Strategic Research Agenda for Metrology in Europe

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Content

1 Introduction

This document sets out the major challenges currently facing European Metrology as envisaged by EURAMET and its stakeholders. It is not intended to define specific projects that will be conducted by specific programmes under national, European and international initiatives over the next five to ten years. The SRA should provide a resource for European and National Metrology Research Programmes. It seeks to be non-prescriptive and strategic in nature. It is intended to be an inspiration for new thinking in important policy areas.

A clear aim is to focus on clear strategic direction which will allow delivery of tangible results maintaining necessary openness and flexibility. This will make it possible to incorporate important and emerging challenges as well as cutting edge scientific advances as they are made. Furthermore, prioritisation of research objectives and projects will have to be made consistent with the aims and objectives of specific programme initiatives.

Context

Metrology, the science of measurement, is an essential tool for scientific research and development as well as for technological innovation. It also underpins modern industrial competitiveness and supports the development of new and improved products and processes. Metrology, through high-quality science research at the frontiers of measurement science, is critical to major advances in science. Global trade and regulations depend heavily on internationally accepted measurements and standards. At the heart of this are the International System of Units (SI) and a Mutual Recognition Arrangements [1] for global acceptance of measurement and traceability of results obtained in different countries.

With rapid advances in technology, ever more precise and reliable measurements are essential to continue to drive innovation and economic growth in a knowledge based society. What we cannot measure, we do not understand properly and cannot control, manufacture or process reliably. Thus, advances in metrology and its effective use have a profound impact on our understanding of and ability to shape the world around us.

Key societal challenges such as sustainability of energy, environment and health also demand new and reliable measurement technologies with traceability that has to be accepted worldwide. Research and development in metrology is thus essential to meet current and future requirements of industry, regulators and policy makers alike.

Governments support a metrology infrastructure because of the scientific, economic and societal benefits it brings and its strong character as a public good that justifies public intervention: it promotes scientific excellence, innovation and competitiveness. Major economic powers are increasing their investment in metrology research and related infrastructures. Given that the investment required is high, a single European state could not compete in the global context. A collaborative metrology effort on the European level is therefore essential to maintain and develop an internationally competitive edge.

EURAMET, through its leadership, has initiated Europe wide joint metrology research programmes in partnership between its members and the European Union under the Framework Programmes 6 and 7 (iMERA-Plus and EMRP), and has just commenced a new joint Programme, the European Metrology Programme for Innovation and Research (EMPIR), worth €600M under Horizon2020.

EURAMET, as the Regional Metrology Organisation of Europe, has provided strong leadership in co-ordinating metrology R&D carried out by its members which currently includes 37 National Metrology Institutes (NMIs) and 75 Designated Institutes (DIs) that have national responsibility in specific metrology fields.

European NMIs and DIs collaborate with NMIs and scientific centres of excellence from beyond the boundaries of Europe, not just through the CIPM consultative committees, but also including organisations such as the WHO, WMO, IAEA, ISO, IEC and a plethora of international academic institutes. Such continued collaboration is essential to ensure Europe's internationally leading capability.

Common vision and goal

Our common vision is to ensure Europe has a world-leading metrology capability, based on robust and high quality science, and an effective and inclusive network based infrastructure to meet the rapidly advancing needs of end users.

Our goals are:

- To ensure that Europe's metrology infrastructure and networks develop in a way that enhances industrial innovation, competiveness and international trade whilst supporting societal objectives and the commitment to sustainable growth.
- To realize the benefits of collaboration and co-operation in addressing challenges that are common to Member countries.
- To identify future trends and needs for metrology research and services
- To give special attention to the needs of emerging members, and initiate, develop and implement activities to assist them through knowledge transfer in achieving metrological capability in carefully chosen areas.
- To provide a clear framework, objectives and outcomes in the implementation of the SRA.

The SRA describes opportunities and challenges for interdisciplinary metrology research covering energy, environment and health of citizens as well as for supporting industrial innovation. In addition, and importantly, it contains work to be done in developing fundamental metrology in support of advancing the international system of units on a global basis.

Research in support of standards

Standards play a vital role in supporting the Europe 2020 strategy for smart, sustainable and inclusive growth. A dynamic European standardisation system is essential to spur quality and innovation and to strengthen Europe's role as a global economic player[2]. Reliable measurement methods and metrology underpins many standards and therefore, there is significant benefit in EURAMET working closely with the European Standards organisations(ESOs) to identify their needs for metrology input to standards currently under development (co-normative) and needs for metrology input for future standards(pre-normative). Both types of input can help to accelerate the development of standards as well as increase their robustness.

EURAMET has signed MOUs with all three ESOs - CEN, CENELEC and ETSI. CEN and CENELEC have already established a joint Group with EURAMET to establish pre-normative research needs for future standards in key sectors/areas.

As standards are increasingly developed on a global basis, it is important that outputs from our metrology research are used effectively to support the developments of international standards where appropriate through ISO, IEC, and ITU. Researchers from EURAMET member organisations participate actively in several hundred standards committees and provide major inputs to the standards. Our aim is to gain increased leverage and outcome from metrology research through new and improved standards.

Learning from the EMRP

The EMRP initiative is the predecessor of EMPIR. It is a joint European metrology research programme implemented by 22 National Metrology Institutes, with five calls for proposals in the years 2009 to 2013. It is based on Article 185 of the Treaty on the Functioning of the European Union (TFEU), which, in implementing the multiannual Framework Programme, makes it possible to co-fund coordinated national research programmes. A significant achievement of EMRP is the strong integration by jointly programming 50% of dedicated national funding for metrology research in Europe. It reduced fragmentation and allowed achieving critical mass by concentrating resources on areas with highest relevance through close collaboration of best researchers. EMRP projects deliver European measurement solutions for major societal challenges and provide common European inputs into standards and regulations.

Through EMRP, €404M was invested in 119 collaborative research projects involving 59 NMIs and DIs from 23 EMRP member states as well as NMIs and DIs in other European countries and globally. The research collaborations included over 350 academic groups and over 300 industrial participants.

The projects are developing new metrological capabilities, knowledge and skills and disseminating them to a wide range of potential users in the industrial, public sector and academic sectors and to the wider metrology community. To date the programme has delivered a significant number of research outputs:

- 715 peer-reviewed publications, a third of which are co-publications
- Over 3,000 conference presentations
- Contributions to 254 standards developing committees (such as CEN, CENELC, ISO, etc)
- Conducted nearly 570 training activities

- 19 patent applications

As two-thirds of projects are still underway the outputs will continue to increase considerably.

The on-going success of EMRP has increased the ambition for the successor initiative and has created confidence that EURAMET is able to implement an even larger and more complex programme than the EMRP. Therefore the European Metrology Programme for Innovation and Research, EMPIR, the successor programme of EMRP, has broadened the thematic scope, both in line with the EUROPE 2020 strategy and responding to the EMRP interim evaluation, in order to address the before-mentioned thematic challenges comprehensively.

The detailed technical challenges facing the European metrology landscape to prepare it for the future, to respond to current and emerging challenges and to facilitate innovation are described below in this SRA document.

Looking ahead

Even though substantial progress has recently been achieved, it has become evident that the European Metrology research system needs to tackle several additional challenges in order to ensure greater impact of metrology research on growth and solving socio-economic challenges. Plenty of metrological challenges in the areas of fundamental scientific metrology and associated with the grand challenges energy, environment and health, as well as metrological contributions to industrial innovation and standardization still need to be addressed.

The network of National Metrology Institutes in Europe is diverse with varying range of capabilities and developmental status. It includes strong global players with long proven track records as well as some recently established and emerging NMIs reflecting diversity of industrial development amongst member states. However, even for the large and advanced economies, NMIs are finding it challenging to provide a comprehensive range of measurement traceability and services to meet national needs. Increasingly this gap is being met by NMIs and DIs of other countries.

It is important to note here that certain end users, particularly SMEs, value measurement services being provided locally. Therefore, a delicate balance is required in the provision of a coordinated European measurement infrastructure that supports an optimum network of local and European centres. Smart specialisation should open up opportunities for NMIs in developing economies. Metrology capacity in these NMIs often have identified gaps such as lack of equipment and facilities as well as skilled manpower, which could be addressed through technical and management training by EURAMET members.

What is needed is a shared and common vision for the development of Europe's metrology infrastructure. Undoubtedly there are complex national considerations which have to be respected if we are to be successful in developing this common vision. Already, however, 50% of national metrology research programmes has been included in EMRP and the next 5 - 10 years will be very important for achieving a truly co-ordinated and shared metrology infrastructure.

EURAMET needs to continue to foster the development of internationally competitive centres of excellence in metrology, and to raise the overall level of metrology capability and quality of service across Europe. It needs to continue to facilitate complementary development, sharing of resources, avoiding unnecessary duplications, establishing joint facilities and supporting horizontal knowledge transfer amongst its members. EURAMET needs to continue developing a growing and sustainable metrology infrastructure, working even more closely with stakeholders.

Implementation of the SRA

Implementation of the EURAMET SRA will be achieved through a variety of mechanisms. It will be pursued by the EURAMET, its TCs, NMIs, DIs and research centres of excellence, championed by key stakeholder bodies, e.g. SDOs, European Technology Platforms[3], and supported through national metrology research programmes and international programmes, e.g. Horizon 2020 calls and European Structural funds, with. Most significant in these will be the European Metrology Programme for Innovation and Research (EMPIR), enabling collaborative, multi-disciplinary research to address the economic and societal challenges as well as in fundamental science to advance metrological capability.

Consultation process

This strategic research agenda has been developed in consultation with the EURAMET Technical Committees that have well-established links with key stakeholders in industry, business, governmental organisations, regulatory bodies, Standards development organisations, academia, and NMIs and DIs globally that have informed their strategies. Furthermore, three EURAMET Task Groups including external stakeholders, were established to cover the areas of health, energy and the environment. Task Groups and the TCs have provided inputs to the challenge driven sections of the SRA. Wider web consultation on the document will be carried out with our stakeholders prior to its publication in the autumn.

2 European Grand Challenges and Innovation

2.1 Health Grand Challenge

2.1.1 Key challenges

Healthcare is considered one of the major European Challenges and a strategic cornerstone in almost all EU R&D programmes. The positive impact that metrology can bring to this critical area means that EMPIR is no exception. In the upcoming decade healthcare will remain a top priority politically as well as socio-economically, and its importance will even be intensified due to demographic change and spiraling costs that put even the richest nations under pressure.

Total expenditure on health in the European region is 9.0% of GDP (2011)(7.9% in 2000) 4

*"Healthcare costs are rising faster than levels of available funding"*5

Notably, the EU is required by its founding treaty to ensure that human health is protected as part of all its policies, and to work with the EU countries to improve public health, prevent human illness and eliminate sources of danger to physical and mental health (EU Health Strategy "*Together for He*alth"[6]).

"As cancer is one of the major causes of ill health in the European Union, associated with a considerable cost to society, it is essential to invest in Europe's future health by taking long-term and sustainable actions to tackle cancer."[7]

A number of significant EU, WHO and other policy drivers[8,9,10,11,12,13] and foresight studies[14,15,16] highlight future healthcare challenges, and requirements for supporting research and technology development. Identified healthcare challenges within Europe include:

- Personalizing healthcare, an ageing population and the related rise in chronic diseases including cancer, neurodegenerative disorders and cardiovascular disease.
- Costly technological advances in screening, diagnostics and therapies.
- More knowledgeable patient demand, and a shifting paradigm from diagnosis and cure to predict and prevent.

Metrology has a critical role to play in addressing such health challenges. There is a significant challenge to develop the necessary metrology as diagnostic and therapeutic methodologies are constantly improved, sometimes with radical innovation, e.g. to ensure their safe and effective application. Recent and ongoing developments require new understanding of the measurand and novel application of biological, chemical and physical metrology. The solutions to many of these challenges require cross-disciplinary research that is best delivered through collaboration between the NMI community and external partners. Such collaborative research brings together different views, techniques and expertise leading to more general approaches and crossfertilisation of concepts. Many Horizon 2020 activities and other health programmes, e.g. European Human Brain Project, EuroBioImaging initiative and the Innovative Medicine Initiative, would benefit from complementary underpinning metrology.

A major trend in metrology for health is to provide not only standards and traceability to the SI but also to perform research and development for better, more advanced measurement procedures in order to improve the quality and comparability of diagnostic results and therapeutic outcomes.

Health metrology has a wide stakeholder base including regulators, clinicians, healthcare providers and related industries (e.g. bio/pharmaceuticals, in vitro diagnostics (IVD), advanced therapies medical products (ATMP) and medical technologies). Europe is a world-leader in many of these sectors, but lags behind North America and Asia in fast-growing technologies of the future. This is a key conclusion of the 2013 Innovation Union Competitiveness Report[17]. The report suggests that Europe risks falling behind in global growth markets such as health and biotechnology. It is worth noting that there is significant investment in health metrology outside of Europe, for example in China, Korea, Singapore and Brazil, as the necessity for healthcare metrology is recognized around the world. Given the global strength of Europe's medical technology and pharmaceuticals industries, as well as the patient led demand for improved treatments, it is imperative that European NMIs continue to be at the forefront of metrology in the sector. The NMIs have a responsibility to support this competitive edge by providing a robust metrological infrastructure and innovative and translational R&D on measurement procedures, international standards and advanced calibration facilities.

2.1.2 Current capabilities and the state of the art

NMIs have supported the healthcare community since their creation through the calibration of medical thermometers, blood pressure devices, audiometry instrumentation, etc. Metrology has contributed to better and more reliable healthcare results by underpinning comparability of measurements and quality assurance. This has been realized through the provision of applicable reference procedures, reference materials, reference data, and delivering traceability to primary or secondary standards, e.g. dosimetry for radiotherapy, cholesterol standards for in vitro diagnostics (IVD). As new treatments have been introduced new metrology has been developed to support them, for example in the field of radiotherapy with the introduction of new modalities. However, many modern innovations in the field require new, multidisciplinary forms of metrology. There is often a high financial cost to the development of metrology capability in this field, in terms of equipment and personnel, which means that collaborative research enabling access to medical expertise and facilities not usually available in NMIs and DIs is often the best way to meet emerging needs.

The health related projects in iMERA-Plus and EMRP have significantly improved the metrological capability in Europe. Combining expertise and resources led to fruitful collaborations with substantial results which otherwise were far out of reach for individual NMIs. The broad spectrum of topics - including breath analysis, brachytherapy, regenerative medicine, infectious disease diagnostics, external beam therapy, traceability of clinical measurements and MRI-safety - demonstrate the enormous diversity and interdisciplinary nature of the projects. Much of this research was exploratory in character and has served as an essential building block for a pan-European effort to tackle upcoming challenges for a much needed future metrology.

There is a considerable diversity in the health related metrology research capability through Europe, reflecting historical levels of investment and research in different NMIs – ranging from world-leading to some institutes being relatively new to the field. The collaborative nature of the iMERA-Plus and EMRP programmes has helped to develop knowledge of health metrology in NMIs to whom this has been a relatively new area. EMPIR gives the further opportunity for developing and extending capabilities in this critical area of health metrology.

The iMERA-Plus and EMRP projects involved non-NMI partners such as academics, clinicians and commercial organizations. This has been a successful way to operate as not only do those partners provide an insight into the end-user requirements, they also provide access to equipment and expertise that is not present in the NMI community. There is a good and expanding use of Designated Institutes where the expertise lies outside the traditional NMI community. This remains an excellent way to gain access to state of the art equipment and specialist expertise to facilitate metrological research. The partners have grown to recognize that metrology compliments their research, product development and treatment of patients and it is expected that such collaborations will be expanded in future research projects.

The original strategic outline of the EMRP for the field of metrology for health[18] was far-sighted and is in most aspects still valid and up-to-date, but not yet fully achieved – as would be expected in a sector based on long-term research. Some of the very promising and ambitious EMRP projects that have achieved their aims would benefit from extension of their activity in order to achieve sustainability and achieve greater impact. Other topics not yet selected for funding are still in demand and should be considered in future calls.

2.1.3 Key activities

Healthcare spend represented 9 % of GDP in 2010 in the EU[19] and is thus of the order of €1 trillion. The most prevalent causes of death in Europe are circulatory system diseases accounting for 39 %, cancer 26 % and respiratory 8 %[20]. However, the life expectancy has continuously risen over last decades due to better healthcare resulting in more survivors with chronic disease and thus a high socio-economic burden across Europe. Furthermore, the relentless rise in costs is not being matched with substantial improvements in outcomes. Our current system of deciding on treatments based on population-based studies is increasingly seen as being ineffective across a wide spectrum of therapies, and is exemplified by the problems of failing “blockbuster” drug development. For example, pharmaceuticals represent already 19 % of the total health spending[36]. Therefore it is clear that new methods are required that can identify the right patient for the right treatment at right point in time. Given the very significant spend on healthcare, improvements in metrological capability and the resultant enabled innovations have the potential for very significant economic and social impacts and benefits.

