engaged in calibration and testing services in the UK, earning a total of £4bn in annual pay. Also the rising demand and the subsequent increased investments in instrumentation indicate their growing importance for the UK's economy. Investment in instrumentation amounted to over £3.6bn in 2017, accounting for 7.2% of total investment in machinery equipment. Based on the analysis provided in this study and considering the share of activities related to electrical calibration of ca. 40% (Pierz 2021), we estimate that **in the UK ca. 800.000 workers are employed in occupations related to electrical measurements**. Out of these, **over 64.800 are involved in activities related to electrical calibration and testing receiving approx. £1.6 bn. of annual compensation**.

Commercial calibration labs that offer calibration services to a wide range of electrical instruments and equipment that are broadly used across industries and sectors can significantly benefit from the transfer and better adoption of primary electrical standards. The research conducted within this study confirms that the transfer and use of primary standards from NMIs to the calibration labs generate positive economic effects through:

- **Increased measurements accuracy**: Calibration labs can use these highly accurate and traceable measurement to calibrate their own secondary standard equipment, which results in higher accuracy and reliability of services they provide;
- **New business opportunities**: The availability of primary electrical standards enables calibration companies to acquire a broader range of customers and offer more precise and specialised calibration services to clients, who have most demanding accuracy requirements (e.g. for calibration of high-precision instruments) or need to comply with specific standards requirements;

- **Support of R&D**: Calibration labs can provide calibration services to the R&D (both public and private) that need to calibrate their equipment against primary standards used in science and innovation, contributing to reduction of the R&D costs ;
- **Collaboration in R&D and innovation projects**: Through the direct access and use of primary standards, calibrations labs can engage in R&D projects, for, example, those that aim at improving measurement technologies and techniques. This can foster learning processes, dissemination of knowledge and technologies, supporting innovations and R&D capabilities;
- **Competitive advantage**: The provision of the highest level of accuracy helps calibration labs to set apart from competitors gain and sustain competitive advantage through providing the highest level of accuracy to its customers;
- **Confidence of customers and prestige**: the adoption and professional operation of primary standards helps calibration labs to increase the trust in the quality of their services contributing to a prestigious reputation of calibration labs. This can also be successfully used for marketing purposes.

Box 4 provides a summary of economic impacts from the adoption and use of a Josephson DC standard at one of the largest commercial calibration labs in Europe based on an interview with two experts and representatives of this company.

Box 4

Impacts from the use of Josephson Quantum Calibrator at a commercial calibration laboratory in Germany

The Josephson Quantum Calibrator (JQC) – a programmable Josephson DC voltage standard – has been in operation since 2017 at the calibration lab. Its introduction was the result of several years of collaboration the calibration lab with the German NMIs and the company Supracon in Jena. JQC is used for numerous applications that go beyond the simple measurement of DC voltage. The system is operated with a dry cooler and not with liquid helium.

Direct economic effects to the calibration lab: The main advantage is linked to the reduction of measurement uncertainties and the ability to realise the highest accuracy directly at the lab at any time and within seconds, quasi at the push of a button. Traditionally it has been very costly to achieve the smallest possible measurement uncertainties, so that the new system enables considerable cost savings along with efficiency improvements and lowering of risks linked to the uncertainty. It eliminates the need to spend a lot of time, money and effort associated with sending the conventional device to the NMIs, on monitoring and checking their functionalities before and after the transport. The new JQC system is user-friendly and does not require highly skilled personnel to be operated. It also helped increase the throughput at the calibration lab, as other (secondary) standards operated at the laboratory and calibrated with the JQC can be used more frequently for calibrating customers' instruments and tools. However, it is very difficult to estimate the concrete effects in quantitative terms.

Higher accuracy and reliability of calibration and measurement services result also in increased customers' trust and better customers' retention contributing to the image of the company. Overall, this helps to gain a competitive edge and foster a higher market differentiation from competitors – being a major factor for an economic success.

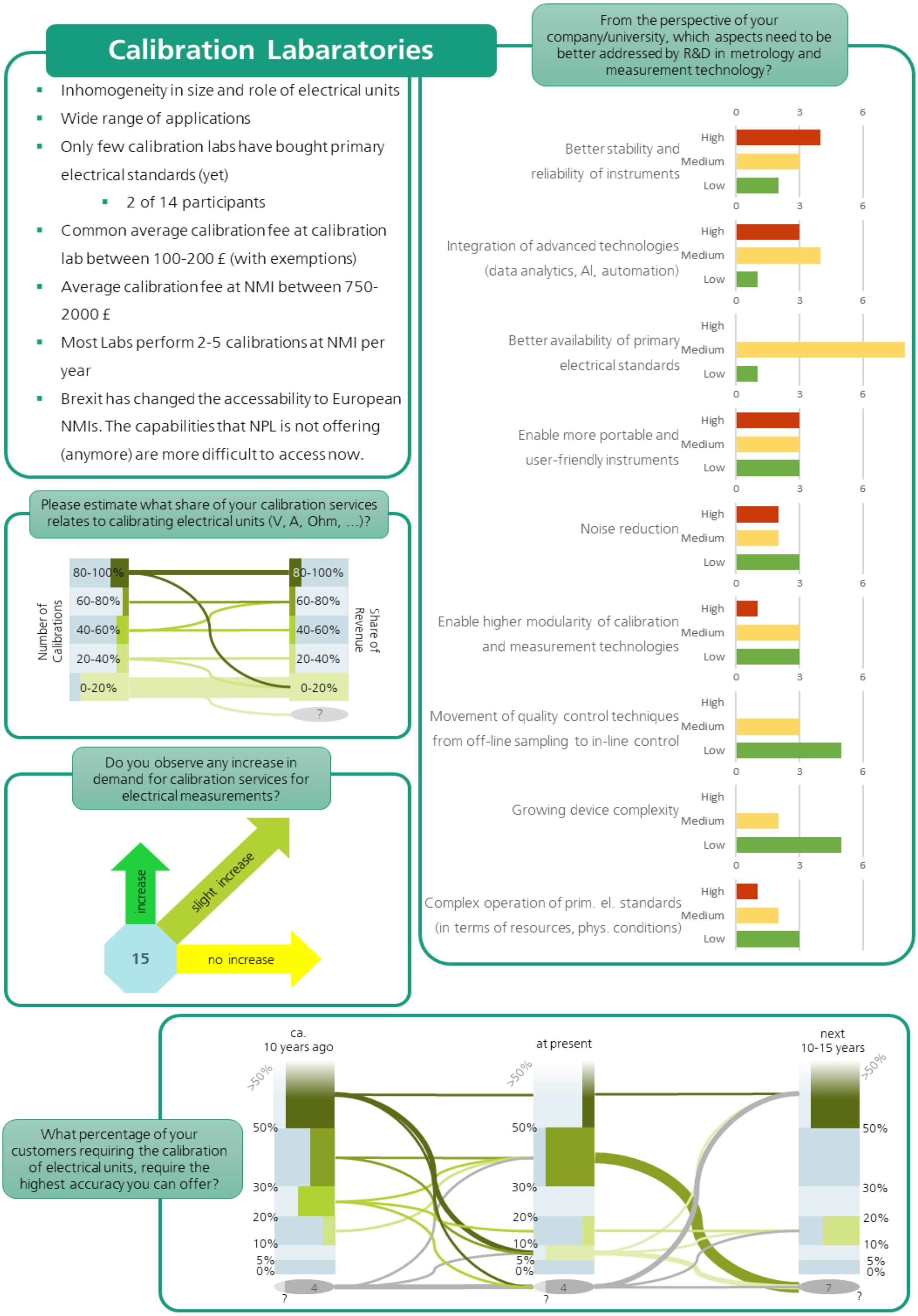
Economic effects to customers: Further benefits of the deployment of the JQC are associated with the shortening of the calibration chain, bringing lower measurement uncertainty and higher precision to the user. High quality is an increasingly important competitive advantage, especially in branches, where brand image, price, reliability, product quality and personnel safety form the key ingredients for success, such as aerospace, military & defense, semiconductors, and medical technology. Cost and process benefits that arise to the customers can be noticeable: sending their equipment to the NMI for a calibration is associated with much higher costs (by ca. 50%) for end users and can take much longer – the throughput time at NMI can be one month, whereas the calibration lab guarantees 5 days turnaround time.

Survey results

To examine effects that result from innovative activities at NMIs and technology transfer to the calibration labs on a broader basis, an online survey was conducted. Although over one hundred of calibration laboratories were approached, only a small share of persons – 14 in total – representing calibration labs, mostly in the UK, agreed to participate. Hence, it is only possible to detect some important trends and patterns within the target group. Figure 11 presents the main insights on the impacts for the calibration labs generated through the survey.

For most of the calibration labs surveyed, the calibration of electrical units plays only a small role (<20% of total number of calibrations and share of revenue). The demand of calibration services for electrical measurements observed by the calibration labs is most likely slightly increasing over time, according to the survey (one third of the participants observe no increase, whereas no participant reported a decrease of demand). The demand for the highest offered accuracy was a bit larger 10 years ago, but is also expected to increase again in the future. The survey revealed that the calibration lab are hoping that future developments in metrology and measurement technology provide improvements of reliability and stability of measurement instruments and the integration of advanced technologies. Some participant reported difficulties in accessibility of NMIs in the EU since the 'Brexit', while hoping for a widening of the services offered by NPL.

Figure 11 Summary of the calibration laboratories' survey on impacts of QEM



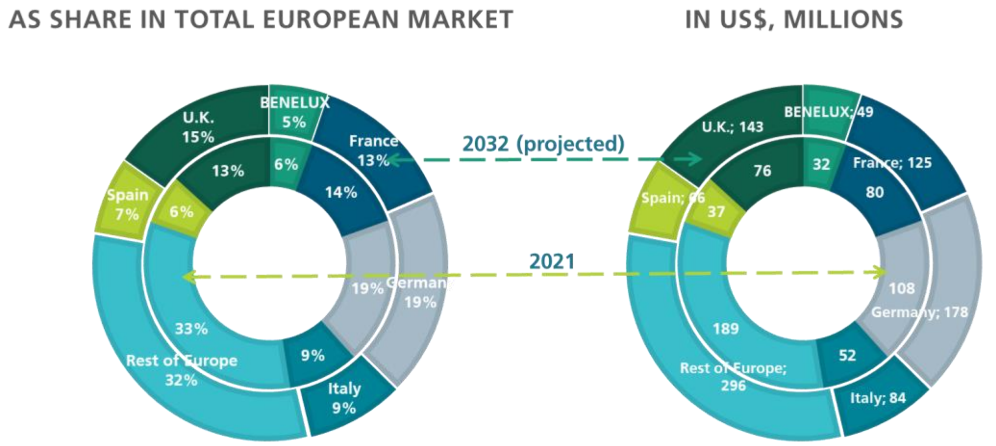
Note: Numbers represent the numbers of replies

Source: Fraunhofer ISI

4.1.3 Impact of R&D in QEM technology transfer to providers of advanced instrumentation

In Europe, Germany, the United Kingdom and France are the major players is the field of electrical calibration instrumentation and equipment (Figure 12). The UK market was valued at US$ 76.3 million in 2021 (Fact.MR 2022). The UK market is expanding fast and according to the forecasts is going to achieve the highest growth among all European countries in the market value almost doubling its market size by 2032.

Figure 12: European electrical calibration equipment market



Source: own calculations based on (Fact.MR 2022)

While electrical measurement instrumentation market is a niche market, it is invaluable from the economic point of view as it provides specialised equipment broadly used across the economy and the National Innovation System. Especially providers of advanced measurement technologies can derive significant benefits from the improvements of primary standards, as those are used for the development of highly precise instruments and tools and enable accurate measurements to keep up with technical advances (EURAMET 2019). The use of QEM for technologies is needed to realise quantum computers, precision tools & instruments. Traceable electrical measurements and calibration are highly relevant for the development and fabrication of the relevant instrumentation. Also the manufacturers of instruments that require small electrical measurements, such as particle counters or radiation dose meters, have benefited from the availability of high accuracy measurement systems.

According to the insights provided by advanced instrumentation companies' representatives within interviews, improvements in the realisation of primary electrical units and their better accessibility enable more precise measurement technology, which again facilitates the development of new products, techniques and processes, unfeasible before. Moreover, instrument providers confirmed that the provision of high precision measurement infrastructure in the field of QEM helps develop a more differentiated technology. It helps maintain competitive edge in terms of reputation and fosters competition of firms representing technology branches where brand image, price, reliability, product represent an important value added for companies.

To sum up, the following advantages arise for the (advanced) instrument manufactures through joint R&D in the field of QEM and knowledge & technology transfer from the NMIs:

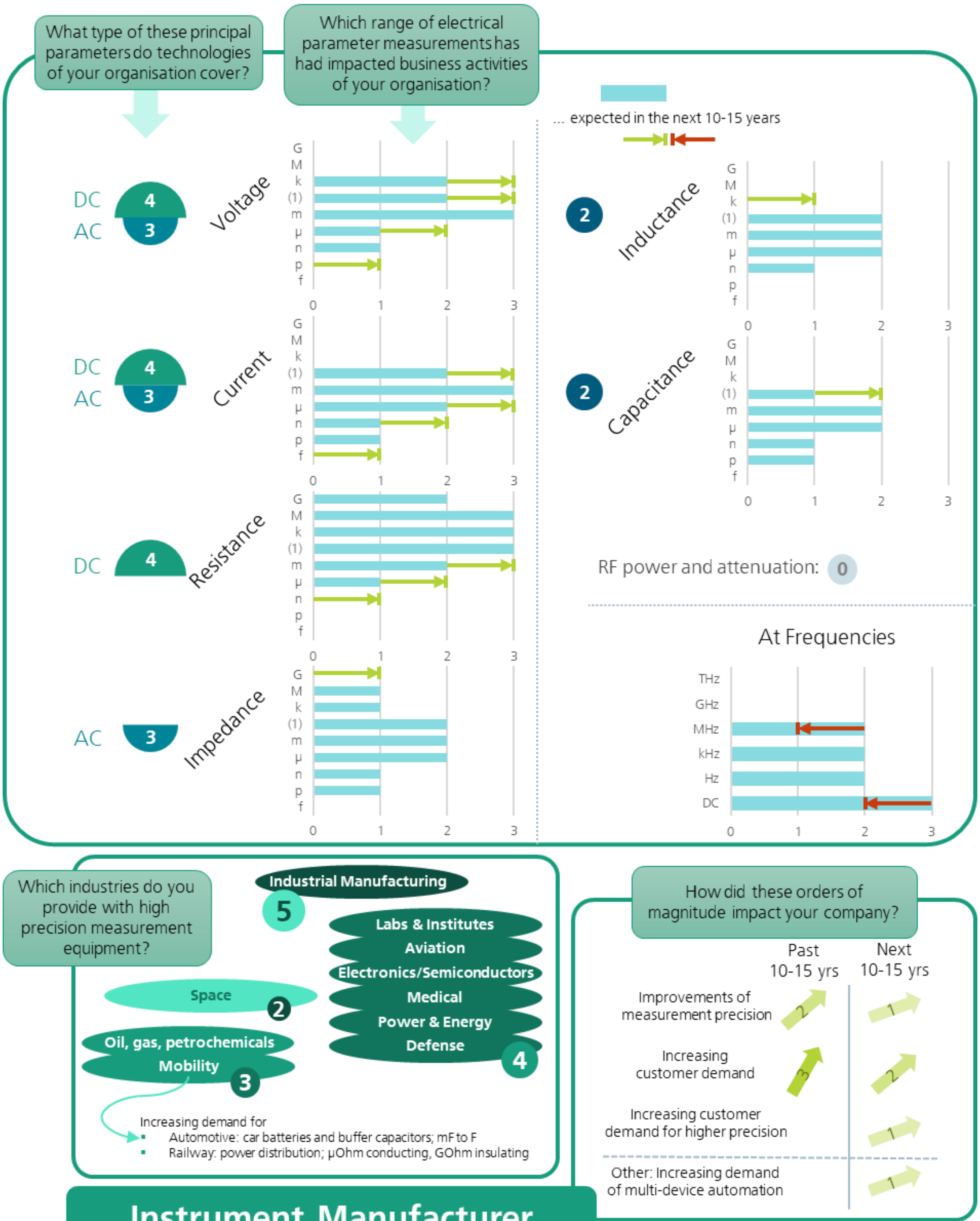
- **Access to the specialised expertise**, which enhance their own R&D and technological capabilities, offering new opportunities to develop and implement more efficient technologies and techniques and to improve the quality and accuracy of products.
- **Bespoke guidance and support**: QEM group offer support and consultancy to companies to solve very specific problems and to provide solutions tailored to the needs of the companies.
- **Access to the state-of-the-art infrastructure** enables instrument manufacturers (especially SMEs) to develop and test new technologies. This compensated for the lack of complex and cost-intensive infrastructure technology otherwise not feasible for the companies providing them new business opportunities and supporting business development (e.g. building of new start-ups).
- **Cutting-edge technology and innovation**: Through R&D collaboration and knowledge & technology transfer from NMI companies and other players have access to the latest advancement in the metrology science and technology. This facilitates the development of innovative measurement technologies with advanced features and functionalities.
- **Reputation and credibility**: Instruments developed in collaboration with NMI enjoy widespread recognition as being developed at the forefront of measurement technology. This helps instrument providers to differentiate themselves from the competitors as market players committed to the highest metrological standards. Enhanced credibility and confidence in products creates a competitive advantage, helps broaden the customer base and enter new markets.

Survey results

To examine effects that result from innovative activities at NMIs and technology transfer to instrument providers on a broader basis, an online survey was conducted. The survey was disseminated through different channels targeting numerous instrument providers in the UK and other European countries. However, only a very small share – 5 companies in total – representing advanced instrumentation providers, mostly from UK, participated in the survey. Hence, it is only possible to detect some trends and patterns within the target group based on the results provided by respondents. Figure 13 presents the main insights on the impacts for instrumentation providers generated through the survey.

Most of the participating companies covered the measurement of current, voltage and resistance. The orders of magnitude that impacted their business activities in the past can be compared to the relevance revealed by the patent analysis (see Patent and publication statistics). This impact mostly goes back to an increasing customer demand. The instruments are provided to a wide range of application areas, such as industrial manufacturing. The awareness for benefits that result from R&D in electrical metrology seems to be rather low, which might explain the low number of participants.

Figure 13 Summary of the instrumentation providers' survey on impacts of QEM



Instrument Manufacturer

- The participating instrument manufacturers cover...
  - ...a wide range of electrical units
  - ...a wide range of measurement instruments (multimeter, voltmeter, ammeter, ...)
  - ...a wide range of application fields
- Low awareness of benefits from R&D in electrical metrology in the past
  - Only one participant named benefits
    (enabling higher value products / new products, increasing customers' confidence in products)

Note: Numbers represent the numbers of replies

Source: Fraunhofer ISI

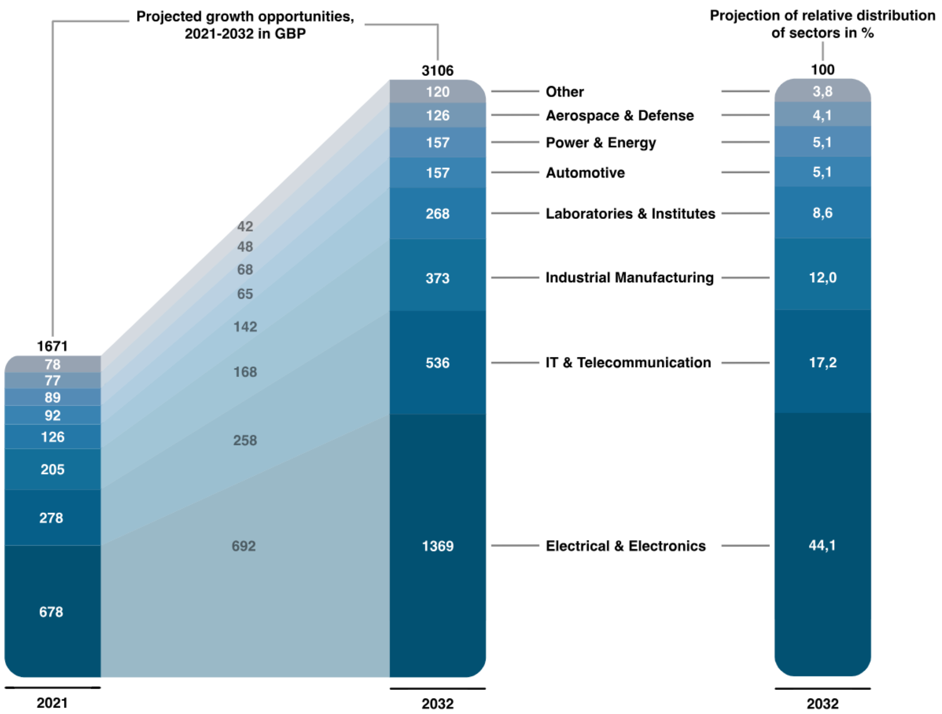
4.1.4 Impact on industrial end users of innovative QEM metrology

Quantum electrical metrology enables enhanced measurement capability by exploiting quantum strategies for improved sensitivity and accuracy of measurements (Somkuwar et al. 2020) from which different industries and application take advantage. As the global supply chain consolidates national or regional markets into the international market, end-use industries require accurate measurement and calibration, to ensure quality and security requirements, reduce the device failures and product recalls in order to maintain quality of products and market share. This necessitates a valid connection to an approved reference standard. As technological sophistication becomes increasingly important and quality being a major factor for sales of products, metrology equipment & services for the use across different industries and sectors need constant advancements. Testing is increasingly moving from labs to manufacturing. Therefore, portable and user-friendly instruments are gaining momentum to be used for quick analysis and verification.

Significant impact is particularly expected from a broader application of electrical measurement technology in a production environment (on the factory floor), where it has substantial effects on quality assurance and reduction of scrap, rework, and re-test. Instruments and sensors used throughout automated production lines rely on robust measurements with rigorous links to the SI unit realisations. They need to be regularly calibrated to ensure the error-free operation of their facilities.

The electrical and electronics segment is by far the largest user of electrical metrology technology accounting for 42% in 2021, followed by the IT & Telecommunication (17.3%) and industrial manufacturing 12.3% (Figure 14). Among intensive users of electrical calibration technologies are also Laboratories and R&D Organisations (8.1%) and the automotive sector (5.8%). The highest absolute growth in use of electrical calibration & measurement technology between 2021 and 2032 is forecasted for Laboratories and R&D institutions, Electrical and Electronics, IT & Telecommunication, Industrial Manufacturing, Power & Energy, and Automotive (Fact.MR 2022).

Figure 14 Users of electrical measurement & calibration equipment by end industries



Source: own calculations based on (Fact.MR 2022)

Industrial sectors where brand image, price, reliability, product quality and personnel safety form the key ingredients for competitive advantage are users of advanced measurement technology. Moreover, providers of strategic technologies and applications, where even the smallest measurement/calibration error can cost millions every year or cause serious harm, have the most demanding measurement requirements. In particular, accurate calibration and measurements are critical for

- **Aviation industry**: The aerospace industry is highly regulated, so they need high measurement and calibration standards to ensure high quality. In complex avionic systems, malfunction of electronic devices can pose serious problems. Accurate measurement is therefore in high demand in the aviation industry. The aerospace industry is a very important sector for the UK. The UK aerospace industry is the second largest (after the US) in the world with a turnover of approx. $32 billion in 2021 and heavily export-driven (98% of domestic production is exported). More than 3,000 aerospace companies operate in the UK, most of them are SMEs, providing over 282,000 jobs. In addition to a strong R&D and manufacturing in this field, the UK has a strong position in maintenance, repair, and overhaul sector (MRO), which provides services – including calibration and testing – to the huge numbers of military and civil aircraft (ITA 2022).
- The commercial **space industry** is another strategically relevant industry in the UK, which is growing rapidly. The country's over 1,500 space companies brought in £17.5B in domestic revenue in 2022, accounting for about 5% of the global sector (PWC 2023). The goal of the UK government is to further expand the domestic space industry reaching 10% of the global space market by 2030. It therefore strongly supports investments in key space technologies (PWC 2023). Satellite anomalies are common and require critical testing to ensure that they are functioning at all times. The demand for advanced test solutions is driven by compute-intensive, high-speed, and high-bandwidth avionics and electronics. Accurate electrical measurements are particularly important in monitoring power consumption, ensuring functioning of electronic components and maintaining communication systems. Precise measurements are applied to optimise performance, detect issues, and ensure the overall reliability of the satellites' operation. Growth opportunities and large public and private spending in the aerospace will also result in high demand for advanced measurement technologies and calibration services.
- **Military and defence** has an increasing need for testing to ensure all equipment is error-free and ready at all times. The sector interrelates and overlaps with aerospace industry. Traceable and highly accurate electrical measurements are of major importance in the military and defence applications to ensure the effectiveness of systems, improve operational efficiency while supporting safety and security. Therefore, accurate and timely calibration of instruments and devices is a critical task. For example, accurate electrical measurements are highly relevant for radar and communication systems, aircraft avionics, satellite-based surveillance (as satellites are equipped with advanced sensors and electronics, where highly precise electrical measurements are necessary to obtain data for intelligence and surveillance). The UK is among countries with highest share of defence spending investment. The UK defence turnover amounted to approx. $33 billion in 2021 (ITA 2022). Its prominent role is manifested through the high share of the UK's industry in the global defence exports - 16%. The strong growth of Europe's defense sector offers a significant opportunity for the region's instruments and calibration service providers.
- **Medical equipment**: High precision electrical measurements are required in various applications, where accuracy and efficacy are important aspects for patient care and achievement of better outcomes in diagnosis, treatment along with ensuring safety for both patients and

care personnel. The measurements are critical for medical imaging and diagnostic equipment, surgical equipment, implantable medical devices (e.g. pacemakers, neurostimulators – see: Neuroprosthetics), radiation therapy (see: Ionising Radiation for Treating Cancer) and many others. The UK medical technology sector plays a significant role for the UK's economy generating an annual turnover of approx. $30 billion each year with a strong contribution from small to medium-sized companies (ITA 2022). As the domestic medical technology sector is heavily export-oriented, it strongly relies on technologies that ensure quality and safety and support technological leadership of market players.