Priority areas for research reflect those of the Horizon 2020 Work Programme "*Health, demographic change and wellbeing*"[21] that addresses major health-related societal challenges and personalizing health care through its activities on:

- Understanding health, ageing and disease
- Effective health promotion, disease prevention, preparedness and screening
- Improving diagnosis
- Innovative treatments and technologies
- Advanced, active and healthy ageing with ICT
- Integrated, sustainable, citizen-centred care
- Improving health information

In response to these challenges, the EURAMET Health Metrology Task Group has considered the metrology requirements through stakeholder consultation (including two workshops) with input from the EURAMET TCs, policy organizations, end-users and technology providers. This review confirmed the underpinning metrology priorities for future European healthcare include the following key metrological challenges.

Measurements and imaging at the molecular and cellular level

Improved imaging and measurement methods and techniques at the molecular and cellular level are required regarding reliability and comparability of measurements, in order to support innovation in, for example, bio/pharmaceuticals, advanced therapies (encompassing gene therapy, cell therapy, tissue engineering, regenerative medicine and bio-artificial organs), targeted drug delivery, engineered/synthetic biology, and medical devices and technologies.

Developments are required, for example, to spatially analyse and map quantitatively the detailed chemical and elemental composition of samples such as biological tissues, solid surfaces or drug suspensions with emphasis on metrological traceability of results, and the repeatability and reproducibility of such methods. Combined spectroscopic and imaging methods for tissue environments would provide reliable and quantitative tools to facilitate research and innovation.

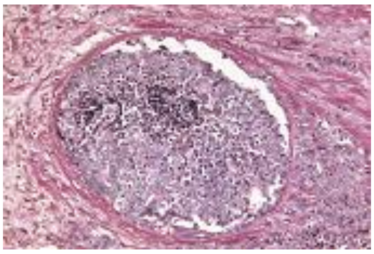
Quantitative diagnostics

Metrological research is required to enable an improvement of quantitative diagnostic methods and for achieving comparability of complementary quantitative diagnosis for quality assurance and reproducibility. This forms the basis for improvements in patient care, predictive and preventative medicine, stratified and personalized medicine and screening, and include point of care testing.

Metrological traceability of results from quantitative diagnostics is still underdeveloped, resulting in substantial retesting of patients when transferred from one hospital to another. Developments for enabling traceable and reliable measurements in diagnostic techniques are required especially in

- biomarker measurements - particularly with respect to measurand definition and challenges of traceability to SI, trace level detection in complex biological systems and realising traceability for multiparametric biomarker measurement

- imaging - improved resolution, sensitivity, quantification and discriminating power of images, e.g. ultrasound, MRI, PET, SPECT, bio-imaging for diagnosis and also for assessing therapies,
- multi-modal diagnostic processes,
- real-time imaging for guiding therapies, and
- improved measurement function of medical devices.



Improvements in the reliability of point of care testing is urgently required, as these tests have the potential to provide rapid diagnosis with consequent patient benefits and potentially reduced financial costs, but at the same time are performed by non-specialists.

Supporting innovation in healthcare

Innovations in healthcare that will deliver

- real-time and non/minimally invasive measurements,
- personalised healthcare, and
- modern therapies,

require metrological research and development in clinical applications to guarantee quality assurance, reliability and comparability of measurements. The acceptance, safety and efficacy of diagnostic procedures and therapies will be assured through such activity.

Innovative practices require metrology developments such as e.g. standards, agreed protocols, quality system procedures, reference phantoms and measurement procedures. Examples include

- dosimetry necessary to underpin the clinical introduction of new radiotherapy modalities, e.g. combined MRI-radiotherapy where the effect of the magnetic field on the delivered dose and its efficacy needs to be established,
- in sophisticated therapy using Hadron radiation,
- characterization of radionuclides for their use in molecular radiotherapy,
- precision medicine - more effective measurement of diagnostic / monitoring biomarkers and increased integration with more patient specific therapies e.g. quantification of the biological effect of treatments to facilitate personalised medicine, measurement of biomarker signatures for cancer, cardiovascular disease or neurodegenerative disease and stratification of targeted therapies based on tumour ‘omic profile,
- novel rapid diagnostic and screening approaches for pandemics and anti-microbial resistance,
- standards for acquiring and storing large multiparametric datasets of clinical multi-centre studies,
- standards and new metrology tools for ensuring compatibility of medical devices and measurement procedures,
- novel metrological approaches and standards to underpin safety and efficacy measurements for emerging gene and cell therapies and engineered tissues and organs.

Further innovations in healthcare will increasingly necessitate greater interdisciplinary metrology application e.g. nanomedicine will drive interface between biochemical with biophysical metrology, and synthetic biology and genome editing will drive interface with biochemical and modeling and engineering disciplines.

Health protection

Metrology plays a critical role supporting the health protection of citizens, for example in food safety, radiological and noise (hearing) protection, combating antibiotic resistance, and infectious disease diagnostics and monitoring. Unsafe food containing harmful bacteria, viruses, parasites or chemical substances, causes more than 200 diseases - ranging from diarrhoea to cancers.

Specifically for food safety, improved qualitative and quantitative measurement methods and standards are required for traceable analysis of residues and pathogens (viruses, bacteria, toxins) in foods and food substances. Of most concern for health are naturally occurring toxins and environmental pollutants.

Procedures for enabling comparability and reliability of measurement results have to be developed. This requires the extension of the existing metrological structures, to deal with the specific challenges of detecting substances and pathogens, and with biological measurements.

New therapeutic and diagnostic methods with their sophisticated radiation fields require metrological improvements in dosimetry for radiation protection of occupationally exposed medical staff. This comprises the establishment of traceability and dissemination in dosimetry, the development of new dosemeters and standards for quality assurance as well as improved accuracy and reliability in dosimetric services. Furthermore, understanding of the risks to the human arising from the radiation around nuclear medicine facilities (neutrons, photons, pulsed fields) needs to be developed further.

Last but not least, there is a need for improvement of data gathering and analyzing methods, the calculation of GUM-uncertainties to strengthen the current and upcoming experimental and instrumental techniques. One of the target areas for making such improvements is the group of imaging techniques, which are increasingly used for quantitative diagnosis, and multiparametric measurements. The evaluation of measurement uncertainty is critical in supporting all kinds of decisions taken on the basis of medical and diagnostic data. Both for personalized healthcare as well as for improvements in medical, clinical, epidemiological studies, and for “big data” scenarios the experience of the metrological community in calculating uncertainties, risks and probabilities is key.

2.1.4 Key outcomes

EURAMET aims to support European industries providing healthcare products and devices with reliable metrology and testing regimes that provide help in meeting regulatory requirements, improving accuracies and efficiency, and reducing time and cost of bringing products to market without increasing risks to patients.

It is envisaged that ambitious, large-scale approaches that are beyond the capabilities of single NMIs and DIs, bringing together multidisciplinary teams, will be required. To enhance the impact of the R&D, the involvement of the user community such as medical practitioners and industry, as appropriate, is necessary.

The expected key outcomes of the metrology research and the development in the grand challenge health includes:

- Metrology and reference measurement systems to support improved, robust, reliable, less invasive and more comparable clinical measurement by healthcare professionals including medical physicists, clinical chemists and pathologists to enable a high level of quality assurance in the clinics & hospital laboratories
- Reduced uncertainty and enhanced comparability and stratification across the range of clinical and diagnostic healthcare measurements, both supporting patient and doctor confidence in more personalized therapeutic decisions, and reducing costs associated with repeated testing and administration of ineffective therapies
- Guidelines and written standards to achieve harmonization between different measurement devices, techniques, and diagnostic modalities
- Determination of fundamental data, algorithms and creating common databases needed for comparing new data analysis tools to prevent wrong medical decisions
- Measurement devices and reliable procedures for new techniques in diagnostic and therapy to enable their introduction in clinical routine and hence to support the European healthcare industry.
- Metrology support for regulatory and quality Standards compliance of new IVD devices and medical instruments, including novel POC and rapid screening tests
- Enabled development and enhanced end user confidence in safety & uptake of novel and advanced therapeutics and targeted therapies and pharmaceuticals
- Creation of an interdisciplinary infrastructure dedicated to metrology in health
- Creation of a network of metrology institutes (NMIs, DIs), international key healthcare organizations, clinics, patient advocacy groups and healthcare companies working towards improved healthcare measurements

2.2 Environmental Grand Challenge

2.2.1 Key challenges

The European Union (EU) have stated that "Environmental quality is considered central to health and well-being.", and have introduced laws "… to ensure the careful use of natural resources, to minimise adverse environmental impact of production and consumption …" Furthermore, the EU strives for "... tighter environmental standards and for effective action against climate change"[22].

The key environmental challenges facing Europe have very significant costs associated with them. To address these challenges, "the EU has agreed that at least 20 % of its €960bn budget for the 2014-2020 period should be spent on climate change-related action." Furthermore, there will be significant costs for adaptation actions to alleviate the effects of climate change[23]. As highlighted by an EC impact assessment[24] "The minimum cost of not adapting to climate change is estimated to range from €100bn a year in 2020 to €250bn in 2050 for the EU as a whole[25]." The EU's General Union Environment Action Programme to 2020 'Living well, within the limits of our planet' states: "In 2011, disasters partly due to climate change resulted in global economic losses of over €300bn.

Many of the challenges that Europe faces in order to promote innovation and ensure sustainable growth in the future are dependent on addressing environmental grand challenges, specifically in the areas of climate change [e.g. Directive 2003/87/EC [26]], and environmental sustainability and pollution [e.g. Directives 2004/107/EC[27], 2008/50/EC [28] , 2000/60/EC [29] , 2010/75/EU [30] and 2002/49/EC [31]]. Furthermore, there are international protocols and treaties to which the Member States in Europe are party, e.g. Geneva Convention on Long-range Transboundary Air Pollution[32], Kyoto Protocol[33], 'Rio +20'[34], and Minamata Convention on Mercury[35] that demand and drive international collaboration on environmental metrology.

"To prevent the most severe impacts of climate change, the international community has agreed that global warming should be kept below 2 °C compared to the temperature in pre-industrial times."[36]

"Preventing dangerous climate change is a strategic priority for the European Union."

"Reining in climate change carries a cost, but doing nothing would be far more expensive in the long run."[15]

It is essential that European (and global) policies on reducing anthropogenic effects on climate and implementing appropriate adaptation measures to climate change need to be based upon sound science and valid climate change predictions. A holistic view, based on comparable data, encompassing the atmosphere, oceans and land as well as solar and terrestrial radiation is essential for reliable climate change modelling.

" 'Uncertainties about the extent of future climate change' and 'unclear responsibilities' were both seen as barriers by a large number of countries [to taking action to adapt to climate change]."37

Understanding and predicting climate change necessitates climate monitoring. Reliable climate predictions require quality models, traceable data and uncertainty budgets. Clearly, metrology has a critical role to play in monitoring, understanding and predicting climate change.

"This means not only to understand climate change but also to establish on the best possible scientific foundation the climate information services expected by decision makers." [38]

EU policy on environmental pollution and environmental sustainability, as illustrated by the General Union Environment Action Programme to 2020 '*Living well, within the limits of our planet*'[39] has targets on various aspects of pollution; for example:

- achieving good environmental status (GES) of EU marine waters by 2020 [40,41,42],
- achieving air quality that does not impact negatively on human health or the environment[43],
- reducing noise pollution[44,45],
- continued implementation of REACH and support for the objective of a non-toxic environment[46,47],
- addressing safety concerns related to nanomaterials and materials with similar properties, and
- ensuring the promotion of an economically, socially and environmentally sustainable future for our planet, for example to support the aim of halting global forest cover loss by 2030.

The successful implementation of such policies requires the necessary underpinning metrological capability to enable their enforcement. As legislation on environmental concerns becomes more stringent, with limit values decreasing and new types of pollutant being encompassed by the legislation, the metrological capability needs to be further developed to support robust, fit for purpose monitoring and enforcement capabilities.

"The 7th Environment Action Programme (EAP) shall contribute to a high level of environmental protection"[48]

Key European environmental challenges:

- Climate change and adaptation
- Pollution and emissions reduction
- Environmental and resource sustainability

Traditionally operating in individual fields, metrology has focused on the improvement of standards for units, carrying out independent research and dissemination. Such an approach allowed achieving knowledge, experience and top level practice in measuring almost any quantity and evaluating uncertainty. Further activities are required in metrology to address the measurement needs expressed by global key institutions such as WMO, GCOS, GAW, IPCC, FAO, IPPC to provide environmental traceable measurements with reliable uncertainty. This means better comparability as well as lower uncertainty and a larger volume of high quality stable standards and reference materials that meet the objectives of these organizations and the global demand for data quality. To reach higher effectiveness, it is essential to combine the expertise achieved in the individual, traditional fields of metrology into new interdisciplinary and multidisciplinary (ID-MD) strategies to be developed and embraced by NMIs as well as the RMOs. Valuable advances and benefits to the society will be achieved if metrologists work under this new ID-MD strategy.

2.2.2 Current capabilities and state of the art

Under the EMRP, the targeted interdisciplinary programme *Environment* 2010 call has delivered valuable results and advances in improving traceability and measurement capabilities for climate and environmental monitoring, as well as the activities planned in the 2013 call on the same programme[49]. New advanced measurement facilities and calibration capabilities were developed. Comparisons were carried out and results benefitted end users, instrument manufacturers as well as metrology laboratories having to deal with instruments used in field measurements for environmental, meteorological and climate investigations. Seminars, trainings, workshops and conferences[50] were organized to make the two communities meet and get mutually involved in common activities.

Metrology in support of the climate change studies deals with a complexity of techniques to measure and record the many "Essential Climate Variables" (ECVs) as defined by GCOS[51]. Grouped in three main domains: Atmospheric, Oceanic and Terrestrial, those variables require a multitude of instruments and methods to be traceable and comparable irrespective of location and time. Remote observation of the Earth from satellites for measurements of atmospheric chemistry, surface radiation budget, and ocean and land cover properties as well as surface based measurements for atmospheric monitoring and soil, snow, ice, deep water and permafrost properties generate daily amount of data requiring robust quality assurance. Only through collaborative European effort, provided previously by EMRP and now by EMPIR, can NMIs contribute to the necessary advances in measurement quality. Activity is required to link to the SI the important variables and to enable rigorous assignment of uncertainty to multi-decadal climate data records which are representative of the globe but derived from local samples.

Past EMRP projects on local pollution have focused on air and water-borne contaminants and on radioactive pollutants. For airborne particulates, metrics that are currently and commonly used are not the most effective when describing effects on human health, and also have limited validity for application to nanoparticles. Emerging parameters are potentially more reliable as indicators of possible health effects, but the metrology for them is not well established and often lacks traceability. The next generation of air quality legislation is being held up as a result of these deficiencies and this need to be addressed urgently. Metrology R&D is required for this and also for other pollutants where current metrological capability does not satisfy requirements – especially for low concentration and isotopically matched reference materials.

Facilitated and encouraged by EMRP projects, metrologists from European NMIs are now members of institutions and committees dealing with environmental issues, e.g. WMO commissions, GAW, ISTI, GCOS GRUAN, BSRN, IRS, GEO and CEOS. Conversely, experts in meteorology and climatology now participate in working groups and task groups of CIPM's CCs and EURAMET. Such inter-exchange of memberships has been established in recent years through the activities carried out by NMIs mainly within EMRP projects and supported by long-term visions. This mutual involvement provides a sound basis for plans aimed at delivering valuable results and impact to society. It ensures relevance to the user community and thus technology uptake, and should be extended to the numerous Institutions dealing with environmental activities.

NMIs have provided critical support in validating the data used to generate climate projections and in providing standards for the evaluation of historic climate records. However, suitable measurement methods to securely transfer traceability to the end user are missing (e.g. monitoring laboratories in the field, including in remote locations).Therefore, additional research efforts beyond the provision of national standards are required. Measurements in a monitoring laboratory must be traceable and of a sufficient quality to meet the legal and scientific requirements at reasonable costs. In many cases the standards or methods need to be autonomous in nature, where stations or test-sites are unmanned.

Facilities developed by some NMIs under the course of the EMRP environment projects, such as stationary laboratory or transportable and mobile systems for the calibration of temperature, pressure, radiation, gas analysis sensors are now available or have to be developed to improve calibration and to evaluate novel wireless, low-cost and miniaturized sensors with respect to their characteristics and dynamics. An example is for assessment of the Day Temperature Range (DTR), considered a robust indicator to capture climate trends. Such low cost sensors may help establish economically viable spatially dense field-based networks, e.g. for noise measurement in urban and marine environments and air monitoring. Furthermore, multi-parameter distributed measurements for environmental monitoring (regulatory) and security (e.g. detecting toxic aerosols in air) are also emerging.

2.2.3 Key activities

The EURAMET Environmental Metrology Task Group has reviewed the metrology requirements of EU policies and directives, of other policy organizations, end-users and technology providers, along with input from EURAMET TCs. This has identified underpinning metrology challenges to address the European environmental challenges, including the following.

Metrology for climate monitoring and meteorology

Metrological research and development supporting climate change understanding, monitoring, modelling and forecasting, is required in a number of areas and for a numerous measurands, each presenting its own challenge.