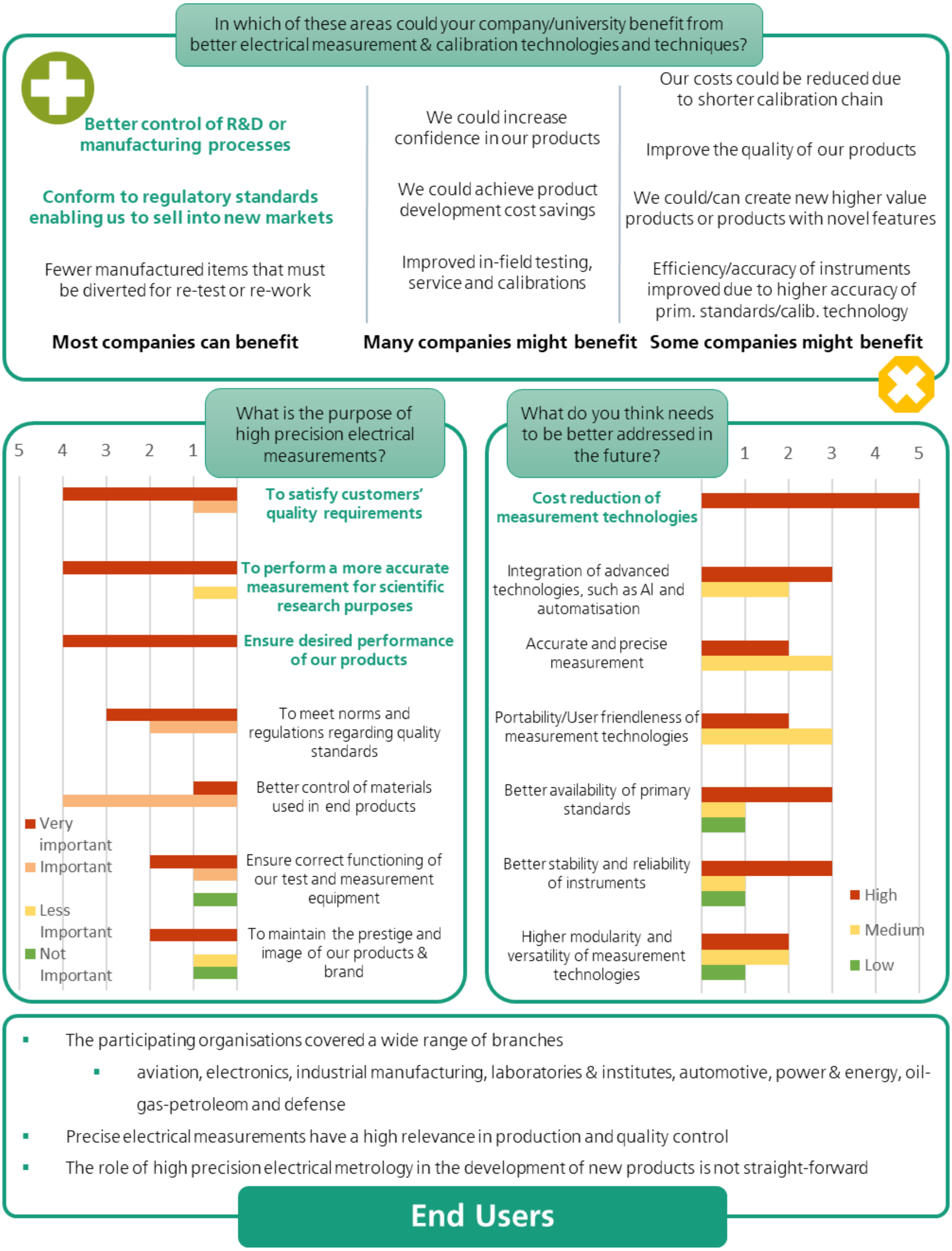
- **Basic science and research**: Traceable high precision electrical measurements are broadly used in the space exploration and astronomy, environmental monitoring (see: Measurement of air pollutants), material research, understanding of fundamental principles (e.g. particles) and many others. Some areas in physics, such as quantum mechanics, particle physics use high precision instrumentation to measure very small electrical signals in experiments that contribute to a better understanding of fundamental principles. They facilitate scientific discovery and technological innovation benefitting the society and economy as a whole.

Survey results

To examine effects that result from innovative activities at NMIs and technology transfer to end users on a broader basis, an online survey was conducted. The survey was disseminated through different channels targeting end users of innovative measurement tools and instrumentation in the UK and other European countries. However, only a very small share of persons – 7 in total – representing user companies, mostly from UK, participated in the survey. Hence, it is only possible to detect some trends and patterns within the target group based on the results provided by respondents. Figure XY presents the main insights on the impacts for instrumentation providers generated through the survey.

Satisfying customer quality requirements, performing accurate measurements for research purposes and ensuring the performance of the products are the main purposes for high precision electrical measurements for the end users. Benefits from improvements of electrical measurement & calibration technologies were found in the control of the R&D and manufacturing processes, as well as enabling the users to conform to regulatory standards for the (new) markets. All companies that participated are hoping for cost reduction of measurement technologies in the future. Overall, the low rate of participating companies and the survey results give clear indications that the awareness for potential benefits from electrical metrology is very low for end users.

Figure 15 Summary of the end users' survey on impacts of QEM



Note: Numbers represent the numbers of replies

Source: Fraunhofer ISI

4.1.4.1 Relevance of innovative electrical metrology for semiconductors and Quantum Computing

In the following, we will discuss in more detail the relevance of electrical metrology for two highly important and strategic technologies applied across various industries and areas of social life: semiconductors and the emerging quantum computing technologies. In both technology areas accurate measurements of electrical parameters and calibration with rigorous links to the SI units represent an important component in R&D and other stages of the value chain, although to varying degrees.

4.1.4.1.1 Semiconductor Industry

The supply of cutting edge electronic components and systems plays an essential role for the innovativeness and competiveness of major economic sectors and technologies. Semiconductors underpin the development of nearly all economic sectors and aspects of social life, while being technological driver for digitisation, automation, e-mobility, connectivity, sustainability and other socio-technological trends. The semiconductor global market grew to £601.7 billion in 2022[26]. Due to the foreseeable rapid growth in chips applications, the market for semiconductors is projected to reach the value of around £0.86 trillion by 2030[27]. Major economies, including UK, allocate huge resources and reinforce efforts to strengthen their R&D and market position in semiconductor technologies. For this, the UK government is going to invest up to £1 billion in the semiconductor R&D during the next decade (Department for Science, Innovation & Technology 2023c). In many countries the demand for advanced measurement and calibration technologies for the semiconductor industry is going to expand due to ramping up of semiconductor R&D and fabrication capacities.

The UK endeavors to sustain its competitive advantage in semiconductor design, R&D and compound semiconductors (Department for Science, Innovation & Technology 2023c), where electrical metrology along with other measurement technologies play a significant role. Metrology, including electrical metrology, is critical for measuring and characterising tiny structures and materials used for advanced semiconductor technology. Semiconductor R&D and manufacturing require a large and diversified set of measurement technologies. They have a significant part in driving innovation and productivity gains within the industry.

- **Relevance of electrical metrology**

Metrology technologies and techniques are utilised by semiconductor manufacturers to verify the integrity of the chips and improve the production efficiency. This benefits the whole semiconductor industry, from R&D and design, upstream material suppliers to the chip manufacturers and distributors. Along with the measurement of electrical parameters, a number of further SI units and metrology techniques, such as optical, dimensional and thermal/thin film metrology are important for micro- and nanoelectronics. It is therefore difficult to isolate individual effects that electrical metrology would entail.

Measurements, including electrical measurements facilitate the development and fabrication of semiconductors and electronics for different critical applications. Electrical metrology is used for the characterisation of novel materials, highly relevant for advanced semiconductors, such as graphene, gallium arsenide, indium phosphide or gallium nitride. For example, for the electrical characterisation of graphene, electrical measurements need to be highly accurate, i.e. very low current,

[26] https://www.mckinsey.com/industries/semiconductors/our-insights/the-semiconductor-decade-a-trillion-dollar-industry

[27] ESPAS 2022. Global Semiconductor Trends and the Future of EU Chip Capabilities.

in the pA range. Graphene enables the development of superior electronics for different applications, such as optical communication (e.g. data centres, also in the night vision applications, hypeporospectical imaging, plastic sorting, bio-sensors for medical applications, different sensors that are e.g. incorporated in the mobile phones etc.). Graphene electronics market size is expected to reach between $1.3 and 1.6 billion by 2028, according to the market research forecasts.[28]

Of all electrical parameters, electrical resistance is one of the most important and commonly used in the development and fabrication of semiconductors, as resistivity is a highly significant characteristics of semiconductor materials. It is a key parameter for the performance of semiconductor devices. In many cases it is necessary to measure the resistance with a high accuracy and a high resolution, in order to detect inhomogeneity in the doping density. For quality control and process monitoring in the wafer manufacturing process, testing the individual sheet resistance is just as essential as for the inspection and sorting of entire wafer batches. Also conductivity is frequently used to characterise electrical properties of bulk uniform materials such as metals or semiconductors (virgin wafers) (Krupka 2013). Electrical impedance is a further quantity of high practical importance for semiconductors.

Metrology and inspection are important for the management and performance monitoring of the semiconductor manufacturing process. They enable the detection of defects and other deviations early, saving costs, improving efficiency, processing productivity and quality of products. Electrical testing at wafer level (before dicing) is carried out to validate electronic functionality during and after the production (Schmitz 2013). As semiconductors become more complex, it becomes increasingly difficult to assess their performance. Impurities and film defects might occur causing performance problems. The early detection of such device defects requires electrical property measurement by probing the device working voltage (Yamazaki 2022). During the fabrication process, in-line electrical metrology is used to early detect process errors in the production line. In addition, they give manufacturers confidence in the quality as well as the purity of the final chips. The circuit boards need to be tested by undertaking various measurements by automated test equipment to test different functionalities, including electrical properties. A retrospective study commissioned by NIST in 2007 found that a significant decrease of scrap (from 7.53% to 0.28%) could be achieved and the rate of rework (from 8.8% to 5.1%) could be lowered owing improvements in the measurement technologies in the semiconductor industry, resulting in billions US$ of cost savings (Gallaher, M. P. et al 2007). Experts and industry representatives surveyed within the present study confirmed that the **deployment of advanced measurement techniques and technologies** throughout the semiconductor development and production process significantly contributes to **substantial cost savings from improved yields (decreased scrap) and throughput (decreased rework**).

In general, benefits from **investments in measurement in the semiconductor industry are linked to** achieving **lower costs of production, better products, and accelerated time to market**. Apart from economic benefits, metrology contributes **to better sustainability of semiconductor and electronics production processes** by reducing scrap. Identifying defects early, as enabled by highly accurate and traceable measurement techniques save scrap and energy-intensive processes employed for waste components and devices.

High precision measurement are important not only for the development and fabrication for nano- and microelectronics, but also for other electronics technologies. One example is the **development of highly efficient power electronics**. The goal is to develop power electronics without any current leakage. Experimentations during which extremely small current flows in the range of pico- and

[28] https://www.statista.com/statistics/1039954/global-graphene-electronics-market-size/; https://www.globenewswire.com/news-release/2023/02/23/2614062/0/en/The-Global-Graphene-Electronics-Market-size-is-expected-to-reach-1-6-billion-by-2028-rising-at-a-market-growth-of-32-7-CAGR-during-the-forecast-period.html

femtoampere are measured is an essential part of the development process. Apart from economic effects, efficient power electronics have a significant role in achieving better power efficiency and addressing sustainability goals.

Important instruments and sensors used throughout semiconductor and electronics production lines rely on robust measurements with rigorous links to the SI unit realisations and need to be regularly calibrated to ensure the precision and accuracy of operations. However, with advances in the structures and materials of semiconductor devices, identifying the causes of yield loss (e.g. through scrap) and establishing improvements can take a long time when only measurement techniques are used. Much better results can be achieved when metrology and inspection data from a variety of different instruments is combined and analysed. By consolidating various data outputs on an integrated platform, including semiconductor device processing conditions data, measurements, inspection data, and analysis data, it becomes possible to identify the different factors that influence yield loss (Yamazaki 2022).

- **Future opportunities for metrology**

Electronic components will also in the future highly rely on robust measurements. However, as microelectronic systems become more complex, with ever-decreasing feature sizes, and extension into the third dimension, along with a growing variety of materials, and a more diverse set of devices, the **measurement challenges also become more complex** (NIST 2023).

Next generation semiconductors face a number of considerable challenges. Among the most pressing is the need of the semiconductor industry to reduce power consumption and to increase the processing speed. The continued miniatuarisation and the emergence of new cutting edge semiconductor technologies pose their challenges also on metrology resulting in a growing need of new and precise measurement practices to enable the measurement of critical dimensions at the desired feature size. Next generation semiconductors need **advanced metrology and characterisation for manufacturing of microchips using 3nm transistor processes and smaller** as well as metrology for security and supply chain verification (see TableAnnex 1 Metrology gaps and needs of the semiconductor industry). The emphasis is especially put on measurements that are accurate, precise and well-tailored to the needs of the production of the semiconductor materials, devices, circuits and systems (NIST 2023). This requires the high level measurement science expertise provided by advanced NMIs, such as NPL, to be applied and developed further in close collaboration with stakeholders from industry, science and development.

An additional point that was stressed in the interviews is a **growing need of new and robust techniques for the analyses and testing of material properties used in semiconductors**, which is essential for characterising microelectronic components made thereof. Specifically, there is a growing need of metrology infrastructure for reliable characterisation of electrical properties of materials and components, essential for the performance of next generation micro- and nanoelectronics. The current methods are too costly, complicated and, in many cases, unreliable as measurements are not traceable. So, apart from the need for traceable measurements with low uncertainties, industrial end-user also require cost-effective novel instrumentation, particularly for high-frequency measurements, to make measurements economically viable (Piquemal 2023).

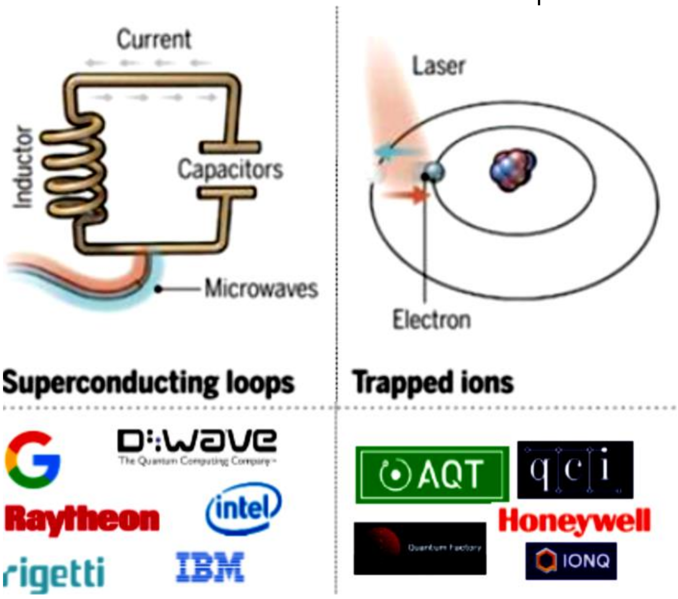
As electronics industry relies on highly accurate measurements, it will benefit considerably from the **further simplification of the exploitation of primary standards, such as Quantum Hall Effect**, and the shortening of the calibration chain to reduce costs and increase R&D and production process efficiency and quality of the product.

4.1.4.1.2 Quantum technologies

Quantum technologies (QT) have a high geopolitical importance for the UK. The technological leadership in quantum technologies could enable large economic, technological and security advantages in the global technology landscape. The UK's ambition is therefore to become a major player in QT and harness its potential in different areas. To achieve this goal, the UK government invested ca. £1 billion in R&D of quantum technologies since 2014 and has committed to invest further £2.5 billion in the development of quantum technologies in 2024-2033 (Department for Science, Innovation & Technology 2023b). Further substantial investments are earmarked for the development of skills and to support businesses and technology adoption.

The Quantum Metrology Institute (QMI) at the NPL plays an important part in the UK's quantum technology ecosystem. The QMI brings together necessary capabilities, knowledge and technology infrastructure in science and metrology to enable better understanding and development of quantum technologies. The QMI provides capabilities for testing and evaluation of quantum technologies, accelerating their commercialisation and adoption.[29]

The umbrella term "quantum technologies" denote different intriguing technologies that are based on the exploitation of quantum properties. The quantum technologies that attracted the most attention address the realization of quantum computers, quantum sensors, quantum communication and quantum metrology. Some of these technologies are expected to have a disruptive effect on the technology landscape throughout the next decades (Mohseni et al. 2017). Quantum computing will enable new and improve existing fields in computer science, such as quantum simulations (e. g. to predict molecule properties), applications in machine learning or other computational challenges in risk analysis or logistics (Hassija et al. 2020). While quantum computers can potentially be used to crack classical decryptions used in communication applications, quantum communication technologies could enable communication paths that are theoretically impossible to eavesdrop on, by exploiting the superposition or entanglement of photons (Gisin and Thew 2007). Sensors based on quantum properties are technically being developed since decades (magnetometers, atomic clocks, ...) (Degen et al. 2017). Sensors based on qubits, however, are being investigated more recently for potential applications in determining various physical quantities with high sensitivity. The related field quantum metrology, which enables the realization of physical units with a theoretically absolute accuracy, does not need further introduction in this report.



Source: Quantum Technologies 2020, Yole Développement, (Jan 2020)

Another important driving force for the advancement of quantum technologies is the development of suitable standards (van Deventer et al. 2022), as discussed in the expert interviews. Due to the novelty of most quantum technologies, their standardisation is a crucial step to facilitate their use in various applications.

Standard [29] https://uknqt.ukri.org/our-programme/

- **Relevance of electrical metrology**

Even though they are somewhat related, the various quantum technologies are fundamentally different and should therefore be carefully distinguished. Nevertheless, they all face many similar challenges and developments in one area of quantum technologies could easily cause spill-over effects into other areas. This also applies, of course, to the potential impact of advances in quantum electrical metrology on other quantum technologies.

Measuring electrical units or other quantities that are measured by being translated into electrical units does play a significant role in most quantum technologies. Quantum computers based on quantum dots, for example, require a stable voltage at the gate electrodes, while measuring currents in the order of 100 pico ampere. While the absolute value of the current is not of interest, as confirmed in the expert interviews, low noise levels are required to see changes (order of 20-50 pA, depending on the measurement time) relative to a reference current. The signal usually lies in the order of 20-50 pA, depending on the measurement time. Again the relative value of the current is not of specific interest, but the error-free detection of the signal (1 or 0). The measurement for reading out the state of the qubit is based on the translation of the spin information into charge information as realized by a Pauli spin blockade and the subsequent measurement of the charge as realised by a single electron transistor. Due to the effects on temperature on this process, the measurements are usually performed at the order of 1 Kelvin temperatures.

Quantum sensors can be based on different quantum effects. Electrical metrology becomes relevant, when the signal is read out or processed electronically. Nitrogen-vacancy centers in diamond, for example, cannot only be used to realize Qubits for quantum computing, but could also be used in highly sensitive room temperature measurement devices for magnetic or electric fields. Sensors based on NV-centers could find their way into various applications, such as in medicine for measuring brainwaves or neurotransmission. While the read out of NV-centers is commonly realized optically, an electrical read out, based on the detection of charge carriers resulting from spin-dependent ionization, is also investigated currently. The impact of quantum sensors is easier foreseeable than of quantum computing technologies, as its impacts well established application fields, such as electro mobility and material research. However, it also has applications in research (e. g. in life science) and emerging technologies (lab-on-a-chip). Some quantum sensors are already well-established, such as SQUIDs (superconducting quantum interference devices), which are based on a Josephson junctions. SQUIDs can measure small changes in magnetic flux, which subsequently can be used to measure electrical currents contactless. SQUIDs are so far mostly used for applications in science, since they can only be operated at temperatures below the critical temperature (in the superconducting phase). If and how SQUIDs can penetrate into commercial technologies for 'daily life applications' cannot be predicted – no anticipated future technology can solely be realised by uzilising SQUIDs so far. However, if high temperature superconductors improve, this path might emerge in the future.

- **Future opportunities for metrology**

The direct potential technological impact of further improving high-precision measurements of electrical units on quantum computing, communication or sensing is not straight-forward visible, as in all areas higher accuracies were not specifically requested by the experts interviewed in the survey, for example due to the dominating technological challenges, such as keeping the set-up free of noise or enabling reliable measurements at higher frequencies. These challenges result in a strong demand for improvements in instrument technologies (e. g. signal-to-noise ratio and signal amplification) for certain quantum technologies.

The current technological challenges for quantum computers depend strongly on the approach that is being used: realizing photonic Qubits, for example, is based on good single-photon sources, accurate phase modulations, relying on stable voltages and temperatures, and finally good single photon detectors.

One main technological challenge for improving the read out of Qubits in quantum dots is the realization of shorter measurement times, i.e. measurements at higher frequencies. This requires a sufficient frequency resolution (1Hz at several GHz) and signal-to-noise ratios. While the accuracy of the current measurements seems to be sufficient in general, the relative current measurements have to be realized at these high frequencies (e. g. detecting differences in the order of 10 pA in less than a microsecond). Achieving this at the required bandwidth is an open technological challenge. One approach is the integration of the amplifier in the cryostat.

Superconducting Qubits are based on Josephson contacts, commonly based on aluminum. One main uncertainty for the control of superconducting Qubits is their control by microwave radiation. The shape and amplitude of the microwave pulse that reaches the individual Qubits cannot be accurately determined currently, due to the large distorting influences that are connected to determining a signal inside the cryostat with instruments placed outside. Since these Qubits are operated at temperatures similar to the temperatures needed for the operation of electrical quan-tum standards, combining both in the same cryostat is in general possible. This could improve the control of superconducting Qubits significantly.

The electrical read out of quantum sensors, such as the NV-center based magnetometer introduced above, could provide useful advantages, such as an easier integration in electronic devices. However, since the absolute value of the magnetic field is defined by a shift in resonance frequency of the microwave excitation, the requirements on the electrical metrology is mostly found in the manufacturing of the electrode. The current measurement has to be sensitive (detecting the signal) but not accurate (determining the absolute value of the signal). Quantum sensors are usually described as 'calibration-free devices'. Even though some calibrated devices for the read out are always needed, the requirements for their measurement accuracy is moderate.

While the role of achieving further measurement precision for quantum technologies was doubted by the experts interviewed, the role that quantum metrology plays for quantum technology was described as extremely valuable, especially due to the role these institutions play in the standardization of quantum technologies, while focusing on academic and industrial players equally. Being located at this intersection, quantum metrology institutions are important players for bringing forward quantum technologies nationally and globally in the future. Many technological developments made for improving quantum standards in terms of accuracy and usability might be transferable to other quantum technologies, as they face comparable challenging.

5 Case Studies

Source: Science of Cities[30]

5.1 Measurement of air pollutants

Air pollution is an important environmental and public health issue. Exposure to air pollutants is a challenge due to the variety of the pollutants, series of adverse health effects and the large number of people at risk. Aerosols are a key component of air pollution and include a mixture of liquid and solid particles spanning in size from several nanometers to tens of micrometers (Wu and Boor 2021). Adverse health effects associated with air pollution include morbidity and mortality due to cardiovascular and respiratory diseases, cancer, asthma, and neural diseases (Wu and Boor 2021). The effects of air pollution can sometimes be observed even when the pollution level is below the level indicated by air quality guidelines (Chen and Kan 2008).

Aerosol measurements are critical for monitoring air pollution, identifying pollutant sources, understanding aerosol transport and transformation mechanisms, assessing human exposure and health risks. In the advanced industrial countries, the amount of air pollution and the concentration of particulate matter (PM) is becoming smaller, so it is more difficult to accurately measure it. The further challenge is linked to the difficulties to measure very small size of some inhalable toxic pollutants – down to 10 nanometers particle size.

There is increasing evidence that fine (PM2.5 – particles with diameters of 2.5 micrometers and smaller) and ultrafine particulate matter (<100nm) have a more adverse effect on human health than previously thought, although the precise toxicological mechanisms are not yet fully understood.[31] PM are inhalable particles, which can penetrate deep into the lungs, causing respiratory and other diseases. It is produced by combustion in industry, motor vehicles (particularly from diesel engines and vehicle tires and brakes), and wood burning solid fuel stoves (Public Health England 2018). The upcoming electrification of the transport sector brings a shift in challenges in terms of generating toxic particle emissions. As electric vehicles tend to be heavier, more toxic emissions will be released primarily due to higher load on tyres and friction when vehicles are rolling on highways or roads. Tireware usually contains heavy metals, inorganic and toxic components, which are released when e-vehicles are driving. They need to be reliably measured to be better controlled and removed.

Highly accurate, standardised and traceable measurement techniques are essential to identify, characterise and improve the understanding of the origin, formation, composition and transformation of pollutants. The knowledge of the origin of the pollutants is prerequisite for legislation. Accurate and reproducible measurements are basis for enforcing air quality regulations protecting human health and supporting research on climate change and atmospheric processes (Beckhoff 2022).

For the measurement of particles in the air the Condensation Particle Counter is used. Lower particle concentrations are linked to lower particle charge concentrations, which is linked to lower currents.

[30] https://nextcity.org/urbanist-news/tools-measure-air-pollution-airbeam-aircaster-epa

[31] https://uk-air.defra.gov.uk/networks/network-info?view=particle

For the reduction of measurement uncertainty, the traceability to primary electrical standards is extremely important for reliable measurements and also to arrive at international comparability of the measurements. The calibration of Condensation Particle Counters (CPC) is based upon the traceability of a reference particle counter. The CPC is calibrated against a reference Faraday cup aerosol electrometer (FCAE). FCAEs measure very small electrical currents down to the femto ampere range, or respectively, electrical charge densities as small as 10 -15 Coulomb/cm^3 (Beckhoff 2019).

Socio-Economic Impacts

Advanced measurement technologies contribute to reducing the potential cost of rectifying and/or preventing damage to the environment and human health from pollutants, toxic substances and greenhouse gas emissions. Accordingly, there are clear positive impacts on society and environment. A recent study carried out by the UK Health Forum and Imperial College London (Public Health England 2018) demonstrated that long-term exposure to particulate air pollution can have an effect equivalent to 29,000 deaths a year in the UK. The total cost associated with effects from PM2.5 incurred to the NHS and social care is estimated to be £1.5billion by 2025, and £5.1billion by 2035. If current air pollution levels persist, the study estimates 1,327,424 new cases of disease by 2035 in England, which are attributable to PM2.5 air pollution levels (Public Health England 2018). Improving the monitoring of airborne particles is indispensable for developing effective strategies to reduce emissions, exposure of the population to harmful components of ambient PM. Reliable measurements of small concentration and small size pollutants enable a more targeted policy on health-relevant components/properties and support the air quality legislation by extending the current legal framework to include metrics beyond PM mass concentration (Beckhoff 2022).