- Climate change is mainly based on **surface air temperature trends**, mostly obtained from records of meteorological observations. Future reference-grade ground based stations for the generation of temperature data purposely designed for climate trend records need metrological support in evaluating sensors characteristics, calibration and measurement uncertainties, and in defining data qualities and target uncertainties. For lakes, sea and ice surface temperature profiles there is need for homogenous methods of measurement. Permafrost temperature is a key parameter in paleo-climatology and geology: measurements practices are emerging but further work is needed to establish dedicated calibration procedures and uncertainties evaluations for sensors immersed in boreholes.
- Physical and chemical properties of the atmosphere, i.e. its physical state, the chemical composition as well as the essential transport processes by means of optical remote sensing methodologies and local “in situ” sensing techniques, focusing on establishing traceability in measurements and the evaluation of uncertainties, for important

atmospheric constituents and their precursors, reaction partners and isotopologues of the atmospheric Water-, Ozone-, Nitrogen-, Carbon- and Sulfur-cycles, and other reactive climate change relevant gaseous components.

- Metrological developments for accurate particulate, aerosol and nanoparticle detection and traceable characterisation of important particulate metrics like size, size distribution, optical properties etc.
- Establishment of traceability and data quality for atmospheric and soil humidity.

- Metrology for determination of relevant parameters in the marine environment (such as sea water salinity, density, pH, composition, heat capacity, sound of speed and dissolved oxygen content) where metrological traceability and accurate measurement are key challenges .
- Metrology to establish and underpin traceability of key ECVs related to land processes, vegetation and the carbon cycle are in urgent demand. Forests are major natural sinks of carbon: however there is no reliable traceable method to establish an uncertainty estimate for the quantity of stored carbon. Here, many of the challenges relate to the complex nature of biological parameters and how they relate to physical measurands such as reflectance and fluorescence.
- Climate trends in the **arctic regions** are significantly amplified [52, 53]: accurate measurements to quickly capture trends are there of unique importance at a global scale. As climate change melts arctic permafrost, it releases large amounts of methane into the atmosphere, creating a feedback loop that triggers additional warming. Global warming also reduces the iced surface in the arctic and anticipates the snow melting day in land areas, changing radiative equilibrium thus amplifying the feedback. The **extreme ranges of variability** of the key-quantities measured requiring higher accuracy than for other areas need dedicated calibration procedures and specific uncertainty evaluation. The **logistical difficulties** in reaching, removing, handling instruments for the calibration campaigns require self-validating in situ measurements and calibration devices operating in **arctic-based research stations**.
- Improved earth observation for climate monitoring using remote sensing techniques is becoming increasingly common and important. Continued development for improving the accuracy and traceability of space and surface based observations of the Earth and Sun are required to meet the needs for long term and global climate data sets. The challenge includes the **traceable linkage between space based and surface based remote sensing measurements**.
- Historical archives used to evaluate climate trend are mostly based on data from meteorological observations. Small to medium scale of **network of reference stations**, purposely installed for climatology are missing and required for the future work of harmonisation and homogenisation [54]. The joint work of NMIs is needed to carefully evaluate all the metrological aspects of such stations networks and collaborate with WMO (CIMO and CCl) for the transnational agreement required, towards a recognized standard at European level, comparable with other already existing networks[55].

Metrology for pollution and resource sustainability

Key metrology challenges for pollution monitoring and in support of resource sustainability include:

- Comparable, accurate and traceable measurements and reference materials are required to evaluate the presence and fate of currently measured and **emerging pollutants in air, water and soil.** Metrological research should also include for the evaluation of carbon sequestration technologies. In many cases, the legislative requirements for measurements are technically very challenging with respect to the relevant concentration ranges as well as the accuracy. In this respect, the development of reference materials and reliable analytical techniques at trace and ultra-trace level, such as hyphenated and fractionation techniques enabling speciation, are essential.

- New and improved metrics and metrology needs to be developed to characterize **particulates** in the environment with focus on particulates in ambient air. Traceable measurements are required for size, number concentration, mass and surface area for particles from a few nm up to several µm, especially at low concentrations and for nanoparticles of different type and morphology. The chemical composition of particulates also remains a key issue for air quality. Robust measurand definitions and measurement methods are required for emerging pollutants and for quantities of interest of particulates, e.g. Cr(VI), oxidative capacity and total carbon.
- There is need to considerably improve the **dosimetric and nuclide specific information** received in real-time and minimizing environmental impacts by developing mobile systems for rapid in-situ measurement to monitor the vicinity of the nuclear facilities (power plants, industrial and medical) during the operation, the decommissioning and in case of accidents. The development of improved measurement systems for free release measurement is also required together with characterisation of radioactive waste. The development of traceable calibration, new reference materials and appropriate technical procedures for measurement and monitoring systems are required.
- Development of metrology for **environmental forensics** and **monitoring the worldwide trade of environmentally critical products** e.g. validated methods and reference materials to verify the geographic and biological provenience of natural products, the origin of fuels, and for identifying the source of pollutants.
- Metrological development for monitoring environmental **noise pollution** in air and in the marine environment, to protect the citizen and enable sustainable exploitation of the environment. Particular opportunities are presented by the emergence of low cost sensors with potential for a network approach to gathering data, with consequent new demands for supporting metrology.

Generic challenges for environmental metrology

Underpinning metrological support is required to develop complex data analysis techniques, to establish traceability and evaluate uncertainties, thus adding value to the interrogation of multivariate data sets that are now routinely produced.

Specific emerging techniques and methodologies with (potentially) well-defined traceability are of considerable importance for environmental, meteorological and climate studies. High resolution spectroscopy, for example, can serve for hygrometry, chemistry (air quality), ionising radiation protection and more. Furthermore, and as supported by EU Decision 1386/2013/EU[56] "*Many environmental challenges are global and can only be fully addressed through a comprehensive global approach ...",* collaboration not just within but beyond the borders of Europe needs to be encouraged in order to reach international consensus on metrological best practice.

Assurance of traceability from NMIs and DIs to end users requires overarching activities including understanding the measurement requirements of field work, calibration transfer protocols, reference materials and devices, and training of technical staff. Links with existing networks and measurement programmes need to be reinforced where existing, and established where appropriate. Metrology activity should also be targeted to (i) supporting and ensuring the continued quality of long term activity, e.g. GCOS GRUAN and WCRP Polar prediction, (ii) challenges concerning the provision of artefact standards over long periods of time, e.g. gas reference standards; and (iii) accommodating the use of established scale parameters, e.g. for salinity, ambient CO_2 and CH_4, where full traceability to the SI is not provided or can be improved, and (iv) improving the accuracy of sampling methodologies, such as the for industrial emissions, and the reliability of data modelling used in environmental studies.

2.2.4 Key Outcomes

The opportunity to involve expertise on key techniques developed outside the traditional metrology fora will be a key element for the success of the environmental metrology strategy. By combining individual measurements through pursuing a novel strategy involving simultaneous multi-parameter measurements and interdisciplinary and multidisciplinary work, the metrology community will achieve novel capabilities and expertise. From such approach, expected outcomes will include:

- comparability of the rapidly increasing quantity of data obtained by a multitude of measurement systems, locations, instruments and methods;
- development of improved measurement methods, calibration standards and guidelines across a variety of technical disciplines as a the result of coordinated research and interaction with relevant stakeholder communities;
- development of novel calibration facilities (including in-situ) , to provide full traceability to stations measuring key parameters for climate, meteorological and the environmental science;
- direct impact and traceability to environmental and climate science R&D through joint activities for implementing metrology laboratories outside of NMIs and DIs, with focus on remote locations such as polar regions and oceans;

- a collaborative support from metrologists addressing the effort started by the climate community in soliciting for the creation of reference networks of comparable surface stations[57];
- delivery of high quality data for accurate determination of trends in global temperature anomalies and in atmospheric trace gases, and in understanding atmospheric processes;
- the creation of common infrastructures and working groups between the metrology and meteorology and climate communities to allow the establishment of robust, durable and unambiguous communication paths, to make progress faster towards a sustainable society;
- support to EU in implementing regulations and formulation of new and better targeted policies in environment through providing standards and reducing uncertainties in calibration and measurements, to reduce the impact of pollution and the cost of damage to health and environment.

Metrology has a key role to play for improving climate predictions to support mitigation and adaptation policies, and for protecting the environment through its role underpinning pollution monitoring and environmental protection. Through the actions here proposed, metrology will further its unique contribution to the benefit of the European society, economy and the environment.

2.3 Energy Grand Challenge[58]

2.3.1 Key challenges

World energy consumption continues to grow. Demand is projected to increase by 37 % to 2040[59] and despite a growth in energy supply from renewables, fossil fuels continue to dominate supply across all regions. The EU-28's import dependency for fossil fuels (53.4 % in 2012) means that it is very sensitive to price fluctuations in the global market[60]. In addition Governments' carbon reduction targets and consumers' expectations of a secure and affordable supply present significant challenges to the sector.

A broad consensus has emerged amongst policy makers, the energy industry and energy campaigners globally that the energy 'trilemma', first coined by the World Energy Council in 2011, succinctly encapsulates the challenges faced by Governments, industries and societies across the world. The trilemma refers to the following three key drivers of energy policy across the globe:

Key energy challenges:

- Reducing carbon emissions
- Maintaining affordable energy
- Securing energy supply

The sustainability of the energy mix and the efficiency with which energy is generated, transformed, transported and used are key aspects of this trilemma that impact both the affordability and security of supply.

Reducing carbon emissions

Tackling climate change by reducing emissions of carbon dioxide has enormous implications for the energy sector, which is responsible for 70 % of global CO_2 emissions (CO_2 emissions from fuel combustion, IET, 2014). The sector's enormous contribution to emissions sees it heavily impacted by the European Union's drive to transition to a low-carbon society, as reflected in the 2020 targets of the EU climate and energy package.

The EU's climate and energy package set targets for 2020 of:

- Reduction in EU greenhouse gas emissions of at least 20 % below 1990 levels
- 20 % of EU energy consumption to come from renewable resources
- 20 % reduction in primary energy use, achieved by improving energy efficiency

The EC proposes that these goals can be met by:

- electrification of the energy market,
- increasing low carbon technologies in the electricity mix from around 45 % today to 60 % in 2020,
- developing and integrating smart electricity grids and technologies enabling distributed generation, electrification of transport, and to respond dynamically to demand side efficiency, and
- implementation of the EU Directive on Energy Performance of Buildings requiring all new buildings to be zero-energy from 2021 onwards.

The EU estimates the level of public and private investment to meet the 2020 targets to be €270bn per year.

Maintaining affordable energy

Access to secure sources of clean, affordable energy is critical to the well-being of nations and their economic stability and growth. Pressure is being put on global energy supplies by the rapid industrialisation of countries such as China and India. This increased demand is reflected in rising energy prices and real concerns over the long-term security of energy supply.

Emission reduction targets and the implementation of new regulations are forcing the closure of existing power plants and increasing pressures on energy generators. With natural resources and their use in traditional fuel plants in decline and global demand for energy rapidly growing, both competition for supply and price are rising.

Rising prices can be buffered by differentiating the fuel mix that Europe is dependent on, developing capacity in European-based low-carbon energy sources and thus reducing its reliance on imported fossil fuels. The development of new technologies for low-carbon energy generation, electrification and smart grids, and improved energy efficiency also provides economic and social benefits. In 2011, investments in renewable energy almost reached the level of investments in power generation based on fossil fuels. Globally, they have passed $250bn[61].

Security of supply

The large increase in energy demand has been reflected in a corresponding increase in supply. But energy demand is still primarily met by oil, natural gas, coal and peat. Notable changes in supply have been an expansion of nuclear power since 1995 and a growth in renewables from 5 % of the energy mix in 1995 to 11 % in 2012 (EU Energy in figures, Statistical Pocket Book, 2014). Given its reliance on fossil fuels and therefore energy supplies from outside of Europe - the EU imports over 60 % of its gas and over 80 % of its oil – the current situation does not reflect a reliable and secure energy mix.

The volatility of availability and price of natural resources and the need to meet clean energy targets are driving the EU and member states to diversify their energy supplies to ensure that a secure mix of clean and affordable energy remains available to their citizens and industries. This drive to increase the diversity of the energy mix has seen a large investment in renewable and low carbon energy generation[62].

However, investment in clean energy technology alone will not address the short to medium term concerns over security of supply and affordability. In Europe, fossil fuels provide for more than 50 % of the electricity production. Therefore, R&D is required not only to support the development of low carbon and renewable energy sources but also to drive greater efficiencies and lower carbon emissions in traditional fossil fuel-based generation.

Addressing the three drivers of the energy trilemma will require significant investment in research and development (the EC estimates over €270bn annually[63]). Metrology is a critical aspect of this investment providing underpinning measurement capabilities, standards and guidance needed to ensure that policy and regulatory targets are met.

2.3.2 Current capabilities and state of the art

Most of the modern innovations in the field of energy production, transportation and consumption require new and interdisciplinary areas of metrology. Within the EMRP calls of 2009 and 2013 under the theme of 'Energy', NMIs and DIs have been running a number of research projects that have significantly improved the metrological capacity relevant to the energy sector in Europe. In these projects, the institutes have been jointly exploiting their extensive experience and diverse facilities in a wide range of metrology fields related to energy. These collaborative efforts appeared extremely fruitful, yielding valuable results which otherwise could not be achieved by individual NMI's.

The spectrum of topics addressed by the joint research projects is very broad, reflecting the diversity of energy applications and the required metrology. A major part of the projects under the 2009 and 2013 EMRP 'Energy' scope are concerned with metrology for energy generation, both conventional and carbon-based generation as well as generation via more sustainable, renewable energy sources. Specifically, projects were launched to aim for:

- Making large scale power plants more efficient by improving the metrology of critical monitoring and control parameters.
- Enabling a new generation of nuclear power stations, addressing measurement challenges posed by new designs.

* Acceleration in making biofuels and renewable gaseous fuels (biogas and/or hydrogen) part of the future European fuel mix via reliable measurement of their key properties, to assess their quality and increase safety.
* Getting data and valuable metrological information for the multiphase production of oil and gas, and the inline detection of viscosity of non-Newtonian fluids in the energy sector.
* Developing metrological tools required to increase the efficiency of current photovoltaic (PV) devices and to enable the production of the next generation of solar cells. Further-more, realisation of a new classification system of PV devices based on their energy production under different operational conditions.
* Delivering calibrated measuring standards and procedures for accurate measurement of vital drive train components used in renewable energy systems such as wind farms.

Further projects aimed to improve electricity transport and increase energy efficiency via:

* Realisation of the metrology infrastructure required for the successful implementation of smart electrical grids and high-voltage DC transmission lines, to cope with the increasing decentralization of power generation and the need for low-loss long distance electricity transport.
* Development of advanced voltage and current sensors for future power grids.
* Enabling natural gas trading in liquefied state (LNG) to facilitate new “medium and small scale” use, like in ground and maritime transportation (vehicles, trucks, trains, and ships).
* Development of metrological tools needed for introducing new energy efficient lighting.
* Enhancing energy efficiency through energy harvesting.

Finally, two projects relate to the characterisation of new materials relevant for the energy sector, such as the structure and unique mechanical, electronic and thermal properties of thin films and fibre reinforced plastics.

Most of the projects have been multidisciplinary, covering several fields of chemical and physical metrology. Together, they delivered many new measurement techniques and methods, sensors, calibration methods and facilities, data sets and best practice guides. This has enabled the energy sector to make significant steps forward in improving energy efficiency and reducing greenhouse gas emissions.

Even though important advances have indeed been achieved in the EMRP projects, the challenging European target in reduction of greenhouse gas emissions can only be reached with significant further metrological developments. Clearly research is needed in areas with no or limited present metrology activity such as energy storage, energy conversion, electrification of transport, and energy efficiency. But also many of the challenges already worked on are so extensive that several (successive) projects are required to cover all needs expressed by European industry and policy makers.

The metrology challenges in the energy area typically require a hitherto unexplored range of interdisciplinary research that not only develops new laboratory standards, but also delivers new methods and instrumentation that are able to achieve sufficiently accurate and reliable results under harsh on-site, industrial conditions.

2.3.3 Key activities

In comparing the 'energy trilemma' and the related metrology challenges to the present state of the art, it is clear that significant research effort is required to achieve the ultimate aim of a European-wide sustainable, affordable and secure energy supply. Following review of key energy strategy documents (4.3.1), the EU SET-plan and input from the EURAMET TCs, the EURAMET Energy Task Group has identified the following key underpinning metrology activities along the energy chain from production, through transmission and storage, to end-use, as well as cross-cutting themes such as energy efficiency and new materials.

Metrology for Energy Production & Conversion

One of the key ingredients for solving the energy trilemma is the increased uptake of renewable energy sources (RES) in the European energy mix, such as wind and solar energy via photo-voltaic (PV) cells and concentrated solar power (CSP). In practice, there is an enormous variation in renewable production size, ranging from large-scale wind parks down to local domestic solar panels. Renewable energy metrology challenges relate to the characterization of critical components in the variety of renewable energy sources, as well as to measurement tools for monitoring and improving their performance and effective life time. These results should feed into new industry standards.