Further social and economic impacts are expected through the ability to measure and control emissions from the upcoming applications with regard to ambient air quality associated with electrical vehicles, automotive brake dust, additive manufacturing and other industrial processes (Beckhoff 2019). The science based and high confidence measurements support the improvement of the environmental legislation that is necessary to achieve the zero pollution goals. In 2022, the European Commission has proposed to revise the Ambient Air Quality Directives to align the air quality standards more closely with the recommendations of the World Health Organization (see the WHO Air Quality Guidelines, published in 2021).[32] The WHO recommends to lower the value for fine particulate matter (PM 2.5 and smaller) by more than half (WHO 2021). The overall goal of the EU is to achieve zero pollution for air by 2050.

To conclude: the greatest socio-economic impact of advanced metrology is linked to reducing adverse effects on human health and ambient environment as well as improving environmental sustainability as consequence of informed environmental regulations and strategies. Also the providers and users of specialised instrumentation and equipment for PM measurement can benefit from the improved measurement techniques and calibration procedures.

[32] https://environment.ec.europa.eu/topics/air/air-quality/revision-ambient-air-quality-directives_en

5.2 Ionising Radiation for Treating Cancer

Ionising radiation is broadly used in medical applications – both in diagnosis and treatment. Advances in metrological science are key to improve safety and efficacy of imaging and treatment and optimise radiation dose delivery along with therapeutic effects while contributing to cost reduction. Realisation of high accuracy measurements supports the development and implementation of more advanced radiation therapy and radio-diagnostic tools into clinical practice, benefiting patients and improving their quality of life.

Metrology underpins the measurement of ionising radiation. Thanks to enormous advances in imaging and technical innovations in radiotherapy, which are also supported by metrology, including electrical metrology, new techniques are now possible, that deliver very precise radiation to the tumor tissues while protecting the healthy tissue. New high precision radio therapy techniques can be used externally and inside the body, known as "radio surgery", where small, badly accessible tumors inside the body are attacked precisely with high doses.

The dose used in radio therapy generates usually a current in the order of several pico ampere, which can be measured by high-precision measurement equipment already with uncertainties of well-below one percent, which is again not the limiting factor for calibrating the radiation source – inaccuracies of 3% are commonly demanded by clinics, which pose no remarkable technological challenge. However, the current trends towards measuring (and applying radiation) with an improved time resolution, which requires measurements in the order of milliseconds, or with an improved spatial resolution, could result in higher requirements for the electrical measurement instruments. Radiation sources are usually compared with check sources to ensure that no changes in radiation intensity occur over time. Check sources have to have long decay time. Their storage and use at medical institutions comes with cumbersome radiation safety regulations. If current measurements are used for the calibration of the sources instead, the check sources could be replaced. Furthermore, by replacing radioactive material based sources by (electrically controlled) linear accelerators, additional flexibility and degrees of freedom in the control of the radiation could be gained. The handling of sources based on radioactive materials could become obsolete. However, so far the latter show still a better stability than linear accelerators.

Socio-Economic Impacts

Apart from being used in diagnostics (X-ray diagnostics), ionising radiation therapy (radiotherapy) has significant economic and societal impacts, as it is broadly used in cancer therapy. Cancer is one of the most frequent cause of death worldwide. In 2021 in England, 134,802 people died from cancer, which makes up over a quarter of all deaths in the country.[33] The cost that cancer incurs annually to the national economy is estimated at £7.6 billion due to premature deaths and inability to work.[34] However, the mortality rates are steadily decreasing since the 1970s and are projected

[33] https://commonslibrary.parliament.uk/research-briefings/sn06887/

[34] https://ukhsa.blog.gov.uk/2016/11/01/understanding-the-costs-and-benefits-of-investing-in-cancer/

to decrease further[35] due to more effective treatments, earlier detection and better prevention strategies.

Today between 25% and 40% of all cancer patients receive radiotherapy. During radiotherapy, ionising radiation destroys tumor cells by damaging their DNA – or at least inhibits their growth. In the best case, the tumor shrinks and regresses completely. Radiation treatments are therefore a frequent measure in the fight against cancer often used in conjunction with other therapies, which significantly increases the treatment success rate.

The reduction of measurement uncertainty and the resulting more effective beam therapy directly impact the patients, as the cancer tissue can be better destroyed while minimising damage to healthy tissue. In the past, patients were treated with four beams irradiating also parts of healthy tissue. Since then a more targeted therapy with multiple beams is possible (also due to highly accurate electrical measurements). The intensity of the dose can be adjusted more accurately to the therapeutic dose required.

Estimating economic benefits from improved ionising radiation based cancer therapy requires putting a monetary value on human health benefits. The technological improvements lead to more effective treatments to those who are treated enabling them to live longer and better-quality lives. This also generates direct economic benefits associated with the productive work and consumption of people who are successfully treated. A recent study of IAEA study on social and economic impact of radiotherapy in Asia and Pacific (IAEA 2022), estimates the net benefit from the access to enhanced capacity in radiotherapy associated with improved survival rates in the region between 0.7 EUR and 2.1 EUR per 1 EUR of costs. In high income countries, radiation therapy proved to be particularly efficient in terms of the cost-benefit ratio, compared to other cancer treatments. For example, the total cost of radiation therapy in Australia is less than 9 cents in every dollar spent on all cancer diagnosis and treatment.[36] Clinical and cost effectiveness of advanced radiotherapies in UK and other countries was demonstrated by different independent studies (see e.g. (Vaidya et al. 2017; Konski 2018). In addition to these benefits in terms of measured economic activity, socio-economic benefits may also arise in the form of increased wellbeing of patients, their families, main application of radiotherapy and is a potential source of significant benefits. Further reducing the cost of radio therapy, to which also advances in electrical metrology contribute, would have a significant economic impact, considering the large number of patients undergoing this therapy. Currently, the radio therapy costs range between 10 and 40k € in some major European countries.

5.3 Earth Observation

Climate change is the greatest existential threat to our planet. Metrology can contribute to increased trust and confidence in the measurements of climate change. Understanding causes, effects and connections behind the climate change can help us better prepare for the upcoming events, manage risks and develop mitigating measures. More than 50% of the world's climate variables are only measurable from

[35] https://www.cancerresearchuk.org/health-professional/cancer-statistics/mortality#heading-Zero

[36] https://www.targetingcancer.com.au/about-radiation-oncology/benefits-and-effectiveness/

space (Fox 2023). Earth observation (EO) satellites are the major means for climate change research to obtain necessary data for generating evidence-based insights to inform policy making and general public.

In many cases, one order of magnitude improvement in accuracy is necessary to differentiate between natural variability of the climate system and "anthropogenic" (human-caused) signal within the shortest time. Such improvements are of major importance, as they would enable more trustworthy climate forecasts and enhanced confidence in adaptation and mitigation strategies and policies likewise (Fox 2023). Apart from the need to improve measurement uncertainties, the most efficient solution involves integration and transferring the existing laboratory-based metrology in the field – the harsh space environment. The major goal of TRUTHS – a satellite mission, led by the UK Space Agency (UKSA) in partnership with NPL and other organisations – is therefore to improve the Earth observation capability through in-flight cross-calibration of satellites and to enhance the capability of measuring the Earth's radiation budget. This requires reduction in measurement uncertainty and traceability to SI references, going back to traceable measurements of current, voltage and power. On the whole, the system contributes to an improvement in data accuracy leading to a better understanding of changes in the Earth's climate supporting important decision-making on climate adaption strategies. Bringing quantum metrological standards (for all kind of physical units) into space, could change space-based research enormously,

Socio-Economic Impacts

EO has rapidly developed in the last years, enabling economic activities and a number of services used by national and local governments, public and private firms, scientists, and citizens. In UK, Earth observation contributes directly and indirectly more than £100 billion to the British economy (PWC 2023). The TRUTHS mission has a large potential to improve the performance of the EO segment, offering an opportunity to value added innovative services generating income and/or increasing efficacy and quality of services. It benefits both – the providers of the services and final users of them. Development of methods to generate robust data based on accurate measurements are of high relevance to climate risk-sensitive sectors such as insurance, energy, and agriculture (Fox 2023). According to the representatives of some commercial end-users, including globally significant insurance companies, the TRUTHS project could "underpin robust and credible products used across the industry".[37]

The project has positive effects on the satellite industry through the access to flexible, multi-functional transfer standards to improve pre-flight accuracy while reducing time and cost for calibration (Fox 2023). Earth observation is an important domain of the space industry gaining steadily in importance – 27% of the 3,372 satellites in orbit (or around 900) are EO satellites, while their share was only 16% in 2014 (OECD 2022). The UK is a world leader in nano and small satellites – 40% of all small satellites currently in orbit are of UK's origin (ITA 2022).

Apart from economic benefits, the TRUTHS project may have a large social impact, contributing towards the achievement of critical societal challenges, including the Sustainable Development Goals. The project allows scientists to implement improved climate forecast models through more accurate climate data and to reliably detect trends to be used for better informed policy making and climate change mitigation strategies. The benefits from this might be huge and difficult to measure as they are related to the wellbeing of people and survival of our planet. Thus, the long term effects involve such aspects as better protecting and improving the resilience of the ecosystems, managing climate risks, and enhancing food security, among others.

[37] https://www.eoportal.org/satellite-missions/truths#climate-change-services

5.4 Next Generation DNA and RNA Sequencing

Next generation DNA and RNA sequencing is key for advances in clinical research and personalised medicine. The costs for sequencing dropped dramatically in the last decade due to innovations in new techniques and technologies. One of such innovations is novel technique for single molecule sequencing of DNA and RNA using electrical signals. The identification mechanism is based on the change of tunneling current as they pass between a pair of nanoelectrodes (Ohshiro et al. 2012). Typical values for electrical current indicating the presence of a base molecule are 100 pA for approx. 1 ms. The nanopore sequencing technology, as developed by Oxford Nanopore Technologies[38] uses nanopores embedded in an electro-resistant membrane. Each nanopore corresponds to its own electrode connected to a channel and sensor chip, which measures the electric current that flows through the nanopore. When a molecule passes through a nanopore, it can be identified through the characteristic disruption it causes to the current in real-time. These technologies enable direct, real-time analysis of short to ultra-long fragments of DNA/RNA in scalable way.

Socio-Economic Impacts

Sequencing technologies based on electrical measurements offer substantial cost savings potential for DNA and RNA sequencing. Using the example of the Nanopore sequencing technology, developed by PacBio[39], cost savings and other benefits can be realised owing to:

- direct sequencing of single DNA molecules that does not require complex and expensive PCR (Polymerase Chain Reaction) amplification, reducing time and cost of sequencing;
- real time sequencing without the need of time-consuming post-sequencing analysis, and simplified workflow, which reduces the overall turnaround time;
- scalability: the technology in question can be used for high-throughput sequencing platforms, enabling the realisation of economies of scale;
- portability and better usability leads to increasing use in decentralised settings, including point-of-care diagnostics, so that there is no need for expensive centralised sequencing facilities. This can make sequencing affordable in lower income countries, benefitting their healthcare system, science and other sectors (such as agriculture).

To conclude, reducing the cost for next-generation DNA and RNA sequencing has significant positive effects, such as broader clinical and research applications, leading to a more widespread use in diagnostics and treatment and accelerating scientific developments based on sequencing. The technology has the potential to contribute to the faster establishment and propagation of personalised medicine, which again has the potential to bring large benefits to patients through targeted genomics-based diagnostics and treatment. Significant implications from the widespread use of cost-efficient sequencing technologies can especially result through benefitting research areas with large socio-economic impact potential. They involve microbiology, microbiome, human genomics, cancer, infectious disease, clinical research, transcriptome, environmental, epigenetics, biodiversity, animal breeding and food security.

5.5 Neuroprosthetics

Electrical signals play an important role as signals acquired from the human body, which can be utilised and applied in the broad field of neuroprosthetics. Signals acquired from muscles or brain,

[38] https://nanoporetech.com/

[39] https://www.pacb.com/

are electrical, mostly voltage signals. Brain activity – i.e. how the neuronal activity processes information – is related to the motion of electric charges, which produce electric and magnetic fields (Rak et al. 2012). Theoretically, the ability to carefully control and correct these electrical signals holds a huge promise to solve different medical problems, such as memory loss, hearing loss, blindness, depression, addiction, strokes, seizure, etc. Another target group represent patients with paralysis and lost functions due to spinal cord or nerve injuries. In this case, the goal is to replace the function that has been lost by means of electrostimulation and then to convert these signals into meaningful control signals in order to restore the lost function. Microelectrodes embedded in the cerebral cortex hold promise for using neural activity to control devices in order to replace natural movements in paralysed individuals (Rak et al. 2012). This is a vision of the company Neuralink – to create a brain interface to restore autonomy of patients and even more – to enhance the human mental and cognitive capabilities.[40]

For stimulating the brain and neurons, a precise control of the electric field in time and space would be necessary. A wide range of current for different brain regions is needed, as some regions require very delicate electrical stimulation, whereas some other regions need a more intense current, but small and precise enough in order not to harm the brain tissue over time. However, what sounds as a high potential technological breakthrough, is difficult to implement due to the high complexity and dynamism (non-linearity) of the brain activities, difficulties to tap into the bandwidth of information, largely unknown long-term effects and ethical aspects.

Currently, deep brain stimulation has been applied for the therapy of neurological and psychiatric disorders (Parkinson, depression) showing promising results. A lot of research is focused on applications in the field of neuroprosthetics with the main purpose to restore damaged functions, such as mobility, or senses, such as hearing and vision of patients. One group of prosthetics involve artificial limbs replacing body parts of patients after injuries and amputations. The activation of remained muscles via electrostimulation triggers signal which can be acquired from the surface of the body and used for the control of prosthetic device. The magnitude of the signal is in the range of up to millivolts, i.e. thousandths of a volt. The acquisition of these signals is a non-trivial issue and an important R&D topic in neuroprosthetics. Classical standard electrical prosthesis works with 2-3-4 control signals, which are taken from the body surface.

A lot of potential holds the possibility to acquire electrical signals directly from the nerve that originally controlled the underlying limb. At the nerve itself, the signal magnitude is in the range of µV. The muscle serves as a biological amplifier of the signal. When the signals can be properly acquired and tapped into, the prosthesis can be controlled according to these signals, which results in an intuitive control of the prosthesis for the user. This is what a lot of R&D currently focuses on. One important topic thereby is the development of appropriate measuring technologies for the nerve signals. Further challenges that need to be resolved for technologies to work properly are associated with small amplitudes of signals acquired from the electrodes. Furthermore, signals might be strongly disturbed by noise and series of physiological and technical artifacts. Latencies of more than 200 milliseconds pose substantial hurdles for the real time usability of prosthetics. Even though the magnetic read-out of the signals is possible in principle, it is not applicable for prosthetics due to the required infrastructure (magnets cooled down to low temperatures). For electrical measurements, however, non-invasive measurement techniques, by the use of adhesive scalp electrodes, and invasive measurement techniques enable short latencies, which is of course dependent on the amount of information processed.

While the non-invasive approach has many obvious advantages, it comes with natural limits due to the distance to the neurons caused by the skull and the capacitive effect of the scalp, which results

[40] https://neuralink.com/

in limitations for the localisation of the signal and unfavorable signal-to-noise ratios. EEG-controlled motor prosthetics are therefore limited in their amount of degrees of freedom (e. g. how many joints can be controlled). Implanted intracortical sensors enable a better localisation and therefore potentially further degrees of freedom. The electrode is placed in the extracellular space. The shape of the measured biphasic signal (tens of millivolts) of the neuron depends on the relative position of electrode and neuron. The pattern recognition algorithms, which allow for resolving the signals of the different neurons (spike sorting) is a crucial element of brain-computer interfaces. Current technological approaches investigate the possibilities to increase the number of contacts / electrodes in a small space. Each electrode has to be manufactured in such a way that only local signals are measured (small electrode), while still providing a reasonably low impedance (large electrode surface). The accuracy of the measurements is not the current bottleneck for the further development of this approach, but the manufacturing of the electrodes and the spike sorting algorithm. However, in principle the amount of neurons resolvable by on electrode could be increased by achieving additional measurement precision at a high measurement rate (e. g. 30 kHz), which could enable the identification of peak features which allow for a better sorting algorithm. Nevertheless, this requires high computational efforts and is not the main trend in the development of brain-computer interfaces.

Socio-Economic Impacts

The range of applications of neuroprosthetics goes way beyond the motor prosthetics and allows direct communication of the brain with a computer. Further advances in this area can have revolutionary implications for populations suffering from very serious neurogenerative diseases, spinal cord injuries and those who have lost their limbs owing to accidents or chronic illness. This kind of diseases and injuries take a significant medical, social and economic toll on patients, their relatives and society as a whole.

The potential impact of neuroprosthetics has gained visibility recently due to the war in the Ukraine and the large number of war invalids with amputated extremities. Around 50,000 Ukrainians have lost one or more limbs since the start of the war with Russia with amputee rate further on rise as the war goes on. Advancements in prosthetics and the hope for further developments of neuroprosthetics gives the injured and their relatives strengths and confidence in the future. According to DelveInsight analysis, the global neuroprosthetics market size was valued at US$ 6.35 billion in 2020 and is anticipated to reach USD 11.32 billion by 2026 with a significant CAGR of 12.76%.[41] The rising incidence of neurological disorders, chronic diseases and nerve injuries, growing amputations cases, public research programmes, technological advancement in related fields and increased R&D activities in neurotechnologies in conjunction with computational technologies are among major factors driving the market growth. High demand for properly working advanced implants that help compensate for or restore the lost functions or senses is expected in the future. Many key academic research centres and companies are proactively working in developing neuroprosthetics devices. Among them are Medtronics, Cochlear Ltd, Abbott, Boston Scientific Corporation, LivaNova, Ottobock, Second Sight Medical Products, MED-EL, Retina Implant AG, Sonova, NeuroPace, Inc., and many others.

The possibility of brain-computer interfaces opens huge opportunities in medicine, psychology, media and military. Especially the medical applications hold tremendous promise for supporting people affected by neurological or other deficiencies, such as strokes, amyotrophic lateral sclerosis, Guillain-Barré syndrome, cerebral paralysis or multiple sclerosis (Rak et al. 2012). Even though broad applications of brain-computer interfaces are not expected in the near future, some technologies

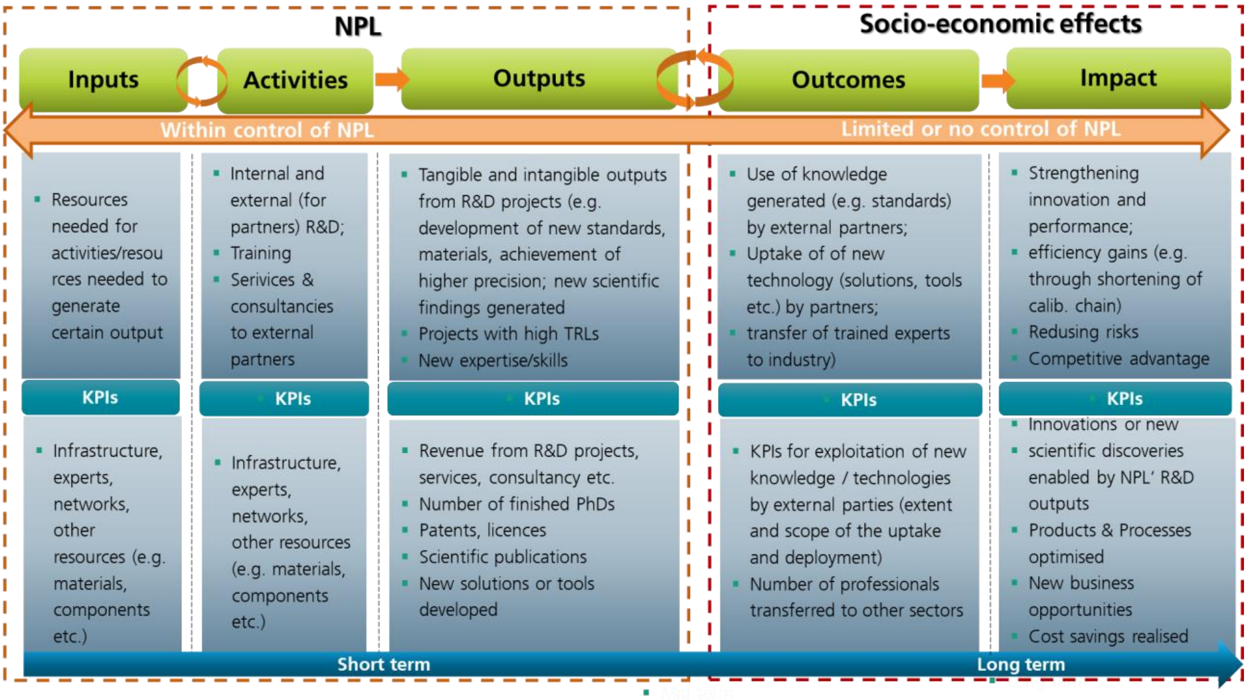
[41] https://www.delveinsight.com/report-store/neuroprosthetics-market-market

are already being developed and used nowadays. The development of sensory (e. g. cochlear implants) prosthetics or motor prosthetics is based on feeding signals (indirectly) into the brain and reading out signals out of the brain, respectively. The latter can be realised by different approaches, of which the measurement of the electrical pulses generated by the neurons is probably the most promising, due the nearly instantaneous feedback.

6 Impact Pathways

The following section summarises the impact pathway from innovative activities in QEM on the basis of collective findings and insights generated in this study. Impact pathways connect R&D activities and outputs from these activities with the economic, societal and environmental effects that contribute to broader long term impacts. The approach of impact pathways allows to gain insights and a systematic overview of all major effects of new technologies in general and QEM in particular. This approach is also useful to define KPIs in order to capture and track the achievement of short-term and long-term goals along the impact pathway.

Figure 16 Exemplary model for an impact pathway

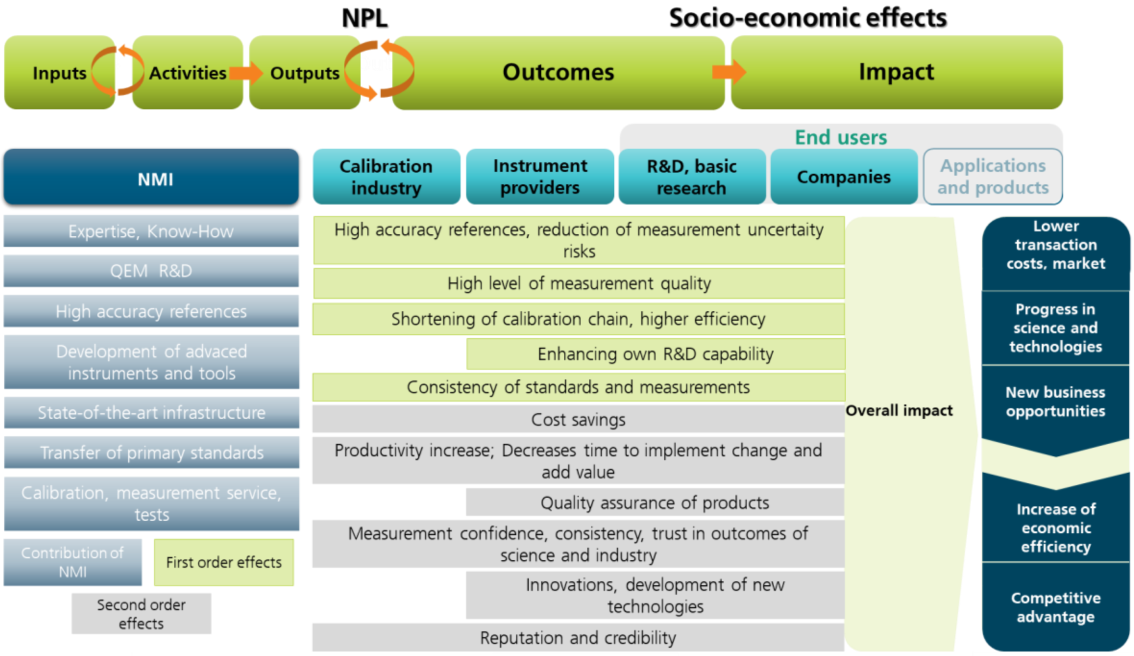


Source: Fraunhofer ISI

Figure 17 outlines a general framework for an impact pathway along a causal chain of events: inputs -> activities -> outputs -> outcomes -> impacts. **Inputs are resources** (human, financial, technical) necessary to perform activities. **Activities imply active leveraging of** tangible and intangible **resources**, they lead to **outputs**, which **are direct results from activities**. **Outputs can be operationalised as KPIs**, which contribute to external outcomes and eventually impacts. This is an important step, as positive impacts are depending on the internal performance, and only when a research group is performing well and delivering on its goals, it can generate meaningful socio-economic impacts. Inputs, activities and outputs are at the direct control of the research group represented by NPL. Monitoring and pro-actively managing these facilitate achieving specific goals. Outcomes are linked to the outputs. Outcomes describe the real world changes that outputs are bringing about to individual external partners when knowledge or technology generated by NPL is adopted and used. They delineate short and medium term effects/benefits to third parties that outputs might deliver. Accumulated over time outcomes form effects at a higher level – impacts that accrue to the economy and wider society. Tracking indicators on output, outcomes and impacts enables assessments, whether investments, R&D projects and other innovative activities are delivering the anticipated benefits.