Given the present low share of RES to the total energy production and their limited output predictability, conventional carbon-based and nuclear power plants will remain crucial in the coming decades for ensuring the continuity and security of our energy supply. At the same time, novel gas and biomass fuelled power plants are being developed with reduced environmental impact. In order to optimize their effective and safe operation, it is necessary to develop more accurate and precise temperature, humidity, flow, radiation, pollutant emissions and electrical measurement tools for monitoring and controlling processes in such power plants and combustion facilities. For biomass combustion plants, systems for reliable field measurements of fuel properties, fuel consumption and particulate emission are needed. Combined with development and metrological characterization of new materials used under extreme conditions in these plants, this will lead to increased efficiency in energy production.

With the increasing variety of energy sources in the energy mix, the importance of efficient conversion between different energy sources increases as well. Measurements are indispensable for characterization of critical components and for achieving insight in the energy conversion process, such as in heat pumps, fuel cells, transformers or motors. Determining the efficiency of the conversion process requires an interdisciplinary approach, with uncertainty requirements that become extremely challenging as the conversion efficiency approaches 100 %.

Metrology for Energy Transport & Storage

An affordable and secure energy supply requires an extensive infrastructure to transport energy from the production location to the end-users. At present, electricity and gas grids are the main infrastructure to serve this need; they face significant new metrology challenges given the increasing amount of RES.

The limited predictability in the daily and even shorter-term fluctuations of RES, combined with large new loads such as electric vehicles, challenges the stability of the electricity grids and endangers both the security and quality of our electricity supply. This calls for development and in-situ application of fast, synchronized measurement devices for grid phasors and grid power quality. Grid modelling should not only determine the best location of these devices, but also support their application to new grid monitoring and control tools such as real-time source location of bad power quality or grid instability. To connect the new instrumentation to the grids, novel non-invasive wideband instrumentation transformers are needed, compatible with present grid automation standards.

The increased injection of biogas, biomethane and hydrogen into natural gas networks requires more research in determining energy content for trade (billing) via fast and accurate gas-composition analysis and also accurate detection of dangerous compounds for human health and safety of appliances.

Storage is required to smooth the discontinuous energy production of renewable energy sources and to support balancing energy production and demand. Storage technology is diverse and ranges from batteries, fuel cells, flywheels, thermal storage and to pumped hydro-power. One further example is Power-to-Gas technology, to convert surplus electricity into hydrogen subsequently fed into the natural gas network or used directly for vehicles or industrial processes. Metrology support for storage applications concerns measurements to characterize and better understand the storage process and to determine its efficiency.

Metrology for Energy Use

A very significant way of contributing to realisation of the Energy Trilemma is a reduction in energy use – one of the three targets of the EU's 2020 climate and energy package. Any energy not used, does not need to be generated and thus directly contributes to a reduced environmental impact, such as CO_2 emissions and waste.

Energy reduction first of all can be achieved by increased customer awareness on their energy consumption, based on advanced energy measurement technology such as the next-generation smart electricity meters and specific sensors for gas quality and heating values.

A major contributor to reduced energy use is enhanced energy efficiency, as recognised by the third EU 2020 energy and climate policy goal. Since ventilation, cooling and heating is very energy-intensive, a significant contribution in energy saving can be made via calibrated tools for controlling and optimizing the heating, cooling and air conditioning of buildings. This is particularly important given the EU directive[64] to have new buildings energy neutral in 2021. The Energy Efficiency Directive (2012/27/EU) sets the principle that energy costs allocation should be based on actual user's consumption. Insofar as thermal energy is concerned, the accuracy of existing individual heat meters is often inadequate, which implies a need for R&D in that area. In the Ecodesign Directive[65], the EU places energy efficiency requirements on a large series of instruments and appliances whereas in many cases the metrology infrastructure to actually verify the compliance on industry products against this directive is lacking or incomplete. For example, traceable measuring techniques need to be developed for the characterization and certification of new Solid State Lightning devices like LEDs and OLEDs, for grid power transformers, for motors, and standby power. It is expected that more metrology challenges arise as the EU expands the range of products falling under this Directive.

Road, rail, water, and air transportation is another energy-intensive industry sector, where significant advances can be made by moving to more sustainable energy sources such as electricity, hydrogen or natural gas. As an example, the required metrology support for electric vehicles (eV's), natural gas vehicles (NGV), or vehicles running on hydrogen covers a variety of research areas such as batteries, fuel cells, frequency converters, motors, and DC electrical metering. Reliable metrological measurement and testing of critical parameters under in-situ conditions, combined with advanced modelling, will provide the necessary scientific under-standing of the performance, lifetime and safety of these vehicles. Novel measurement and modelling tools are required as the basis for future harmonised test protocols and standards.

Liquefied natural gas (LNG) is another promising fuel for a variety of applications including transport, but requires new calibration technologies to determine, in a faster and accurate way, the composition, density and calorific value of LNG in custody transfer and when used as a fuel.

A so far unexplored metrology area is the measurement support to re-use of energy waste.

Efficiency and other cross-cutting subjects

Energy efficiency is not only a crucial theme in energy use, but in the whole energy chain from generation, transmission, distribution, to the end user. Even small improvements in efficiency have a large impact of the environmental footprint of our energy infrastructure when they are made in devices from which millions are used (such as PV panels and solid state lighting) or in devices that convert large amounts of energy (such as power plants and grid power transformers). Metrology research is crucial for development of characterisation and test methods to provide insight in the loss mechanisms and to accurately quantify the efficiency improvements realised by new technologies.

Energy efficiency clearly is not the only parameter in the overall optimisation of processes in energy production, transport, and use. As indicated in the first challenge of the energy 'trilemma', a major parameter also to be taken into account is the impact on environment, for example in emission of CO_2 and other greenhouse gases, and in noise pollution (see also the Grand Challenge "Environment", section 2.3). This calls for interdisciplinary metrology projects where both energy and environmental knowledge is combined for finding the overall optimal solution.

Materials and modelling, described below, are two other cross-cutting areas in energy metrology research.

Metrological characterisation of new materials with unique mechanical, electronic, thermal, and chemical properties is required to support their use in energy-related applications. Validated evaluation techniques are needed for increased safety, lifetime, efficiency and sustainability of these materials. Examples to indicate the breadth of the area include light-weight strong materials for larger-size wind mills, new ceramics that support higher-efficiency operation of power plants at higher temperatures, new materials for PV solar cells, new magnetic materials for high-efficiency power electronics, and materials and coatings for energy-efficient windows.

Modelling can provide unique insights in all processes of the energy chain, especially when combined with measurements to validate and refine the models that are developed. This requires bringing together mathematical and metrology experts with user experts in the field. The specific metrology added value in modelling lies in the determination of key parameters in the model, sensitivity analysis, the impact of uncertainty in input parameters on the accuracy of the model output, and the validation of the model in laboratory or on-site tests.

2.3.4 Key outcomes

The expected outcomes of the metrology research and development in the grand challenge of energy cover the diverse range of stages in the energy chain and many industrial sectors. The outcomes are expected to include:

- Enabled development and enhanced uptake of renewables in the European energy mix, such as solar power and wind, via new measurement tools to facilitate innovations in generation, to characterise and improve their performance, and to enable compliance with EU regulations.
- Metrology tools to support the use of sustainable carbon-based energy sources such as biofuels and biogas, and lower-carbon sources such as gas and LNG, to lower CO_2 emissions.
- Facilitated trade (billing) in a wide range of energy carriers, such as electricity, (bio)gas, biofuels, and LNG, via reliable and accurate measurement of the energy transferred between trading partners.
- Supported efficiency enhancements in conventional energy sources and power plants, including nuclear, via the realisation of measurement tools for improved in-situ monitoring and control of critical processes and for the development of improved materials.
- Improved energy conversion/storage processes, e.g. hydrogen, fuel cells and power-to-gas technologies, thereby facilitating increased uptake of renewable sources hindered by their inherent fluctuation in power output.
- Improved monitoring and control of electricity and gas grids, enabling increased stability and quality of supply and to enable increased renewable energy contributions to the grids.
- Facilitated innovation in energy-efficient devices and products, e.g. solid state lighting devices (OLEDs), motors and transformers to enable compliance with EU regulations such as the Ecodesign directive.
- Reduction in energy consumption through more efficient energy use and thermal efficiency in buildings (in preparation for the 2021 requirements of the EU Directive on Energy Performance of Buildings), transportation, and industrial processes.

* Tools for determining efficiency in the complete energy chain from generation, transport, conversion and use, enabling knowledge-based improvements.

The outcomes of this energy metrology research will support and foster innovation, assure fair trade, contribute to reduced environmental impact of the energy infrastructure, and provide reliable data for public discussions on the reliability, safety and sustainability of energy sources comprising our future energy mix.

2.4 Innovation

2.4.1 Key challenges

Innovation, defined as the introduction of new products and services into the market, is at the heart of Europe´s 2020 agenda. This is illustrated by the "Innovation Union 2020" stated goal for Europe to become "the most innovative economic driving force of world economy by 2020". One of the targets of Europe 2020[66], through the Innovation Union flagship[67], is to boost innovation, research and development in Europe.

***"Industry must be placed centre stage if Europe is to remain a global economic leader"*[68,69]**

***"The main economic driver of economic growth in the EU is innovation"*[70]**

To remain competitive on the global scale, European industry must not slacken in striving for better quality, high-technological and innovative products for which metrology is a key support. Breakthroughs are only possible if the underpinning measurement capabilities exist. This applies not only to the EU's Key Enabling Technologies (KETs)[71], identified as micro- and nanoelectronics, photonics, nanotechnology, industrial biotechnology, advanced materials and advanced manufacturing technologies, but also to traditional but important industrial areas.

Industrial growth, especially in technology-intensive areas, is associated with underpinning metrology and imposes a need for novel measurement technologies:

> *"A striking result of a recent study[72] is that measurement knowledge is more strongly associated with novel than with 'catch-up' innovation; that is, it underpins cutting edge product and process innovation creating high-value jobs."*[73]

The above clearly indicates the importance of innovation to economic growth in the EU, and also the importance of metrology in that innovation process, which is illustrated below.

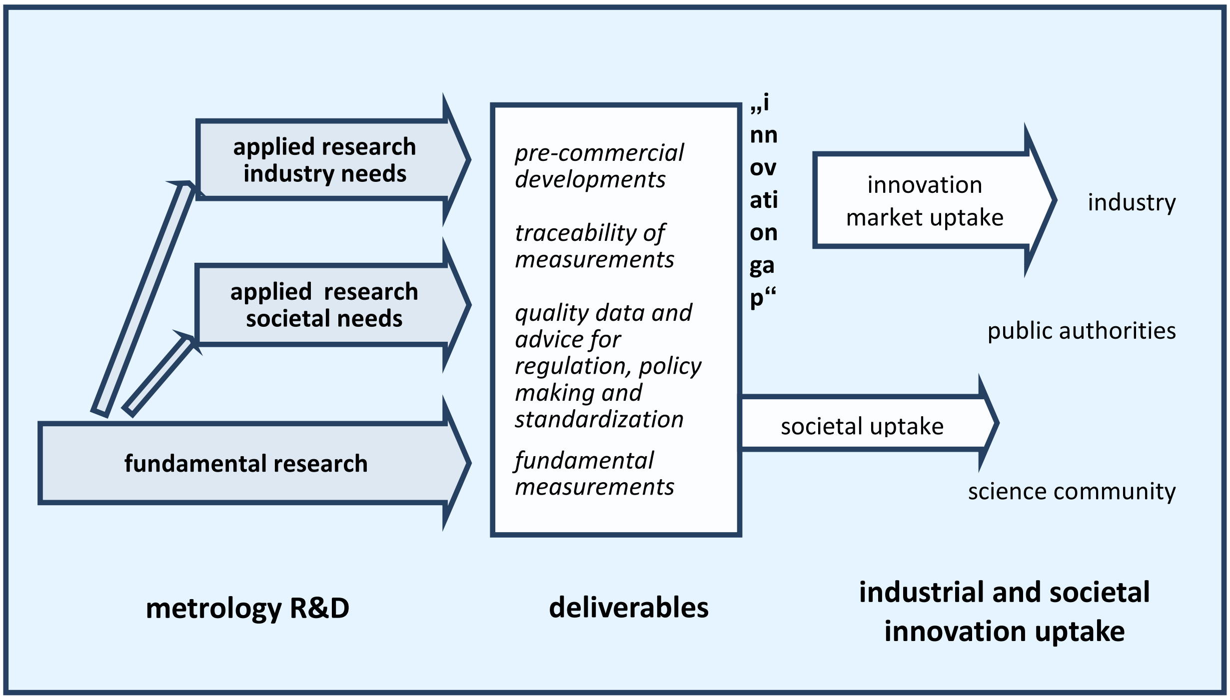


Figure: The metrology innovation chain

2.4.2 Current capabilities and state of the art

In the EMRP, two calls for industrial metrology were launched in support of the innovation agenda[74], funding about thirty metrology projects on topics including, for example, optical and RF communications, microwave clocks for industrial applications, biomaterials, surface chemical analysis, electronic and optical devices, quantum communications, thin film, ultrafast electronics, advanced magnetics and dimensional metrology at various length scales. These projects have delivered a range of products including new measurement techniques, calibration methods, data sets and best practice guidance as well as publications in the scientific literature.

The strengthened profile of innovation is a key difference between EMPIR and the predecessor initiative EMRP. The area of *"Innovation"* aims at giving a technology push to European industry by developing and exploiting cutting edge measurement technologies. It requires an explicit, industry-oriented, technological transfer approach to drive uptake.

Metrology R&D projects focused on innovation will be supported in EMPIR primarily through its Innovation calls. EMPIR will also support industrial uptake and impact by setting up dedicated post-research activities (see Section 5). Innovation will be supported, for example, by the development of well-designed and timely European standards. Furthermore, greater impact on innovation can be achieved by building strong relations with industry and their increased participation in collaborative research projects. Such increased inclusiveness in research projects will also improve scientific excellence as NMIs and DIs will have better access to researchers across disciplines, e.g. medical, thereby creating a more effective and efficient research network to drive innovation.

"What we cannot measure, we do not understand properly, and cannot control nor manufacture or process reliably."

"... ever more precise and reliable measurements are essential to drive innovation and economic growth within our knowledge based economy"

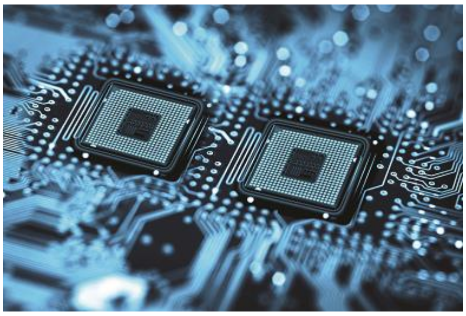
EMPIR Impact Assessment report[75]

2.4.3 Key activities

Innovation covers a vast landscape of established as well as technological advanced industries. Thus metrology R&D in support of innovation needs to be focused on those areas that have potential for high impact on innovation and consequently economic growth. Crucially however, the horizontal, underpinning character of metrology means that the benefits of metrology R&D are not limited to specific technical branches, but can be realised in other areas where advanced measurements are needed.

For the above reasons it is considered inappropriate to identify specific activities for metrology R&D to address. However, the R&D must be aimed at driving innovation in industrial processes and facilitating new or significantly improved products through the development of measurement technology for industrial application, for example new sensors, in-process measurements, and materials characterization.

Demonstrable, evidenced needs and the engagement and participation of industry in the R&D are considered factors that will contribute critically to the success in achieving impact. Furthermore, metrology activities are likely to achieve greater impact if they have strong interactions with complementary R&D activities across Europe, e.g. Horizon 2020 and the Graphene Flagship[76] project, through which greater leverage can be achieved.



Metrology impact on innovation will be achieved through participation, for example, in Horizon 2020 projects. Within the framework of EMPIR, metrology R&D enabling innovation will be supported through industry-focused research projects as well as projects focused on increasing impact (see Section 6).

2.4.4 Key Outcomes

The outcomes of metrology R&D projects supporting innovation are considered to be many, reflecting the breadth of the innovation landscape. Outputs of metrology R&D activity will include, for example, new and improved measurement and characterisation technologies, reference materials, transfer standards, calibration practices and documentary standards. Such outputs will enable industry to innovation more effectively in materials, processes and products and achieve improvements in efficiencies and performance. The benefits will be realized across a wide industry landscape. The increased level of industrial innovation enabled by metrology advances will lead to increased economic activity, improved competitiveness and economic growth in Europe.

3 Metrology Research Supporting the Redefinition, Realisation and Dissemination of the SI and Derived Units

3.1 Introduction

A key objective of EURAMET is to develop and disseminate an appropriate, integrated and cost effective measurement infrastructure for Europe taking into account the needs of end users in industry, business and Government[77]. Such an infrastructure needs to be fit for purpose and delivers the necessary tools to enable innovation and economic growth in Europe and addresses societal needs, particularly in the grand challenges in health, energy and the environment that face Europe. Innovation at the frontiers of technology requires advanced metrological capability: a capability that needs to keep pace, providing the necessary tools in a timely manner.