The largest impact on innovations and the National Innovation System as a whole is expected through the pathway of R&D activities, as well as knowledge and technology development and their transfer. The following graphical representation (Figure 17) briefly outlines how innovative QEM creates value to the economy and the innovation system along the identified impact pathway. They generate first order effects, which are immediate consequences from the activities, achievements and services provided by the NPL, such as shortening of the calibration chain, reduction of measurement uncertainty and enhancement of external partners' R&D capability. Such first order effects lead to second order effects that accrue to the stakeholders along the calibration chain: calibration industry, advanced instrumentation, and end users. The effects on them were discussed in more detail in sections

Figure 17 Impact Pathway of Knowledge Development & Transfer



Source: Fraunhofer ISI

The effects from NPL's activities and outputs should not be understood as unidirectional and linear. Rather, they are interlinked and reinforce each other at different stages. The core activities at NPL is research that aims at advancing the measurement science as well as problem-driven R&D performed by NPL scientists that focus on solving technological challenges, problems of industrial and academic partners, and develop new solutions. Of critical importance are joint R&D activities with external partners that promote learning and help to access external knowledge and cutting edge technological infrastructure enhancing the R&D capability of external partners. Through ensuring high accuracy measurement and calibration standards, the NPL contributes to high performance of technologies and supports innovations. Particularly those industries that rely on highly accurate measurements, benefit considerably from the transfer and exploitation of simplified primary standards, such as Quantum Hall Effect, enabled by the R&D activities of NPL.

In summary the concept of impact pathways illustrates how the provision of advanced measurements and standards by NPL helps to verify and improve product quality and increase customers' confidence. When accumulated over time, these effects result in longer-term socio-economic impacts, such as cost savings, higher efficiency of processes and improved productivity, reduced market entry barriers, better quality of products, and new business opportunities, such as development of new businesses (e.g. start-ups). This again leads to economic effects at a systemic level, such as economic growth, overall increase of the economic efficiency, competitive advantage associated with the improvement of innovation power and attractiveness of the relevant domestic business sectors, creating additional incentives for future investments and contributing to market development.

7 Discussion and Outlook

R&D in the field QEM at advanced and high-profile NMIs, such as NPL, significantly contributes to the advanced R&D capabilities of the National Innovation System as a whole and the high-tech industries in particular. The simplification and better usability of the realisation of electrical primary standards, made possible through the R&D activities of the QEM group at NPL and other NMIs, fosters the widespread adoption of primary standards and bring the accuracy improvements closer to the industrial end users enabling considerable cost savings and other advantages. Technology developed by QEM experts equips metrological, academic and industrial players with higher measurement accuracy in fields such as ionising radiation, Earth Observation, Next Generation Electronics, particle counting, optical measurements, and material characterisation. Moreover, improvements in measurement technologies, including electrical metrology, enable and drive industrial innovation in advanced production and instrumentation. Although the future applications are somewhat difficult to predict, the research found that advanced electrical metrology has a high relevance for future innovations and technologies. The effect of these improvements will eventually spread to broader user groups and industries, where more efficient and sensitive technologies and processes will allow for higher quality and efficiency for a variety of products and services. All this considered, R&D and other activities performed at and offered to external partners have a noticeable socio-economic impact on final users and contributes to solving critical societal challenges.

The technological impact path based on traceable measurement accuracy seems obvious: first, research in metrology achieves higher precision in realising electrical units: this advancement is transferred to implementing higher measurement precisions for electrical units (measurement instruments), which finally leads to the development of new technologies exploiting the enabled precision – the higher measurement accuracy is used in development, production and use of technology-based products. However, in reality we observe difficulties at different steps:

- The higher precision in primary standards cannot be transferred straight-forward to secondary standards / measurement instruments, since the calibration process and quality of measurement instruments reduce the accuracy available at the application stage. Environmental effects, such as instable temperatures or electrical noise during the measurements/calibration further limit the "accessible" accuracy. Controlling the environmental parameters during the measurements is a challenge, which is most of the time more relevant than the accuracy of the electrical standards. However, moving the primary standards "forward" in the calibration step by making them for example more accessible to calibration labs could reduce the losses during the "transfer of the measurement accuracy". Overall, the additional accuracy can only be achieved with additional control of the potentially distorting or noise generating parameters in the measurement set-up.
- Technologies usually rely on different types of parameters – measurement of time, temperature, light intensities, and so on simultaneously. In most application cases, the accuracy of the electrical measurements is not the limiting factor for improving the products quality and functionalities. In many aspects, electrical metrology is ahead of the metrology for other physical parameters (especially considering the measurement accuracy in terms of ppm). The challenges that hinder the improvement of current high-end technologies or the development of new technologies are often not found in the accuracy of electrical measurements. If other challenges cannot be overcome, an improvement measurement accuracy cannot be exploited in that sense.

- In many cases in which electrical measurements are needed, the accuracy of the measurement is not crucial, but their capability to measure (small) signals. In these applications not the value of the signal is needed, but only the information about if there is a signal or not (binary true/false measurement).
- In other cases, not the absolute values of the electrical units are required, but relative measurements are needed. These do not necessarily require traceability of electrical units. An impressive example for this is that many researchers in fundamental research fields do not (regularly) calibrate their measurement equipment.
- And finally it should be mentioned that technological improvements of end products is not required or not wanted in many cases: many products based on electrical measurement "fulfil their task" already well enough and don't need to be improved technologically, if this comes with development efforts or higher costs.
- Nevertheless, many application fields already show the 'in-principle' potential to technologically benefit from advances in electrical metrology, even though the technological impact paths can often neither be predicted not outlined beforehand.

Box 5

Quotes from the interviews

„The hunt for ppm is over"

- Expert on quantum technologies about the need for more accurate electrical measurement technologies.

„The metrology institutes understand academic and industry players and can support the interests of both, which is extremely valuable"

- Expert on the role of metrology institutes in standardisation processes.

„The develop of new technologies in our field is based on research so far from the applications that we cannot afford it. Therefore, it's good, if there is a research institute that can invest time, money and man power to provide know-how that we can eventually commercialise."

- Expert from a company that sells quantum sensors on the role of NMIs in the R&D of new technologies.

„There are fundamental physical limits and there are apparent technological limits. It should be mentioned that these apparent limits could be shattered by good ideas and new technologies almost every time."

- Expert from a company that sells quantum sensors on the role of NMIs in the R&D of new technologies.

7.1 Recommendations on enhancing impacts from innovative QEM

- Providing more value and focusing on a particular or specific customer challenges is necessary for economic success. R&D activities aiming at the transfer to the industrial sector should be to a large extent guided by the needs and requirements of potential users. Needs and requirements identified within this research involve the following: Even though the availability of calibration is the most obvious requirement, it should be underlined. The industrial sector is dependent on calibrations to ensure product quality and other aspects – if the calibration is not available easily (e. g. NMIs in Europe have to be approached, which became harder after Brexit), this hinders development, production and quality testing of products. Due to the current geopolitical situation, many end users and calibration labs therefore depend on the services offered by NPL. Therefore, the QEM group should ensure to cover the orders of magnitude at the relevant frequency ranges of the required electrical units by the British industry.

- The need for calibration is strongly based on the need for certifications for products. Therefore the industry requires calibration labs and NMIs to be accredited to give out the relevant certificates. This need is currently well addressed in the UK for electrical units. We recommend to consider this important issue for other unites as well.
- The cost for calibration plays a relevant role in the continuous expenses of companies in many economic sectors. Lowering the cost of calibration is a straight-forward need of these companies, which would have a direct economic impact. Besides lowering cost, we also recommend to consider public support schemes for calibration activities.
- High precision is important in selected areas, but the challenge is to realise it in an application-specific way (under conditions relevant for a specific application, i.e. taking into account temperature, humidity, condensation, etc.). A good control of the conditions during the measurement is therefore a requirement to exploit the measurement precision offered by instruments and calibration. Since metrologists are experts in the control of environment conditions during measurements, a know-how transfer in these topics is highly desired. Vice versa, a better understanding of the conditions under which most measurements are performed in the industry, would enable a more targeted research and development and NPL.
- Similar to the conditions during the measurement, robust measurement equipment is required, as well as robust calibration processes to prevent the drift of measurement parameters. This is a prerequisite to enable the exploitation of high measurement precisions in a meaningful way.
- Shortening the calibration chain is a path that incorporates benefits mentioned above – more cost effective and quicker calibrations might be enabled. The usability, portability and miniaturisation of secondary and primary standards is therefore a main path for improvements within the calibration chain and therefore at least indirectly desired by most industrial sectors. Ultimately, the commercial availability of user friendly standards for industrial end users might replace the need for involving external players, such as calibration labs and NMIs, in the routine calibration of electrical measurement equipment to some extend in the future (certification will still be required).
- Only some indications could be found for the need for further advancements in measurement accuracy for technological applications. In most cases, other technological and economic challenges dominate the R&D of industrial players. However, even though extremely high-precision electrical measurements are not actively demanded currently, the future potential is still given in-principle. The measurement accuracy of electrical units is entering a level were electrical noise caused by room temperature seems to become a natural limit for further improvements. However, technological improvements in many sectors found paths through apparent limits (e. g. the fulfilment of Moore's law for computer chips). The survey cannot predict the path towards further accuracies and their commercial exploitation. The experimental realisation by further research, such as on the realization of a quantum standard for ampere, should therefore be continued to enable the potentials hiding in further measurement accuracies.
- Users are increasingly interested in measurement systems that incorporate multiple measuring capabilities, combinational and modular instruments as one-stop shop for end users. Considering standards, it would be preferable for users to have a high temperature Quantum Hall Standard coupled with a Josephson standard to have the realization of voltage,

current and resistance combined in one quantum device. Therefore, improving the flexibility of primary and secondary standards is an intriguing part for technological advancements for QEM.

- The potential benefits of cutting-edge digital technologies are often discussed only vaguely. This holds also true for quantum electrical standards and high precision electrical measurement devices: while the automation and digital read-out of electrical calibration and measurements enables a well-pronounced technological impact, the potentials of AI technologies could not be resolved in this study. The mapping of these potentials could be the goal for further activities of the (quantum) electrical metrology and instrument manufacturers.
- In the production environment there is an increasing need for automated and scalable technologies (e.g integrated with robots or sensors for improved measurement times). Need for quicker non-contact machines that combine self-calibration options and automated material handling capability to achieve quicker turnaround. Scalable and automated measurement technology and inspection tools to identify defects in the production environment are in high demand.

Finally, our study indicates that users of advanced metrology on the one hand are largely content with the available tools and methods. On the other hand there is only limited awareness of the important role of advanced metrology for the development and adoption of emerging technologies. Enabling the exploitation of the high precision achieved in primary standards, require improvements along the whole traceable calibration chain. The accuracies achieved so far, are often better than needed, considering the environmental conditions of the final application areas (stability of temperature). The end users need to be provided with ideas how to exploit this additional accuracy, which asks for a communication channel between metrology research and R&D of industrial companies.Therefore, in order to enhance impacts from innovative QEM, it is not sufficient to develop cutting-edge technologies. Rather, awareness raising among potential users is needed. Accordingly, we strongly recommend to consider implementing information, communication and other awareness raising measures to prepare users for the expected developments.

A.1 Annex

Table 1: Semiconductor-related R&D needs in metrology

The following most critical metrology R&D gaps, challenges and needs for the development of future oriented and advanced semiconductor industry have been recently identified by NIST. They need to be addressed to strengthen the technological leadership and competitiveness of the semiconductor industry (NIST 2023):

TableAnnex 1 Metrology gaps and needs of the semiconductor industry

Metrology R&D Gap	Industry Needs	Actions Required
Metrology for materials property, purity and provenance	Meet increasingly stringent requirements for semiconductor materialspurity, physical properties, and provenance through the development of new measurements and standards.	Develop measurement technologies, properties data, and standards focused on defect and contaminant identification to support uniform materials quality and traceability across the supply chain.
Advanced Metrology for future microelectronics manufacturing	Critical metrology advances needed to keep pace with cutting-edge microelectronics and semiconductor manufacturing to maintain a competitive advantage	Advance the physical and computational metrology tools adaptable to next-generation manufacturing of advanced complex, integrated technologies, and systems
Enabling Metrology for Integrating Components in Advanced Packaging	Enabling metrology that spans multiple length scales and physical properties and supports acceleration of advanced packaging concepts for future-generation microelectronics.	Develop metrology for complex integration of sophisticated components and new materials to support advanced microelectronics packaging industry.
Modeling and simulating semiconductor materials, designs, and components	Improve the tools needed to effectively model and simulate future semiconductor materials, processes, devices, circuits, and microelectronic system designs	Advanced design simulators using multi-physics models and next-generation concepts such as artificial intelligence and digital twins to support microelectronics design.
Standards for new materials, processes, and equipment for microelectronics	New or improved standards and validation methods to accelerate the development and fabrication of next generation semiconductor technologies	Develop standards, validation tools and protocols for next-generation materials, processes, and equipment, to support fast innovation and cost-competitiveness of the industry
Metrology to improve security and provenance of microelectronic-based components and products	Innovative metrology to foster and enhance the security and provenance of microelectronic components and products across supply chains and increase trust and assurance.	Comprehensive approach to hardware security protection that includes standards, protocols, formal testing processes, and advanced computational technologies, while facilitating assurance and provenance of microelectronic components across the supply chain and end products.

Source: << (NIST 2023)

1 Publication bibliography

Ahlers, Franz Joseph (2016): Quantum resistance metrology based on graphene. European Metrology Research Programme. Available online at http://www.ptb.de/emrp/graphohm.html.

Anzivino, G.; Bai, J.; Bencheikh, B.; Contin, A.; DeSalvo, R.; Fagen, S. et al. (1999): Failure modes of large surface avalanche photo diodes in high-energy physics environments. In *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 430 (1), pp. 100–109. DOI: 10.1016/S0168-9002(99)00203-X.

Beckhoff, Burkhard (2019): Aerosol metrology for atmospheric science and air quality. EMPIR.