To achieve this aim, fundamental and high level metrology R&D has, and continues to advance metrological capability by:

- focusing on underpinning the redefinition of the SI, based on the constants of nature, as requested by the General Conference on Weights and Measures (CGPM) under the Metre Convention, and
- addressing the high level metrology capability that is required for the improved realisation and dissemination of the primary and derived units of the SI.

Such fundamental and high level metrology R&D has been carried out through EMRP, and will continue through EMPIR. It enables high quality science research at the frontiers of metrology to be carried out, enabling Europe to maintain its scientific international competitiveness and recognition.

Outcomes of the research are expected to be:

- Implementation of the proposed redefinition of the SI.
- Practical realisations of the new definitions of the SI base units and affected derived units.
- Improved dissemination of standards, traceability of measurements and uncertainties.
- Innovation, particularly in advanced technologies, enabled through advanced metrology capability
- Critical contributions to addressing Europe's grand challenges in Health, Energy and Environment, support to growth in Europe through increased innovation.

Key fundamental and high level metrology challenges in each of the technical committee areas of EURAMET are presented, in alphabetical order, in sections 3.3.-3.11, following the section on fundamental scientific metrology 3.2. Finally within this chapter, generic challenges in mathematics and modelling for metrology are presented in 3.12.

3.2 Fundamental Scientific Metrology

3.2.1 Key challenges

Excellent science is the first pillar of Horizon 2020, aiming to reinforce and extend the excellence of the Union's science base and to consolidate the European Research Area in order to make the Union's research and innovation system more competitive on a global scale.

Horizon 2020 aims at raising the level of excellence in Europe's science base and ensuring a steady stream of world-class research to secure Europe's long-term competitiveness. It will support the best ideas, develop talent within Europe, provide researchers with access to priority research infrastructure, and make Europe an attractive location for the world's best researchers.

> ***"Excellent Science" aims to reinforce and extend the excellence of the Union's science base and to consolidate the European Research Area in order to make the Union's research and innovation system more competitive on a global scale.***[78]

Research focused on fundamental scientific metrology is EURAMET's response to this Horizon2020 aim. Research at the frontiers of measurement science is critical to major advances in science, and vice-versa, and the take-up of excellent science from outside the NMIs and DIs is a key element in the long-term development of metrological capabilities. Discoveries associated with new technologies, mainly in quantum physics, have enabled important changes in the world of metrology, in both the realisation of the base SI units and the redefinition of units leading to an improved International System of Units (SI).

3.2.2 Current capabilities and state of the art

NMIs and DIs develop and maintain the highest-level measurement standards in order to serve even the most demanding stakeholder needs for traceability to the SI – with a need to improve further as stakeholder needs require. By definition, no absolute SI-traceable measurement can be better than the best standard for that measurement quantity in an NMI or DI. As a consequence, a number of globally competitive, superior and unique measurement capabilities are available and could be used for high-risk explorative research on topics such as optical clocks, highest-quality sources and detectors for the entire electromagnetic spectrum, mass spectrometry, nano-dimensional tools, and many more.

In the EMRP, fundamental science R&D addressed topics including quantum tools for better time by using quantum entanglement to improve optical clocks, quantum communication and security by communicating with single photons, quantum computing by controlling single-photon microwave radiation on a chip, and exploiting electron spin by putting the theory of spintronics and spin-caloritronics into practice. Furthermore, a new technologies call funded twelve metrology projects on topics supporting the competitiveness of the European semiconductor industry in micro- and nano-electronics, exploiting nano-object properties and nano-electro-mechanical devices. These projects have delivered a range of achievements including publications in the scientific literature, new measurement techniques and data sets.

3.2.3 Key activities

Fundamental scientific metrology:

- aims at excellent science exploring techniques or methods which have not been considered in metrology so far, and
- shall bring together the best scientists in Europe and beyond, whilst exploiting the unique capabilities of the National Metrology Institutes and Designated Institutes.

In contrast to the following chapters addressing needs for the redefinition, realisation and dissemination of the SI and Derived Units, this chapter on fundamental scientific metrology does not predefine specific technical topics. However, it is expected that the R&D will include high risk research proposals on topics such as:

- Novel approaches to overcome noise limits and reduce the invasiveness of measurements.
- Quantum enhanced SI standards, where the quantum strategies will be exploited to increase the sensitivity and accuracy of measurements. Entanglement of quantum objects of different nature, control of quantum mechanical coupling, squeezing of quantum states, and quantum non-demolition strategies for measurements are among the concepts exploited to this end.
- Consistency tests in electrical quantum metrology and determination of fundamental constants. Universality tests verify consistency of the same quantum effect in different materials and also the consistency of different quantum effects based on the same fundamental constants.
- Metrology for solid-state quantum engineering.
- Fundamental metrology on the single atom / single molecule level to support down scaling of technologies. The ultimate down scaling will eventually lead to devices and materials having single-atom or single-molecule based functional units.
- Quantum optics through interdisciplinary research efforts in manufacturing microsystem engineering (optical microcavities, MEMS and waveguides), nanotechnology (nano-structured materials such as quantum dots, carbon nanotubes and diamond nanowires), telecommunications (novel optical fibres) and optics (nanophotonics).
- Basic research on the interaction between light and matter, on novel materials, and on new structures.
- New optical clocks with many potential atomic reference transitions, including nuclear transitions. In parallel with this, better understanding is required of atom and ion trapping technology, atom manipulation techniques and optical frequency measurements based on frequency combs.

3.2.4 Key Outcomes

Impact on excellent science and the take-up of forefront scientific approaches for metrology will be achieved by building strong relations with academia and their increased participation in collaborative research projects. Such increased inclusiveness in research projects will also improve scientific excellence as NMIs and DIs will have better access to researchers across disciplines, e.g. medical, thereby creating a more effective and efficient research network.

Reflecting the nature of this research, expected technical outcomes are not specified. The key criteria and metrics for prioritisation and evaluation are the ones used in competitive science.

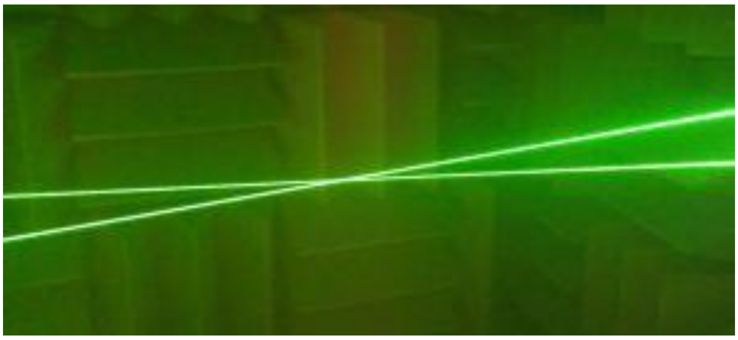
3.3 Acoustics, Ultrasound and Vibration

Every member of society has an intrinsic connection with and is impacted by acoustic phenomena. Hearing is vital for communication, noise can have serious detrimental health effects, and ultrasound is a widely used tool is medical diagnostics and therapy. Acoustic measurement therefore has immense impact. Basic research delivering advances in measurement capability is essential to underpin the applied research capable of delivering societal, environmental and industrial impact.

3.3.1 Optical realization of acoustic standards

The key fundamental metrological challenge for acoustics, ultrasound and vibration is to ensure the provision of robust primary standards and measurement techniques into the future. In keeping with the principles of the 'new SI', the next generation of acoustic measurement standards will eliminate the reliance on transducer artefacts for their realization and will instead be traceable through optical techniques to fundamental basic units, thereby securing the future metrological infrastructure.

Optical techniques for the measurement of sound have already been developed for both air and water, for ultrasound and for vibration measurement. However, the technology is at different stages of development and objectives are distinctly different in the different media and frequency ranges of importance.



Application of optical techniques is most disruptive for sound in air where Doppler anemometry and photon correlation spectroscopy have recently been successfully demonstrated. However, further research is needed to bring these techniques to the point where there is comprehensive coverage of the required frequency and dynamic ranges, where measurement uncertainties are fully established, and the methods validated.

In both air and water, exploitation of acousto-optic interactions offers potential for further novel measurement capabilities, from accurate and non-invasive point measurements, to two-dimensional area scans of propagating sound waves and quantified visualisation and mapping of complex acoustic fields.

For ultrasound, traceability to the metre, and primary level realisation of the acoustic pascal, is provided through the measurement of ultrasound displacement using optical interferometric techniques. Whilst current NMI calibration capability for secondary devices such as miniature hydrophones extends up to 20 MHz, there are demands for calibrations up to 100 MHz due to proliferating high resolution medical imaging applications. This will demand the ability to measure acoustic displacements at the picometre level, posing severe challenges due to sensitivity to background vibration. There is need to exploit novel methods of high amplitude ultrasound generation, potentially using photoacoustic techniques.

3.3.2 Metrology for infrasound and airborne ultrasound

Noise is one of the most significant environmental stressors with strong influence on well-being and quality of life. Increasingly, noise sources are appearing with frequency content just outside the hearing frequency range for which methods are not well established. Measurement traceability for sound field parameters in these extended frequency ranges needs to be better established.

3.3.3 Acoustic vector quantities

While sound pressure is the basis for most acoustic measurement, other acoustic quantities such as particle displacement and particle velocity are becoming increasingly important. Indeed the optical techniques described above typical use these quantities to derive sound pressure. However there are applications where the primary interest is related to the fluid motion. For example, it is known that the acoustic sensitivity of many marine species is related to particle velocity and not the resulting acoustic pressure. To meet these needs, new basic measurement capability for vector sensing in acoustic fields is needed.

3.4 Chemistry

Metrology in chemistry is a rapidly growing field of metrology, strongly driven by societal needs for reliable chemical measurements as well as legislation and international agreements. The central aim for NMIs in the field of chemical metrology is to establish an international primary reference network for traceability that provides measurement stability, comparability and coherence in all aspects of chemistry and biochemistry. Priority activities have been identified as: the development of reference materials, metrology for the identification and analysis of macromolecules and biomolecules, and measurement capability for trace chemical analysis, and are presented below.

3.4.1 Reference materials

Today, chemical measurement provides a huge and ever increasing range of information. Chemical measurement tasks require high purity reference materials that can provide traceability to the SI, and new concepts and measurement techniques of higher accuracy and with improved detection limits are being developed and used. However, higher order[i] reference materials and high purity materials that serve as reference points are badly missing. To a large extent, this field is not covered to date because of the high costs involved in the production, maintenance and supply of such materials. Yet, these materials are an integral part of traceability in chemistry and needed to fulfil the requirements of European directives e.g. environmental protection, food analysis and medical diagnostics. The goal of the metrological research is to improve the quality of those measurements, and thus will focus on new reference measurement methods and traceability dissemination mechanisms. In this way assurance of measurement will be provided right down to the user level in areas where it is currently absent.

[i] Higher order reference materials – typically materials used to calibrate reference measurement devices.

3.4.2 Metrology for identification and analysis of macromolecules and biomolecules

The chemical identification and analysis of macromolecules and biomolecules is arguably one of the fastest growing fields of research of today. Typically in such evolving branches of science, a metrological infrastructure is emerging but is still in its infancy and needs support to follow the evolution of the technology. The tools required to tackle the problems in the biochemical area must be able to identify ever-larger molecules such as proteins, metalloproteins and their metabolites, including their structure, and quantify them in their native environment on a primary level.

Concepts for primary measurements of proteins and pathogens (viruses, bacteria, toxins) are difficult especially for the latter, and are still largely missing today. Such concepts may be based on traceable measurements of characteristic parts or metabolites of those measurands. The matrices are mainly bodily fluids but also tissues and cells, water (environmental studies) and food. Research into entirely new approaches for primary methods is needed. They will be based, however, largely, but not necessarily, on the principles of ratio primary measurements such as those used by ID-MS. These tools will be able to circumvent the limits set by the relative mass resolution of today's mass spectrometry or use different principles for the detection and identification of the molecules, for example, optical spectroscopies such as IR and Raman spectroscopy or NMR based methods. The information on the structural state of the analyte will be of key importance. Different forms of a molecule (isomers) must be distinguished. Future, more sophisticated diagnostic tools will also analyse multiple markers simultaneously. Concepts for providing in-line traceability to higher order methods for testing devices and multiplex testing devices will be needed to improve measurement uncertainties at point-of-care testing.

3.4.3 Measurements for trace chemical analysis

Trace analysis is essential in almost all chemical sectors. This may be environmental monitoring of pollutants in air, water and soil but also for waste monitoring, measuring impurities in industrial products and as residues in food. This is particularly important as limit values set by legislation decrease. Furthermore, EU legislation requires that long-term trends of pollutant concentrations are established, thus requiring stable measurements over time and underpinned by traceability. Clearly, small concentration levels must be measured with very small uncertainties.

The measurement of trace analytes for environmental and climate monitoring over very long periods of time (i.e. decades and more) requires extremely accurate measurements near the detection limits in water and air. The tools required must be able to detect minute changes of trace compounds, traceable to the SI with very low, well understood and well documented measurement uncertainties so that this information is useful to detect long-term trends with confidence. Also, the records of today must be understandable by future generations. This needs improved tools based on analytical techniques such as species-specific ICP - MS in water analysis or permeation tube systems in gas analysis. Remote sensing becomes increasingly important and will profit from optical tools like laser spectroscopy. Such measurements need a better knowledge of scattering cross sections of specific trace gases.

Further improvements of measurement technologies for trace analysis of analytes in gases and in solution and their traceability to higher order references will also continue to be an underpinning requirement in many areas of manufacturing industries like electronics and other micro-technologies. Manufacturing has now even reached the nanoscale and requires traceable analytical tools that are applicable on surfaces and in micro- and nanometric dimensions. Although many such tools are in use or under development, traceability to the SI is largely missing to date. Also, new technologies in electronic industries, applications of new materials require extremely accurate knowledge of ever smaller concentrations of pollutants, dopants and additives, sometimes in extremely low concentration ranges in functional materials. Nanotechnology is another upcoming technological field, but is also of environmental concern. The application of metrological tools to the chemical analysis of nanoscale structures and particles needs to be addressed and is already widely discussed on a global level, for example, in the framework of the CCQM.

Beyond the practical needs for chemical measurements in all aspects in life, metrology itself as a fundamental research field will continue to need extremely accurate information about the chemical state of matter used to define other SI units and their realization such as in case of the kilogram.

3.5 Electricity and Magnetism

3.5.1 Quantum electrical metrology

Nanotechnology gives access to dimensions in which quantum effects govern the functionality of devices. This creates opportunities to harness quantum effects for technology and to realize novel paradigms for functionality: examples are quantum-computing, -communications, -sensing and -metrology. Since innovation relies on reliable and accurate measurements, new quantum-based metrology is required to advance and exploit quantum technologies. Metrology itself should be based on universal standards that are independent of time and space. To this end, the SI base units are to be linked to fundamental constants of nature. The links are realized by quantum effects, which provide unprecedented accuracy. The key challenge is that to further increase sensitivity and accuracy of measurements, fundamental science needs to provide strategies to overcome noise limits and reduce the invasiveness of measurements.

For more than three decades European R&D in quantum electrical metrology has been a very active and prolific area, playing a leading role on the international scene. Remarkable results have been obtained on the quantum Hall effect in graphene, on single electron pumps and on different ac Josephson devices by NMIs within iMERA-Plus[79] and EMRP[80] projects. A large effort is also invested on fundamental tests (quantum metrology triangle) and the determination of fundamental constants (h, e, α), placing some EURAMET NMIs at the forefront in the discussion of the redefinition of the SI.

The priority activities within quantum electrical metrology are presented below, in chronologically order:

3.5.1.1 Practical realization of the new definitions of the SI units

The practical realization of the new definitions of the kilogram, the kelvin, and the ampere will be linked to the Planck constant *h*, Boltzmann constant *k*, and the elementary charge *e*, respectively. This comprises, in priority, the realization of the quantum ampere through the development of quantum meters and sources, and improvements to the quantum Hall effect and single electron transistors (SET) by using new materials (e.g. graphene). The improvement of watt balances to make the link of the kilogram to *h* more reliable, accurate and practical, and the development of quantum noise thermometry to realize the kelvin by a quantum method for *k* using Josephson devices are highly desirable.

3.5.1.2 Consistency tests in electrical quantum metrology and determination of fundamental constants

Universality tests verify consistency of the same quantum effect in different materials and also the consistency of different quantum effects based on the same fundamental constants. This work will focus on studies of single electron transport in different semiconducting and metallic devices and on novel quantum resistors (graphene). Experiments to verify the quantum metrology triangle, formed by the Josephson, quantum Hall and single electron transport effects will be continued. This addresses the quantum foundations of the watt balance and the quantum ampere realizations. Next generation experiments will also be developed to determine improved values of the fundamental constants.

3.5.1.3 Metrology for solid-state quantum engineering

Novel solid-state technologies based on quantum effects require metrology beyond the present SI. Traceability and comparability need to be established for solid state quantum measurements which will allow reliable fidelity testing of solid state quantum devices, e.g. single photon sources.

3.5.1.4 Quantum enhanced electrical SI standards

The quantum strategies will be exploited to increase the sensitivity and accuracy of electrical measurements. Entanglement of quantum objects of different nature, control of quantum mechanical coupling, squeezing of quantum states, and quantum non-demolition strategies for measurements are among the concepts exploited to this end.

3.5.2 Fundamental electrical metrology on the single atom / single molecule level

Fundamental electrical metrology is required to support down scaling of electronics. The ultimate down scaling will eventually lead to devices and materials having single-atom or single-molecule based functional units. Testing of such functional units requires the measurement of advanced EM properties on the atomic level. Ultimately, routine measurements of single quantum entities of spin, flux, and charge in materials and devices are required. Fundamental electrical metrology on the single atom / single molecule level is in its infancy but capabilities and competences exist in some NMIs as well as in European academia.

The priority is the development of characterization tools for nano and quantum structures and the implementation of traceable characterization of atomic-scale devices. At first, this implies accurate technical means for the detection and manipulation of single quantum entities (spin, flux, charge, photon) and new metrological concept beyond classical EM measurements. The question of traceability of such highly sensitive measurements will have to be tackled. The usual path via reference materials can only be followed once robust atomic-scale assembled reference materials are available.

3.5.3 Electrical metrology from DC to THz

Modern electronics is based on micro- and nanostructures, processing digital signals at high clock rates, requiring traceable measurements of ultra-small quantities (voltage, current and capacitance) and arbitrary signal waveform well in the MHz frequency range. The development of semiconductor devices working above 100 GHz is hampered by the level of measurement technology. Metrological support is imperative for improved and new technologies involving RF to THz systems. Even though requirements are become more demanding, European industry requires calibrations that are cost-effective and fast in order have a competitive edge. To this end, transportable, intrinsically referenced standards and calibration instrumentation must be developed for on-site use by the end-user. The intrinsically referenced standards include quantum standards and scaling instruments with self-calibrating capabilities, the latter being needed to transfer the absolute accuracy of the quantum standards to the magnitude and frequency ranges of interest.

The priority activities for electrical metrology from DC to THz are as follows:

3.5.3.1 Improved and extended scales of electrical units over the frequency spectrum from DC to THz

This includes the calibration of complex valued signals from DC to MHz, the electrical traceability for sensors of non-electric dynamic signals, the traceability of measurement of small quantities or extreme impedances, a reference data library (with uncertainties) for electromagnetic material measurements on the micro/nano scale, the development of broadband guided wave RF standards over large dynamic ranges and broadband RF standards for free space measurements, and the traceable measurement of integral quantities (electrical charge, voltage impulse) for the calibration of coulometers and fluxmeters.

3.5.3.2 Simplified "fit for purpose" calibration tools and intrinsically referenced calibration systems

Practical realization of the quantum standards will be based on large-scale integration of semiconductor, graphene, superconductor and single-electron technologies. DC and AC standards of voltage, current and impedance for a wide range of magnitudes and frequencies, and quantum traceability for digital electrical measurements including general purpose DC/AC bridges will be made available. The scaling instruments with self-calibrating capabilities will include quantum ratiometric DC and AC standards (based on Josephson and Hall devices), superconducting DC and AC current comparators, high-accuracy mixed-signal electronics. It is expected that simple and transportable quantum standards will be developed as well as liquid-Helium free turn-key (U, Z, I) quantum calibrator covering extended scales and arbitrary signals.

3.6 Flow

3.6.1 New fundamental standard for absolute molecule counting

Up to now the volume and the mass of gas flows are quantified by measuring devices which are calibrated by standards with traceability to the SI units for length, mass and time. Unacceptable uncertainties due to technical and procedural reasons when using conventional calibration procedures are encountered, in particular in the case of measurements of small flow rates (nl/h) of gas or the use of devices which can only be calibrated via downscaling techniques.

To address this, an innovative measurement principle based on absolute molecule counting should be developed in the coming decade. A multidisciplinary approach particularly involving the existing expertise in absolute molecule counting in the Technical Committee for Metrology in Chemistry (TC-MC) is a prerequisite for success. This ambitious and new method for flow metering will lead to a traceability chain based on the SI-units of Ampere, Mol and Seconds. This new approach has the capability for achieving improvements in the areas described above as well for underpinning traditional calibration procedures and will enhance the accuracy and reliability of flow metering in general.

3.6.2 Micro and nano-scale flow metrology

In order to provide traceability for micro and nanoflows, in particular for the biomedical field (e.g advanced cell therapies) and drug delivery, it is necessary to develop new micro and nano flow primary standards and primary facilities, down to 1 nl/min with a target uncertainty < 0,5 %. For label-free phase sensitive techniques used in cell therapy, it is foreseen that the flow area will have a substantial role.

Accurate volume determination needs calibrated instruments traceable to the International System of Units (SI). Currently this can only be achieved gravimetrically for liquid volumes higher than 1 μl due to limitations in the calibration method. There are several non-contact dispensing technologies and other liquid delivery devices that work in the sub-microlitre range and are normally used for automatic liquid handling. The dispensing results obtained with these devices typically have good precision but the accuracy of the dispensed volume is usually much harder to establish, in particular because only very few methods are available that can measure liquid volumes in the sub-microlitre range (e.g. optical or photometric methods). In addition, the majority of these methods are not traceable to the SI and therefore results obtained with different methods by different laboratories are difficult to compare. In order to provide traceability to instruments working on the sub-microlitre range it is necessary to improve the existing methods, establish traceability to the SI and to develop new measurement methods that will provide accuracy in the sub-microlitre range of less than 0,5 %.

3.6.3 Gas flow metrology at high temperature and high pressure

The measurement of gas flows at large, industrial scale flow rates (> 100 m^3/h) and at high temperature (> 250 °C) or pressure (> 50 bar) is more and more important for a wide range of industries such as automotive, aerospace and energy generation. For these applications monitoring and measurement of gas flow are typically carried out using devices which are calibrated at standard test facilities under conventional flow conditions rather than the real conditions as found in-service. The deviation in measuring results due to the different flow conditions can be taken into account by using theoretical or empirically-established correction factors. Because of the various influence factors in the correction process, the final uncertainty values are rather high. Thus there is need to develop high quality reference standards and procedures to enable traceable measurements to be made, with appropriate uncertainty levels, in support of improvements in the efficiency of processes, e.g. power conversion and production processes.

3.7 Ionising Radiation

In support of EU policy, Euratom[81] aims to progress nuclear research with focus on improving nuclear safety, security and radiation protection, as well as delivering a low carbon energy system through nuclear fission and fusion. Euratom also aims to support the development of medical applications of radiation, including the secure and safe supply and application of radioisotopes. In support of these key strategic European activities, development of the necessary fundamental and underpinning metrology is essential. Priority activities where metrological focus is needed have been identified and are presented below.

3.7.1 Development of the metrological infrastructure to underpin the development, operation and safety of advanced ionising radiation systems

Metrology capability need to keep pace with the demanding requirements of rapidly developing novel radiation sources such as high-power lasers (e.g. ELI-NP), Hadron therapy, and synchrotron radiation and spallation sources (e.g. ESS). Most existing measurement techniques are unable to cope with the extremely short but intense pulsed radiation bursts of such facilities, and no appropriate standards exist for high energy gamma and neutron radiation for the ITER fusion project.

Activity to develop the radiological measurement infrastructure for application to novel radiation sources is required, and needs to be carried out through European collaboration and with a focus on instrumentation, standards and protocols. For pulsed fields there is need for development of detector technology, faster instrumentation and improved signal processing to enable reliable measurement and accurate energy spectrum determination. Metrological challenges include detector 'dead-time', degradation and activation effects that are increasingly significant when characterizing pulsed and high intensity radiation fields. Furthermore, standards for high energy neutrons are required (currently limited to 20 MeV).

3.7.2 Underpinning metrology capability for nuclear and atomic data determination with significantly improved uncertainties

As reported by the IAEA[82], nuclear and atomic data are used for a wide range of applications in energy, medicine and industry, ranging from fission reactor technology and cancer radiotherapy to oil exploration. However, with increasingly demanding requirements, data are missing and requirements on uncertainties are not always met (IAEA[83]).

> *"[atomic and nuclear] data are essential in addressing at least two major world issues - carbon-based polluting impact of energy production across the planet, and radiotherapeutic treatment of various forms of cancer."* [84]

European NMIs have expertise in the development and evaluation of nuclear decay data, neutron cross sections and atomic and molecular cross sections[85,86,87,88]. Development of enabling metrology for nuclear data is required, guided by requirements e.g. IAEA[89], and will benefit by collaboration with nuclear structure physics projects at large gamma arrays in Europe (e.g. CERN) and European facilities for neutron cross section measurements. With increasing demand for improved nuclear data, developments in techniques such as coincidence counting and more accurate methods and instrumentation for beta spectrum and alpha emission determination are required. Detector technology continues to be developed, e.g. arrays of silicon, but their potential for delivering improved accuracy and uncertainties needs to be validated. Mass spectrometry, with significant and as yet largely unexploited potential for application to long-lived radionuclides, needs to be developed further for determining nuclear data. Furthermore, nuclear data are underpinned by primary standards such as neutron fluence, and thus improvements in these standards will contribute to improvements in nuclear data quality.

3.7.3 A new quantity that describes the real biological effect of radiation, to complement or replace the current quantity "energy deposited per unit mass"

To improve radiotherapy and radiation protection the biological effect of the radiation needs to be better understood. However, the current unit of absorbed dose is not the optimal quantity for predicting biological response and needs to be modified by factors taking into account the relative biological effectiveness (RBE) of different kinds of radiation if anticipated improvements in individualized healthcare treatments and health protection are to be achieved. There is need to better understand the effect of radiation on cell damage, including the contribution of biological factors that may vary between individuals, for this disruptive breakthrough to occur. Furthermore, there is still uncertainty regarding the effects and risks from low radiation dose, which has a significant impact on costs for radiation protection and nuclear waste disposal, and also on the incidence of secondary tumours arising from radiotherapy.

3.8 Length

3.8.1 Enabling progress in fundamental scientific metrology

Progress in fundamental metrology is often dependent on high accuracy manufacturing and dimensional metrology capabilities. The most prominent examples come from the proposed new SI[90], where experiments for the accurate measurement of the constants h[91], N_A[92] and k[93] require progress in dimensional metrology. This also holds for research work on other fundamental constants, such as precision experiments for determination of the gravitational constant *G*.

Priority activities are defined by the Avogadro (volume, surface layer, lattice spacing of ^{28}Si spheres), watt balance (velocity, position, assembly of components), AGT (resonator volume) and DCGT (effective area of pressure balances) experiments and the realisation of the proposed new SI. Also, new experimental setups and dimensional metrology capability are required to investigate possible deviations from the inverse square distance dependency of Newton's law of gravity, and may also help to resolve the existing discrepancies in gravitational constant *G* experiments. Progress in angle metrology targeting at nanoradian uncertainty and interferometry (*e.g.* for satellite formation flying or gravitational wave detection experiments) as well as characterisation methods for the thermal stability of high-tech materials (CTE < $5{\cdot}10^{-10}$) are needed as well. Also accurate manufacturing and dimensional metrology are indispensable for tests of the equivalency principle, targeting at uncertainties at and below 10^{-15}.

3.8.2 Dimensional control of large science instruments, structures and facilities

Many facilities required for fundamental science are dimensionally very large yet their ability to operate accurately requires very precise dimensional control, *e.g.* multi-decametre next generation optical telescopes (E-ELT[94] 40 m diameter, nm-level surface form), LHC successors (ILC[95], CLIC[96], TLEP[97] requiring tens of µm over 0.1 km to 100 km), synchrotron beam lines (10 nm over 50 m). Traceable metrology to achieve these accuracies does not exist and non-ideal environments compound the problems. Ultimate limits are lack of precise knowledge of 3D refractive index of air, accurate angle metrology coupled with refraction effects and poor compensation for thermal expansion in end user environments.

Priority activities include improved accuracy, speed, dynamic behaviour and in-situ traceability of 1D to 3D metrology systems for 10 m to 1000 m range, including use of multilateration techniques, improved 3D refractometry, improved angle metrology (higher resolution, 2D and 3D), multi-wavelength and novel absolute distance techniques, thermal compensation, validation and calibration techniques. The priority would be on increased accuracy at medium range (10 m - 100 m). The key outcome would be improved technical capability and efficiency of the facilities, e.g. particle beam lines, due to better set-up, yielding better quality scientific data with consequence benefits.

3.8.3 Support for nanoscience

Nanotechnologies and nanoscience are triggered by diverse fields and applications[98]. Miniaturization in industrial environments and the relentless requirements of the International Technology Semiconductor Roadmap (ITRS)[99] are driving processes to sub-nm accuracy level for critical features and positioning tasks[100]. Fundamental **key challenges** are an improved understanding of the measurement processes and probe-sample interactions, the traceability of measurements, improvements in instrumentation, reliable calibration standards, arising (quantum) effects for increasingly mesoscopic systems, and the metrological characterisation of novel artificial materials (metamaterials), devices and nanophotonic structures.

Priority activities include improved understanding of probe-sample interactions, supported by advanced modelling of more realistic and complex (3D) structures. The efficient combination of measurement methods (cross calibration) should be investigated as well as measurements in UHV to harsh environments. New measurement systems based on ion microscopy, nonlinear optical microscopy, Mueller polarimetry, X-ray scattering, electron beam and X-ray tomography tools have to be further developed and investigated.

The evaluation of possible interferences between dimensional- and analytical metrology is required. The development of new and improved devices based on nanotechnology will improve the sensitivity and application range (due to sensor miniaturization) in many sensing applications. Ultra precise small range positioning systems will be a key for optimisation of *e.g.* scanning microscopy. Virtual instruments, which simulate complex measurement tasks, are necessary to assist in determination of uncertainties.

3.8.4 Accurate long range metrology – from km range to traceable verification of GNSS systems

Global Navigation Satellite System (GNSS) dimensional accuracy at ground level is limited by propagation and clock errors, and critically by local errors[101]. The latter often requires independent site calibration. With the introduction of GLONASS[102] and Galileo systems, GNSS systems may achieve millimetric accuracy but there is no way to verify that the claimed accuracy is being achieved or to detect the presence of local path errors. Furthermore, in unstabilized environments, the refractive index is not constant and single point measurement of it is meaningless leading to inaccuracy of optical-based verification systems. Despite these issues, future legislation[103,104,105] will require more accurate metrology from GNSS. Another fundamental problem is the accurate determination of the scale factor in GNSS reference frames. Complex, continuous 3D transformations must be performed for the determination of these “local ties” at geodetic fundamental stations where GNSS and space geodetic reference sensors are co-located[106].

Priority activities involve the development of a combination of technologies to the next level: novel refractive index-compensating optical absolute distance measurement e.g. using waveband restricted optical fs comb systems, multiple wavelength techniques, compensating optics for turbulence beam wander; rugged EDM systems, total stations with longer ranges. These could then be used to measure specifically designed baselines, for GPS calibration, and to develop better monitoring systems at geodetic fundamental stations. Furthermore, better methods for coordinate transformation between different geodetic models and improved operational processes to achieve 1 mm accuracy when comparing GNSS and baseline measurements, need to be researched. This work would eventually underpin the European reference system (ETRS89)[107] for geographical coordinates and geospatial information which is being legislated for use across Europe.

3.8.5 Realisation of the metre for nanoscale

SI metre realisation as optical wavelengths necessitates sub-division to reach nm/sub-nm levels and optical sub-division is already hitting a natural limit. The CCL has taken note of this and highlighted[108] the need for research into more applicable metre realisations at the sub-nm scale and the potential utilisation of the lattice parameter of silicon or other suitable crystalline materials.

X-ray interferometry (XRI), as used for silicon (Si) bulk lattice determination for Avogadro traceability, is being developed specifically as a technique for disseminating measurements to industry. Activities are required to extend the range of XRI and improve its environmental stability, aiming for international acceptance of traceability to Si lattice spacing as a primary realisation of the metre for sub-nm scales. This, together with improved robustness, will lead to dissemination outside of an NMI environment via transfer standards providing a route to traceability that obviates the need for fringe division. Further on, the potential of atomic scales or quantum standards such as atomic lattices as natural rulers, as well as self-organized artificial gratings, has to be investigated. There is also need to develop a new generation of frequency stable lasers in compact rugged designs with simple user interfaces for application in optical frequency standards and length metrology.

3.8.6 Metrology for nanomaterials

Challenges for dimensional metrology of nanomaterials, e.g. nanoparticles and nanostructured materials, are in making measurements in the range below 10 nm, the fact that number based data need to be determined, and that the nanoparticles are often embedded in a solid matrix. In the case of nanoparticle agglomerations, preparation techniques are necessary in order to measure the primary particles.

There is a need to improve measurement technology to cover the range from 1 nm to 100 nm. Sizing metrology needs to be combined with analytical multi-parametrical methods, needed to first identify the particles in a complex metrics before they can be measured, for example AFM can provide simultaneous information about topography as well as electrical or mechanical or properties such as hardness. However, standardized sample preparation protocols need to be developed and suitable reference materials and inter-laboratory comparisons are needed to validate the methods.