Beckhoff, Burkhard (2022): Advanced aerosol metrology for atmospheric science and air quality. EURAMET e.V. – the European Association of National Metrology Institutes.

BIPM; OIML (2021): National Metrology Systems Developing the institutional and legislative framework. International Organization of Legal Metrology (OIML); International Bureau of Weights and Measures (BIPM.

Bordy, Jean Marc (2022): Support for a European Metrology Network on the medical use of ionising radiation (EMPIR).

Britvitch, I.; Johnson, I.; Renker, D.; Stoykov, A.; Lorenz, E. (2007): Characterisation of Geiger-mode avalanche photodiodes for medical imaging applications. In *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 571 (1-2), pp. 308–311. DOI: 10.1016/j.nima.2006.10.089.

Campbell, Joe C. (2007): Recent Advances in Telecommunications Avalanche Photodiodes. In *Journal of Lightwave Technology* 25 (1), pp. 109–121.

Chen, Bingheng; Kan, Haidong (2008): Air pollution and population health: a global challenge. In *Environmental health and preventive medicine* 13 (2), pp. 94–101. DOI: 10.1007/s12199-007-0018-5.

Cova, S.; Ghioni, M.; Lacaita, A.; Samori, C.; Zappa, F. (1996): Avalanche photodiodes and quenching circuits for single-photon detection. In *Applied optics* 35 (12), pp. 1956–1976. DOI: 10.1364/AO.35.001956.

CRISTAUDO, N. A.; Mayo J. J.; MITCHELL, P.E (2018): The challenge of determining the economic value of metrology. In *OIML BULLETIN* LIX (1).

Degen, C. L.; Reinhard, F.; Cappellaro, P. (2017): Quantum sensing. In *Rev. Mod. Phys.* 89 (3). DOI: 10.1103/RevModPhys.89.035002.

Department for Science, Innovation & Technology (2023a): Science & Technology Framework. – taking a systems approach to UK science & technology. Available online at https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1140217/uk-science-technology-framework.pdf.

Department for Science, Innovation & Technology (2023b): National Quantum Strategy.

Department for Science, Innovation & Technology (2023c): National semiconductor strategy (Policy Paper). Available online at https://www.gov.uk/government/publications/national-semiconductor-strategy/national-semiconductor-strategy.

Dias, C.; King, M. (2022): A meta-analysis of NPL's impact case studies: charting NPL's economic and societal benefit mechanisms.

Fact.MR (2022): Global Electrical Calibration Equipment Market. Forecast, Trend Analysis & Competition Tracking – Global Review 2017-2032.

Fennelly, C. (2021): Quantifying measurement activity in the UK.

Filtz, Jean-Remy (2015): Developing traceable capabilities in thermal metrology. EMPIR. Available online at http://www.eura-thermal.org/.

Fox, Nigel (2023): Metrology to establish an SI-traceable climate observing system. EMPIR.

Gallaher, M. P. et al (2007): Economic Impact of Measurement in the Semiconductor Industry. National Institute of Standards and Technology.

Gisin, Nicolas; Thew, Rob (2007): Quantum communication. In *Nature Photon* 1 (3), pp. 165–171. DOI: 10.1038/nphoton.2007.22.

Gonçalves, Jorge; Peuckert, Jan (2011): Measuring the impacts of quality infrastructure. Physikalisch-Technische Bundesanstalt.

Hassija, Vikas; Chamola, Vinay; Goyal, Adit; Kanhere, Salil S.; Guizani, Nadra (2020): Forthcoming applications of quantum computing: peeking into the future. In *IET Quantum Communication* 1 (2), pp. 35–41. DOI: 10.1049/iet-qtc.2020.0026.

Hobbs, Matthew J.; Grainger, Matthew P.; Zhu, Chengxi; Tan, Chee Hing; Willmott, Jonathan R. (2018): Quantitative thermal imaging using single-pixel Si APD and MEMS mirror. In *Optics express* 26 (3), pp. 3188–3198. DOI: 10.1364/OE.26.003188.

IAEA (2022): Social and Economic Impact Assessment of the RCA Programme. Radiotherapy Case Study. International Atomic Energy Agency.

Innovate UK (2023): UK Photonics 2023: The Hidden Economic Engine. Available online at https://photonicsuk.org/wp-content/uploads/2023/06/UK_Photonics_2023_Hidden_Economic_Engine.pdf.

ITA (2022): United Kingdom – Country Commercial Guide. The International Trade Administration U. S. Department of Commerce. Available online at https://www.trade.gov/country-commercial-guides/united-kingdom-aerospace-and-defense.

Karar, A.; Musienko, Y.; Vanel, J.Ch. (1999): Characterization of avalanche photodiodes for calorimetry applications. In *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 428 (2-3), pp. 413–431. DOI: 10.1016/S0168-9002(99)00177-1.

King, M.; Renedo, E.; Croucher, D. (2022): Review of the evaluation activities for the NMS.

King, Michael; Lambert, Ray; Temple, Paul (2017): Measurement, standards and productivity spillovers. In Richard Hawkins, Knut Blind, Robert Page (Eds.): Handbook of innovation and standards. Cheltenham, UK: Edward Elgar Publishing (Edward Elgar E-Book Archive).

Konski, Andre (2018): Cost effectiveness of prostate cancer radiotherapy. In *Translational andrology and urology* 7 (3), pp. 371–377. DOI: 10.21037/tau.2017.12.38.

Krishna, S.; Kwon, Oh-Hyun; Hayat, M. M. (2005): Theoretical investigation of quantum-dot avalanche photodiodes for mid-infrared applications. In *IEEE J. Quantum Electron.* 41 (12), pp. 1468–1473. DOI: 10.1109/JQE.2005.858791.

Krupka, Jerzy (2013): Contactless methods of conductivity and sheet resistance measurement for semiconductors, conductors and superconductors. In *Meas. Sci. Technol.* 24 (6), p. 62001. DOI: 10.1088/0957-0233/24/6/062001.

Link, Albert N. (2021): The Economics of Metrology. University of North Carolina at Greensboro (Working Paper, 21-01).

Mohseni, Masoud; Read, Peter; Neven, Hartmut; Boixo, Sergio; Denchev, Vasil; Babbush, Ryan et al. (2017): Commercialize quantum technologies in five years. In *Nature* 543 (7644), pp. 171–174. DOI: 10.1038/543171a.

Moszyński, M.; Kapusta, M.; Balcerzyk, M.; Szawlowski, M.; Wolski, D. (2000): Large Area Avalanche Photodiodes in X-rays and scintillation detection. In *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 442 (1-3), pp. 230–237. DOI: 10.1016/S0168-9002(99)01226-7.

NIST (2023): Metrology Gaps in the Semiconductor Ecosystem: First Steps Toward Establishing the CHIPS R&D Metrology Program. CHIPS Research and Development Office.

OECD (2022): Earth's Orbits at Risk. 1st ed. Paris: Organization for Economic Cooperation & Development.

Ohshiro, Takahito; Matsubara, Kazuki; Tsutsui, Makusu; Furuhashi, Masayuki; Taniguchi, Masateru; Kawai, Tomoji (2012): Single-molecule electrical random resequencing of DNA and RNA. In *Scientific reports* 2, p. 501. DOI: 10.1038/srep00501.

Palubiak, Darek; El-Desouki, Munir M.; Marinov, Ognian; Deen, M. Jamal; Fang, Qiyin (2011): High-Speed, Single-Photon Avalanche-Photodiode Imager for Biomedical Applications. In *IEEE Sensors J.* 11 (10), pp. 2401–2412. DOI: 10.1109/JSEN.2011.2123090.

Pierz, Klaus (2021): Graphene Impedance Quantum Standard. EMPIR.

Piquemal, François (2023): Electrical nanoscale metrology in industry. Available online at https://www.euramet.org/research-innovation/search-research-projects/details/project/electrical-nanoscale-metrology-in-industry.

Public Health England (2018): Estimation of costs to the NHS and social care due to the health impacts of air pollution: summary report. Available online at https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/708855/Estimation_of_costs_to_the_NHS_and_social_care_due_to_the_health_impacts_of_air_pollution_-_summary_report.pdf.

PWC (2023): Expanding frontiers. The down to earth guide to investing in space. PwC Strategy& (UK) Ltd.

Rak, Remigiusz J.; Kołodziej, Marcin; Majkowski, Andrzej (2012): Brain-computer interface as measurement and control system the review paper. In *Metrology and Measurement Systems* 19 (3). DOI: 10.2478/v10178-012-0037-4.

Renker, Dieter (2002): Properties of avalanche photodiodes for applications in high energy physics, astrophysics and medical imaging. In *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 486 (1-2), pp. 164–169. DOI: 10.1016/S0168-9002(02)00696-4.

Robertson, Kristel; Swanepoel, Jan A. (2015): The economics of metrology. Australian Government (Research Paper).

Rutz, Frank; Bächle, Andreas; Aidam, Rolf; Niemasz, Jasmin; Bronner, Wolfgang; Zibold, Andreas; Rehm, Robert (2019): InGaAs SWIR photodetectors for night vision. In Bjørn F. Andresen, Gabor F. Fulop, Charles M. Hanson (Eds.): Infrared Technology and Applications XLV. 14-18 April 2019, Baltimore, Maryland, United States. Infrared Technology and Applications XLV. Baltimore, United States, 4/14/2019 - 4/18/2019. SPIE. Bellingham, Washington, USA: SPIE (Proceedings of SPIE, volume 11002), p. 37. Available online at https://www.spiedigitallibrary.org/conference-proceedings-of-spie/11002/2518634/InGaAs-SWIR-photodetectors-for-night-vision/10.1117/12.2518634.full.

Schmitz, Jurriaan (2013): Advances in Wafer-Level Electrical Characterization. MESA+ Institute for Nanotechnology, University of Twente, Enschede, Netherlands (Conference Paper).

Schmoch, Ulrich (2007): Double-boom cycles and the comeback of science-push and market-pull. In *Research Policy* 36 (7), pp. 1000–1015. DOI: 10.1016/j.respol.2006.11.008.

Singh, Anand; Srivastav, Vanya; Pal, Ravinder (2011): HgCdTe avalanche photodiodes: A review. In *Optics & Laser Technology* 43 (7), pp. 1358–1370. DOI: 10.1016/j.optlastec.2011.03.009.

Somkuwar, Atul S.; Satish; Siwach, Praveen K.; Kumar, Ajeet; Shukla, Ajay K.; Kushvaha, Sunil S. et al. (2020): Electrical and Electronics Metrology: From Quantum Standard to Applications in Industry and Strategic Sectors. In Dinesh K. Aswal (Ed.): Metrology for Inclusive Growth of India. 1st ed. 2020. Singapore: Springer Singapore; Imprint Springer (Springer eBook Collection), pp. 457–521.

Swann, Peter G.M. (2009): The Economics of Metrology and Measurement. Report for National Measurement Office, Department for Business, Innovation and Skills.

Tassey, Gregory (2008): The Roles and Economic Impacts of Technology Infrastructure. National Institute of Standards and Technology.

Toyoda, Masahiro (2002): Measurement of the characteristics of a quadrant avalanche photodiode and its application to a laser tracking system. In *Opt. Eng* 41 (1), p. 145. DOI: 10.1117/1.1418222.

Vaidya, Anil; Vaidya, Param; Both, Brigitte; Brew-Graves, Chris; Bulsara, Max; Vaidya, Jayant S. (2017): Health economics of targeted intraoperative radiotherapy (TARGIT-IORT) for early breast cancer: a cost-effectiveness analysis in the United Kingdom. In *BMJ open* 7 (8), e014944. DOI: 10.1136/bmjopen-2016-014944.

van Deventer, Oskar; Spethmann, Nicolas; Loeffler, Marius; Amoretti, Michele; van den Brink, Rob; Bruno, Natalia et al. (2022): Towards European standards for quantum technologies. In *EPJ Quantum Technol.* 9 (1). DOI: 10.1140/epjqt/s40507-022-00150-1.

WHO (2021): WHO global air quality guidelines. Particulate matter (PM2.5 and PM10), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide. Bonn, Germany: WHO European Centre for Environment and Health. Available online at https://www.ncbi.nlm.nih.gov/books/NBK574594/.

Wu, Tianren; Boor, Brandon E. (2021): Urban aerosol size distributions: a global perspective. In *Atmos. Chem. Phys.* 21 (11), pp. 8883–8914. DOI: 10.5194/acp-21-8883-2021.

Yadav, Sandeep; Scherer, Thomas M.; Shire, Steven J.; Kalonia, Devendra S. (2011): Use of dynamic light scattering to determine second virial coefficient in a semidilute concentration regime. In *Analytical biochemistry* 411 (2), pp. 292–296. DOI: 10.1016/j.ab.2010.12.014.

Yamazaki, Genta et al. (2022): Yield Improvement Solution for Semiconductor Manufacturing to Support Increasing Sophistication of Digital Society. In *Hitachi Review* 71 (4).

Zhao, Hao-Yi; Naseem; Jones, Andrew H.; Chao, Rui-Lin; Ahmad, Zohauddin; Campbell, Joe C.; Shi, Jin-Wei (2019): High-Speed Avalanche Photodiodes With Wide Dynamic Range Performance. In *J. Lightwave Technol.* 37 (23), pp. 5945–5952. DOI: 10.1109/JLT.2019.2944098.