3.8.7 Advanced quantitative high resolution microscopy

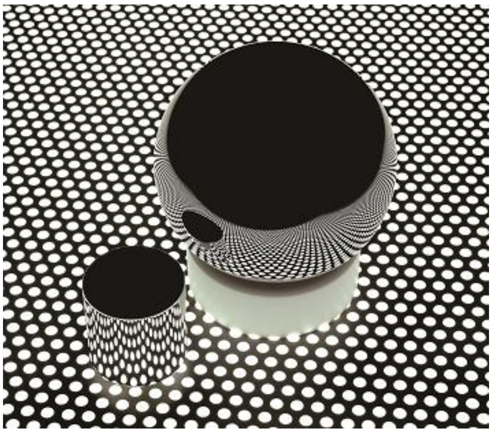
High resolution atomic force microscopy is limited mostly to free surfaces. For hidden surfaces, like deep holes of small diameter, *e.g.* diesel injection nozzles, measurement capability is limited. For more complex geometries, e.g. membranes containing well defined pores such as used in batteries, precise replication of the pore surfaces requires a better understanding of replicating material performance. Replica techniques have been applied to reproduce atomic steps[109], but are not industrially exploitable yet.

There is need for development of the piezoresistive and electrical cantilever principle from 1D scanning to higher dimensional measurements, e.g. the size and shape of pores, requiring new techniques, standards and reference samples. The complementary techniques of IR tomography (several 100 nm - several µm) and TSEM or TEM tomography methods (<100 nm) also needs to be developed. There is also need for increased understanding and better reproducibility in using replication materials.

3.9 Mass and Related Quantities

3.9.1 Mass

Since 1889, the unit of mass has been defined as the mass of a unique object known as the International Prototype Kilogram. However, the way in which the SI unit of mass is defined (and realized) is expected to change most probably in 2018. It is now practical to define the kilogram in terms of a constant of physics, which by its nature is invariant and universally accessible. This not only requires development and improvement of primary realisation experiments, watt balance and X-ray crystal density (XRCD), but also a means for dissemination from the unit realized in vacuum to mass standards in air in order to continue to provide traceability for the mass user community, e.g. legal metrology and pharmaceuticals, and also those communities served by the derived quantities like pressure, force, density and viscosity. Additionally, the redefinition of the mass unit allows realization of the mass scale at any nominal value (not just 1 kilogram) and so allows the opportunity to improve traceability and uncertainty for small mass values which will be of benefit, for example, to the pharmaceutical and biotechnology sectors.



Priority activities include Improvements of the XRCD and watt balance experiments up to (and beyond) the 2 parts in 10^8 level required for the re-definition of the kilogram (as recommended by the CCM[110]). Furthermore, there is need to develop procedures and equipment for fixing the Avogadro (N_A) and Planck (h) constants with direct relation to the International Prototype Kilogram in a way that minimizes the uncertainty in the determination of N_A and h. There is also need to put into place means to disseminate (and maintain) the unit of mass from the primary realisation experiments following redefinition. In the longer term a definition in terms of a fundamental constant should be fully exploited by exploring ways in which the unit can be realised more cost effectively and robustly and also to allow the realisation and dissemination of the scale independently at smaller (milligram) mass values.

3.9.2 Pressure metrology

Pressure metrology is a key metrology for industry, research and society. Pressure plays an important role in an extremely wide range of applications where it is a control parameter essential to the efficiency and safety of the processes, e.g. in petrochemical and transportation industries, as well as in environmental monitoring. Furthermore, innovative advanced science and industrial technologies, e.g. particle accelerators and high pressure processing, require traceable measurement of extremely low and high pressures.

Fundamental research for physics with contribution to the new realisations and definitions of SI units, in particular determination of the Boltzmann constant and a new thermodynamic realisation of temperature scale (see Section 3.11.1), require very accurate absolute pressure measurement. A new definition of the temperature unit kelvin in terms of the Boltzmann constant (k_B) is expected under a precondition that k_B is determined with a relative standard uncertainty better than $2 \cdot 10^{-6}$. One of the promising methods is the dielectric-constant gas thermometry which, to achieve the target, requires new absolute pressure standards for the range of 2 MPa to 7 MPa. Alternative techniques for k_B determination based on calculable capacitors, microwave resonators and refractometry present methods for alternative realisation of the pressure unit.

In order to support innovation and efficiency in industrial production and processes such as in power plants, cleanroom technologies, petrochemical and pharmaceutical production and the storage of nuclear and toxic wastes, there is need for improved realisation of the pressure unit in the intermediate vacuum-to-pressure range (~1 Pa to ~10 kPa) through the development of primary liquid column manometers and alternative pressure standards based on optical methods as well as characterisation of force-balanced piston gauges, and methods for its dissemination.

3.9.3 Force and torque metrology

Force and torque metrology is critical in an extremely wide range of applications in industry and research. It plays an important role in, for example, material testing and engineering across automotive, aerospace, aviation, energy production (power plant, off-shore) sectors for which traceable force measurements are critical for control and safety. In micro- and nanotechnologies and in healthcare for both diagnostics and therapeutics, traceability for smaller forces is required.

Fundamental research in force and torque metrology is required for the extension of standards and transfer standards to both smaller and larger values with reduced uncertainties, under static and dynamic conditions.

Priority activities include for the development of new standards for smaller and larger forces and for larger torques. In many cases a single component stepwise static calibration alone is not appropriate, especially if the application conditions are different to those during calibration. Consequently, there is increasing demand for single and multicomponent measurements of force and torque, up to MN and MN·m respectively, as well as stepwise, continuous, alternating and non-alternating measurements, with reliable traceability to the SI.

Small forces down to picoNewtons (pN) are become increasingly important in, for example, micro- and nanosystems in the handling and assembly of parts as well as in dimensional quality assurance by contact methods such as scanning probe and nano-CMMs. For measurements in small bore holes, for example, small and flexible probing elements have to be used leading to probing forces from some pN to some µN. The traceability of forces by using small masses is limited to > 10 µN, thus presenting challenges in ensuring the traceability of such dimensional measurements. Measurement challenges also relate to the interaction forces between the probe and the workpiece (and similarly, between the handling device and the components in assembly processes) and interaction effects (e.g. indentation of soft materials).

3.9.4 Density and viscosity metrology

Density and viscosity metrology is important for trade in goods, e.g in the gas and oil sectors, and in industrial processes, particularly for design and control and thus optimising product quality and process efficiency. Density also has an important role to play in the fundamental metrology, in both the realisation of the new definition of mass and for pressure.

The awaited new definition of the kilogram can be realized by x-ray crystal density (XRCD) method. The homogeneity of the silicon crystal used in the XRCD method is very important and can be checked by flotation density comparison. However, the precision of this method has to be improved to reach relative uncertainties below $1{\cdot}10^{-8}$. High precision density comparisons can also allow the use of cheaper silicon of natural isotopic composition, instead of isotopically enriched silicon, to realize the new kilogram definition. The development of methods and equipment for this density comparison would also allow to disseminate the density unit at the highest level of accuracy to NMIs.

Improvements in density realization will also help to build liquid column manometers, with integrated density measurement, for the primary realization of the pressure unit in the low pressure range (1 Pa to 10 kPa) with unprecedented accuracy.

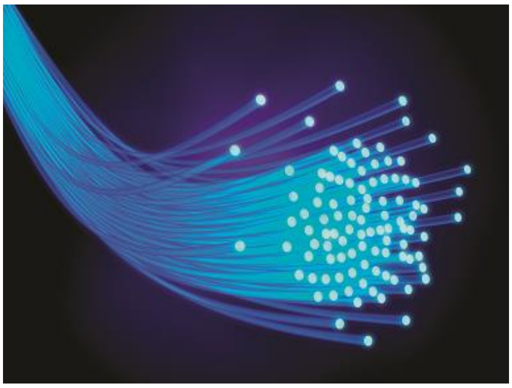
The investigation of surface effects in the hydrostatic weighing method will allow improved volume measurements of solid artefacts used to determine the air density in balances. Thus the mass of steel mass standards can be calibrated with lower uncertainty by comparison with Platinum-Iridium (PtIr) or silicon mass standards by measuring the air density with higher accuracy.

Furthermore, new methods for the primary realisation of viscosity at intermediate viscosity (1000 m^2/s) are needed to improve the accuracy of the viscosity scale.

3.10 Photometry and Radiometry

3.10.1 Basic Science – Quantum Optics

The present Photonic era is based on rapidly developing optical technology and photon devices and will especially impact on the fields of quantum communication, quantum computing, quantum enhanced measurements beyond the standard quantum limit, and radiometry as well as in the emerging field of bio-photonics. These applications require quantum optical metrology based on better standards and calibration chains, as well as new optical quantum standards and metrics.



The European research activity in quantum optics has been prolific and active on fundamental theory and also on technology developments (single-photon sources (SPS) and detectors (SPD), and techniques for characterizing them). Currently, SPSs (and, to a lesser extent, SPDs) do not possess the properties necessary for the above-mentioned applications. State-of-the-art SPSs have limited performance in terms of efficiency and photon flux, and lack indistinguishability between the emitted photons. The full characterisation of single-photon states requires the development of new metrics and measurements.

The physical and technical limitations of today's optical components can only be overcome through interdisciplinary research efforts in manufacturing microsystem engineering (optical microcavities, MEMS and waveguides), nanotechnology (nano-structured materials such as quantum dots, carbon nanotubes and diamond nanowires), telecommunications (novel optical fibres) and optics (nanophotonics). More fundamental limitations must be tackled by basic research on the interaction between light and matter, on novel materials, and on new structures with revolutionary photonic properties. This will require work in quantum optics, quantum information, materials science, and solid-state physics over the next decades.

"Basic Science, Quantum Optics" priority activities for the next decade is as follows:

3.10.1.1 Low-cost, high-accuracy transfer standards

High-accuracy (primary or transfer) standards operating in the single-photon regime, and which can be embedded in quantum optical technologies, are required. The latter will require the development of robust techniques for applying the transfer standards to the single-photon regime.

3.10.1.2 Single molecule biophotonics

Single quanta of light are essential for elucidating fundamental quantum principles, but they are also ubiquitous in the life sciences. The most efficient detection techniques for fluorescent biomolecules are sensitive at the single photon level. Individual particles of light are also of direct relevance in biological processes as they may affect the structure of individual molecules, which in turn can transduce signals in living organisms. Single molecules can also be considered to be single-photon sources. We still have to learn about the relevance and evolutionary advantage of quantum physics in photosynthesis. The target is to investigate interactions between single molecules and quantum optical fields.

3.10.1.3 Certification of quantum-optical based systems

Quantum Key Distribution (QKD) has extremely strong privacy properties potential for use as a privacy enhancing technologies (PET) to enforce protection of personal data, as set out in the Commission's communication[111,112]. The standardisation initiative active for QKD systems is the European Telecommunications Standards Institute's Industry Standards Group (ETSI-ISG). This judges as mandatory the need for traceable measurement at single photon level. The target is to develop the metrological expertise and capabilities to meet the needs of future developments in QKD systems, and quantum networks using photons to link quantum processing nodes. Components of these systems include single- and entangled-photon sources, single-photon detectors, true physical quantum random number generators, quantum repeaters and integrated waveguide circuits.

3.10.1.4 Quantum Enhanced Measurements

Quantum enhanced optical measurements e.g. the exploitation of quantum phenomena such as entanglement and other non-classical state correlations to yield sensitivity and accuracy better than purely classical approaches, are among the challenges. The statistical scaling of uncertainties with $\sqrt{n}$ (where n is the number of uncorrelated and independent measurements) is referred to as the Standard Quantum Limit (SQL) or "shot noise" in quantum optics. A more favourable statistical scaling of uncertainties can be achieved if non-classical correlations (e.g. entanglement) are used to correlate the probe fields before letting them interact with the system to be measured, allowing the SQL boundary to be exceeded. The target is to develop theoretical and technological capabilities for operating optical systems (e.g. sub-shot noise imaging, ghost imaging, phase measurement) or opto-mechanical systems (micro-cavities), in the quantum regime, beyond the SQL.

3.10.1.5 SPS establish new standards

The target is the development of highly efficient single-photon sources (SPS) for the realisation of SI traceable radiometry at the single photon. In radiometry a predictable single-photon source, i.e. a source that emits a calculable number of photons at a specific rate and wavelength, could act as standard source. Validation of these sources as primary standards with self-consistency within 10^{-5} will require the development of methodologies for the characterisation of the efficiency of the photon collection system and comparison with existing standards.

Additional research priorities have been identified below.

3.10.2 Primary standard detector

It is expected that in the near future four of the seven base units of the SI system will be redefined: the kilogram, the ampere, the kelvin and the mole, where each of these units will be based on a fixed numerical value of a fundamental constant: the Planck constant, the elementary charge, the Boltzmann constant and the Avogadro constant. Radiometry contributes to this change by a conversion coefficient to photometric units giving CIPM a firmer basis for fixing the fundamental constants in their revision of the SI. Development of new improved standard detector (based on photoelectric effect in silicon) and its subsequent exploitation to measure fundamental constants to 1 ppm will demonstrate the equivalence among primary standards. Further exploitation of the improved primary standard detectors will aim to shorten the traceability chain.

3.10.3 New transfer standards

LED based transfer standards: Incandescent lamps are widely used as working standards. However, the EU has started to phase out incandescent lamps for general lighting purposes in favour of energy efficient LEDs. Lamp manufacturers may no longer continue to maintain the expertise and facilities for producing incandescent lamps. Consequently, new methodologies for source based standards, most probably using LEDs, will be needed.

VU, EUV and THz transfer standards: Technical innovations in Vacuum Ultraviolet (VUV), Extreme Ultraviolet (EUV), and Terahertz (THz) radiometry are increasingly important in space and climate research (solar VUV emission), semiconductor industry (EUV lithography, EUVL) and security (THz scanner). The growth of these fields will require traceable radiometry in these extreme spectral ranges. In cooperation with detector developers, new types of semiconductor photodiodes will be characterized for responsivity, stability, homogeneity and linearity in the VUV and EUV spectral ranges for potential use as transfer standards. The potential application of free electron lasers to EUVL for traceability requires online intensity monitoring of femtosecond EUV pulses at frequencies beyond 100 MHz.

3.11 Thermometry

Temperature is one of the most frequently measured physical quantities in science and industry. That implies that precise knowledge of temperature and related quantities is fundamentally important for many applications. The development of new and more efficient production techniques and energy saving measures will help to deliver the Europe 2020 strategy through promoting sustainable economic growth[113]. The ability to reliably measure temperature is also critical in understanding and addressing many of the challenges facing Europe including climate change[114], energy security[115] and the burden of increasing healthcare costs. Thus this TC provides essential underpinning metrological support to many of the EU's strategic priorities.

Key metrological challenges are identified below.

3.11.1 Metrology for the SI unit and the measurement of thermodynamic temperature: redefinition and realization

With the redefinition of the kelvin in 2018, the measurement of thermodynamic temperature, T, that is primary thermometry, (to determine T-T_{90} and T-T_{2000})[ii] is growing in importance. These measurements and capabilities are essential for implementation of the new guide for temperature measurement, the *Mise-en-Pratique* of the definition of the kelvin (*MeP*-K), and in the longer term to support the development of a new unified temperature scale in the 2020s. In support of the *MeP*-K, practical primary thermometry is necessary to address the growing requirement for *in-situ* traceability and long-term driftless (or self-validated) temperature monitoring. In the short to medium term (prior to the new temperature scale) underpinning technologies need to be exploited to facilitate improvements to the current ITS-90 realization (and so extend its life). To do this, attaining accuracies below the millikelvin level are required through in-depth studies of the ITS-90 defining fixed points and thorough investigation of the intrinsic performance of current interpolation instruments. In parallel, novel thermometry approaches need to be investigated (e.g. replacement of current interpolating sensors, new interpolation schemes, optical methods) to support the *MeP*-K and for the future temperature scale. Such low uncertainties (below 1 mK) are required to ensure low uncertainties are attained in the dissemination chain, but are also required in high value manufacturing.

[ii] T_{90} and T_{2000} represent temperatures taken with the two temperature scales currently in place, the International Temperature Scale of 1990 (ITS-90) and the Provisional Low Temperature Scale of 2000 (PLTS-2000).

In the longer term (2020s+) fundamental challenges associated with traceability at the extremes of temperature such as below 0.0001 K or above 3500 K (e.g. plasmas), as well as the meaning and measurement of temperature in the very small low particle number regime, need to be addressed.

3.11.2 Metrology for humidity and moisture

Humidity and moisture comprise several quantities related to temperature, mass and amount of substance that are frequently measured because water molecules interacting with other molecules in gases, liquids and solids influence a wide range of physical, chemical and biological processes. Research is needed for removing fundamental obstacles to improving reliability in, for example, monitoring global warming and moisture control in high-tech production. More fundamental and universal definitions are needed to obtain comprehensive SI traceability in relative humidity and moisture measurements, improved uncertainty is needed in calculations of water vapour pressure in pure phase and mixed with other gases, and new methods are needed for primary realisations of humidity and moisture units in wider ranges.

3.11.3 New technologies for temperature measurement

New technologies mean that new temperature sensing methods, e.g. new thermocouples or surface-embedded (or deposited) sensors, will need characterizing and their reference functions determined. Novel thermometry approaches such as those based on optical methods, for example, fibre Bragg gratings, Raman scattering and fluorescent time decay, need to be quantitatively assessed, requiring improved thermal environments for their calibration and characterization. Possible thermometry methods, such as Raman scattering in solids, micro-fluorescence, advanced thermal microscopy, are all in use and/or under development but the issue of traceability on the small scale has yet to be addressed. More conventional thermometry methods at lower temperatures still in need of further development are, e.g., magnetic and noise thermometry. At the very small scale in low particle number systems, where equipartition may not have taken place, careful thought needs to be given to ensure that the concept of temperature itself still applies.

3.11.4 Metrology for thermal properties

At high temperatures there is a need to develop new measurement techniques for thermal transport properties, using both steady-state and transient methods. Steady-state methods are often used in developing thermal conductivity reference materials to provide traceability for industries. However, at higher temperatures steady-state methods face challenges in material and sensor degradation. In contrast, transient methods use relatively simple measurement techniques but rely on complicated mathematical models. The consequence is that measurement uncertainty analysis needs to be further developed.

Underpinning metrology for thermal transport properties at micro to nano scales is needed to support R&D and manufacturing of new high-tech innovative materials and devices. This includes areas such as thermoelectric thin films, photoelectric thin films and thermal and environmental barrier coatings.

There is also a need for reference materials for thermal conductivity, thermal diffusivity, specific heat capacity and bulk density: collaboration on this with the research community related to the International Union of Pure and Applied Chemistry (IUPAC), the International Confederation for Thermal Analysis and Calorimetry (ICTAC) and the International Association of Chemical Thermodynamics (IACT) is essential.

3.12 Time and Frequency

Time is one of the seven SI units, measured with an accuracy of 10^{-15} to 10^{-16} and is the most accurately measurable of the SI units. That is why time and frequency measurements are used to increase the accuracies of other units. Realization of the unit of time plays a central role within the SI because it is used in the realization of the meter, volt and ampere. Also, the best current time and frequency standards available, having accuracy of the order of 10^{-17}, are an important reference for various tests of fundamental physics including Einstein's general relativity.

In supporting economic growth, the need for better atomic clocks and time-frequency measurements in communications, network management, avionics, defense, navigation and space applications is increasing. Two current examples of important drivers for development of time and frequency metrology are European space projects: the Atomic Clock Ensemble in Space (ACES), which is to fly on the International Space Station, and the European Global Navigation Satellite System (GALILEO). Requirements relate to a faster internet, faster data transfer in telecommunications, and time stamping and electronic signatures in secured communications and financial transfers: all important drivers for the development of time and frequency systems.

3.12.1 The development of accurate ground atomic clocks

Europe has a long-established capability in microwave atomic clocks and now about eight European primary frequency standards contribute to the realization of the International Atomic Time (TAI) scale. Current research within EMRP[116] is on high-accuracy optical clocks with trapped ions focused on the development of ultra-precise optical clocks using laser-cooled trapped ions with target accuracy order of 10^{-17} level. Further work [117] is on international timescales with optical clocks, opening the possibility of a future redefinition of the second in terms of an optical transition frequency.

Present research and development related to ground atomic frequency standards follows two distinct threads: (i) laboratory primary clocks and (ii) clocks for industrial applications [118] including miniaturization. The strategy for development of laboratory clocks is based on improvement of microwave clocks and the development of new optical clocks. Microwave standards would be improved through better theoretical knowledge of the interactions between atoms and electromagnetic fields, and also through the use of low noise and high-quality electronics and cryogenic oscillators.

For new optical clocks there are many potential atomic reference transitions, including nuclear transitions: research is necessary to define the best candidate. In parallel with this, better understanding is required of atom and ion trapping technology, and new and improved tools for local frequency comparison (at a level exceeding that of present state of the art), local oscillators, laser stabilization, atom manipulation techniques and optical frequency measurements based on frequency combs are required.

3.12.2 Time and frequency dissemination and comparison

In Europe, many atomic frequency standards have been developed in different metrology institutes and in industry. These clocks are installed in space satellites and ground stations, research centres, and in the industrial and defence sectors. For dissemination of the time signal to users and for comparisons there is (i) NTP time dissemination through the internet (accuracy 1 ms) widely used for computer time synchronization, and (ii) time and frequency dissemination through radio broadcast antennas (μs accuracy). The next step is dissemination through GNSS satellites. Using satellite common view based methods it is possible to achieve about 5 ns accuracy, whereas Two-Way Satellite Time and Frequency Transfer (TWSTFT) methods provide 1 ns accuracy in the realization of the time scale UTC. Accurate time transfer between two geographically distant sites is dominated by satellite systems (GNSS or TWSTFT). In the last 10 years, time and frequency transfer via developed fibre infrastructure is a good alternative to satellite methods and timing accuracy at the 100 ps level is achieved.

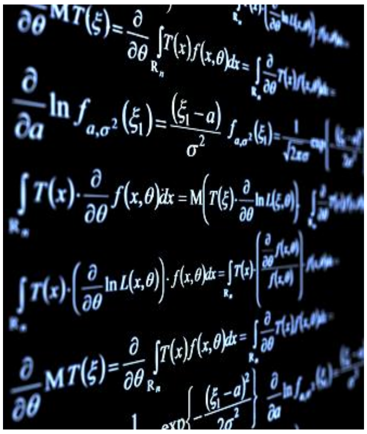
Nowadays, time and frequency transfer (TFT) support emerging applications in energy and environment. TFT is very important for time synchronization of deep space tracking networks and for GNSS.TFT has a great role for new clock development and is especially important in optical clock comparison, geodesy, radio astronomy, space exploration and realization of UTC. These main triggers introduce new targets for time and frequency community related to TFT for the next 10 years. Through joint research on development of new systems and improvement of current techniques for ground systems, frequency transfer uncertainty will be improved from 10^{-17} level to < 10^{-18} in the pan-European area. Also time transfer uncertainty will be improved from <1 ns to <100 ps. A similar goal exists in the strategy plan related to space systems. Improvements can be expected by utilizing of the additional signals from GNSS which will allow real time determination of the propagation delays through the atmosphere, utilization of higher data rates in TWSTFT, and reduction of noise and delay variations in ground equipment used for the reference signals.

3.12.3 Accurate time scale generation and traceability

Currently 30 countries are represented in the EURAMET TC for Time and Frequency. These institutes contribute to the generation of the UTC time scale using more than 130 commercial Cs and H masers. The different CNSS receivers used during time scale generation and the results related to national time scales and uncertainties are published on the BIPM web site. Several institutes use primary frequency standards which are used also for time scale generation. One of the aims of research and development projects and comparisons are the development of new standards for time scale generation and industrial applications, dissemination of time and frequency information with low uncertainty, and the comparison of reference equipment for improvement of uncertainties in time scale generation.

3.13 Mathematics and Modelling for Metrology

Measurement uncertainty evaluations underpin metrology. Without them measurement results cannot be compared, either among themselves or with reference values given in a specification or standard. The foundation of traceability is the propagation of uncertainties from primary standards provided by national metrology institutes (NMIs) to industrial end users. Unreliable evaluation of uncertainties or insufficient analysis of interlaboratory and key comparisons can seriously affect the quality of the European (and international) metrology systems which may have a huge negative economic impact. Therefore, research on advanced uncertainty evaluation or aiming for harmonization of methods in emerging areas like network metrology, inverse methods and dynamic measurements are an important element in a programme of R&D addressing the SI. Such research could greatly assist in accelerating the progress of the work of the Joint Committee for Guides in Metrology (JCGM) and standardization committees (e. g. OIML, CEN, ISO) towards new documents and guidelines, thereby yielding great benefit for European economies by supporting manufacturing and trade.



Modelling is an essential tool in metrology, providing critical understanding of the performance of complex measurement systems and their uncertainties, and thus also providing evidence-based guidance for their development and optimization. Modelling is critical in the analysis and interpretation of data, e.g. from multi-parameter measurement systems, measurement networks and for image analysis. Modelling, e.g. atomistic, thermodynamic and multi-physics modelling, can also be used to reduce the amount of testing required by improved selection of measurement parameters, or replace the need for measurements, with particular benefit for measurements that are either difficult, costly or hazardous to perform (e.g. radioactivity, harsh and dangerous environments). Modelling is an essential element in developing and maintaining an effective metrology infrastructure.

4 Building capacity for a coordinated European measurement infrastructure

4.1 Introduction and key challenges

The need for capacity building in NMIs and DIs is always present and is required to follow both the demands of stakeholders and the development of technology, and also to develop scientific and technical research capabilities in areas of strategic national and regional importance. Capacity building is necessary to create and sustain a balanced and integrated European metrology network, its infrastructure and research capability, providing support to all European nations and thus enabling Europe to remain competitive internationally.

The necessity for capacity building in emerging NMIs was highlighted by the external EMRP Midterm Evaluation 2011[119]:

> *"EMRP is not having the desired effect in terms of capacity building in those countries with limited or no metrology research capability ..."*

Capacity building is required in individual NMIs and DIs, in particular in emerging NMIs and DIs, and also to provide shared high level capability particularly in support of international research efforts, for example for advanced neutron metrology facilities for application to fusion (ITER) research and accelerator technologies (e.g. Hadron therapy) and metrology for earth observation (climate change monitoring).

Recognizing these issues, there is need for capacity building to underpin the vision of a coherent, efficient, sustainable and integrated European metrology network, which:

- is demand-oriented,
- adequately responds to the needs on various technological levels,
- recognises national, regional and European needs,
- makes use of all member states' representation in the bodies of EURAMET to develop a strategic approach - adopting smart specialisation[120] and avoiding unnecessary duplication, and
- provides knowledge transfer across Europe.

A strength of the European metrology landscape is its heterogeneity across the European countries, with obvious cost-benefits to providing the European metrological infrastructure. Future capacity building activity needs to continue taking advantage of this by avoiding unnecessary duplication.

A particular challenge for capacity building is to increase the capability of partially developed or emerging metrology systems in areas of national and regional importance. Current metrological capabilities in emerging European NMIs varies, starting on one hand with NMIs that do not yet have approved and published CMCs in the BIPM KCDB[121] nor QMSs acknowledged by EURAMET TC-Q[122], to emerging NMIs that have already started to participate in EMPR projects[iii]. Small and emerging NMIs may face a lack of critical mass and resources. Very often,

[iii] As of August 2012, EURAMET members comprised of 108 institutions in total: 37 National Metrology Institutes, 71 Designated Institutes. Ref http://www.euramet.org/fileadmin/news/Impact_Assessment.pdf

in the beginning of the development, metrological and research capabilities serve to assure traceability for legal metrology needs[iv] in the country and only later are further research capabilities established.

4.2 Scope of activities

Metrology capacity building activity is expected to be supported by various national, regional and European funding mechanisms, including infrastructural funding[123]. Within the framework of EMPIR, and as foreseen in the co-decision on EMPIR[124] (Annex II), two capacity building mechanisms are present:

- Research Potential projects:
  Projects for the development of research capabilities in NMIs and DIs
- Human & Institutional Capacity Building:
  Activities for the consolidation of the metrological core competence of NMIs and DIs

Research Potential projects (RPot) are aimed at the development of the potential for metrology research of the participating organizations which have evident need to establish or further develop basic levels of metrological research expertise in particular measurement areas. They aim to enable future participation in research projects.

The projects need to: be demand oriented, have a European dimension and critical mass, focus on EURAMET's infrastructure and expertise to provide appropriate internal knowledge transfer to emerging members, be based on horizontal collaboration for the development of new metrological infrastructures in a coordinated way ("smart specialisation"), and demonstrate significant impact to the entire quality infrastructure.

Human & Institutional Capacity Building (HI-CB) activity is mostly related to basic development of the metrological infrastructure that includes the following:

- training on specific measurement procedures and improvement of traceability and uncertainty,
- training on comparisons and proficiency testing,
- training on metrological infrastructure, NMI management and implementation of relevant EU legislation,
- training for preparation for participation in metrology research projects,
- training, events and preparation of materials on awareness raising, and
- short mobility grants (e.g. attached to a comparison exercise).

4.3 Key outcomes

The key outcomes of the capacity building projects and activities are expected to include:

- research potential established or improved in institutes, enabling their successful participation in future research projects
- new/improved measurement capacity established in institutes

[iv] Legal metrology comprises measurements related to consumer and business protection, health protection and environment protection.

- improved management and planning in the institutes, including strategy development, smart specialisation, sharing of resources on national and international levels, consolidation of the existing measurements in institutes

To ensure maximum benefit from capacity building investment, there is need to establish a metrology capacity map and also to identify national, regional and European priority needs in order to establish an action plan for future capacity building. This is particularly relevant to identifying the shared high level capability that needs to be developed across Europe in support of multinational activity, e.g. fusion research.

5 Increasing the impact of metrology research

5.1 Pre and Co-normative Metrology Research

5.1.1 Key challenges and background

Documentary Standards produced by Standards Development Organisations (SDO) and Measurement Standards with traceability to the SI produced by NMIs have common goals, in particular:

- underpinning regulations,
- improving performance, quality and reliability,
- ensuring compatibility between products,
- improving efficiencies and reducing costs, and
- instilling confidence.

NMIs and SDOs also have the common goal of improving consensus for the benefit of the economy, society and the protection and sustainability of the environment. The technical specifications of documentary standards promote the use of robust, reliable measurements and good practice in their use; robust and reliable metrology underpins the value contribution made by (technical) documentary standards. It is an essential partnership.

> *"The metrology community should enable better and/or faster regulations and standards, by providing the often-missing independent scientific input on measurement methods and their limitations."*[125]

There is, as one would expect, a history of collaboration with SDOs in metrology research projects, both informally at the project level with experts from NMIs being on Standards development committees, and formally. The SDOs can provide invaluable guidance on standardisation needs with potential for high impact, whilst the NMIs can provide neutral technical expertise to the standards development process. To illustrate the formal interaction, in the EMRP Energy and Environment calls of 2013, relevant CEN and CENELEC Technical bodies were invited to identify their needs to EURAMET. This resulted in ten funded projects addressing those needs.

The Co-operation agreement between CEN-CENELEC and EURAMET (2010) has the aim of promoting the value of standardization within EURAMET's projects and to encourage CEN and

CENELEC to inform EURAMET about metrology research needs identified during standardization. Active collaboration has been facilitated through the establishment of formal liaisons between EURAMET TCs/EMRP projects and CEN/CENELEC Working Groups.

Reinforcing the importance of the need for cooperation between metrology and standards activity, the impact assessment report[126] accompanying the Commission Proposal on the follow-up to EMRP identified, on the basis of the interim review of EMRP, that "*the lack of dedicated instruments supporting regulatory / standardisation roadmaps limits industrial exploitation, and thus the broader economic impacts*". To address this, a targeted programme on pre- and co-normative research has been established within the framework of EMPIR.

5.1.2 Scope of activities

The aim of pre- and co-normative research is to develop the metrological basis that is required for documentary standardisation, for example the development of traceable measurement methods and the provision of validated data sets. To maximise its impact, pre- and co-normative research needs to address the specific, documented and prioritised demands of the European and International Standards Developing Organizations (SDOs) for metrology that has potential for high impact. It is to be expected that such standardisation needs will be driven by legislation and EU directives, as well as by industrial needs.

Pre and co-normative research should also address the "grand challenges in standardisation" and strategic priorities for European standardisation, e.g. as identified by the European Union[127], where the metrological R&D needs of several Technical Committees, and potentially of more than one SDO, can be addressed. Greater impact can be expected to be achieved by adopting a grand challenge approach.

5.1.3 Key outcomes

The outcomes of the pre and co-normative research are expected to include:

- More responsive metrological research capability underpinning priority Standardisation activities, including in support of regulations and EU Directives.
- Increased mutual cooperation of European NMIs and DIs with CEN/CENELEC and other international SDOs, leading to a better targeted and coordinated European metrology infrastructure.
- Increased impact of previous iMERA-Plus and EMRP research projects, leveraged through new and improved International Standards.

Furthermore, such collaborative research will foster the development of standards as important routes to impact from the outset of metrology research projects, to the benefit of all parties.

5.2 Support for Increasing the Impact of Prior Research

Depending on the nature of a metrology research project the full exploitation of results, for example in terms of technology transfer to industry or contributions to standardization, is not always possible during the project's lifetime but requires a process after the end of the project. In other cases, unexpected results are generated which could be exploited in a way that was not foreseeable or achievable within the project lifetime. Opportunities to maximise the impact of research outputs of prior projects needs to be exploited.

Within the framework of EMPIR, the specific instrument *Support for Impact Projects* (SIP) aims to realize the potential for further exploitation of knowledge generated in prior metrology research projects. Such further exploitation may include:

- An identifiable contribution to a documentary standard in response to a request from a Technical Committee or Working Group of a European or International standards developing organization (SDO).
- An identifiable contribution to a regulatory process in response to a request from a European or International regulatory body.
- Transfer of specific technology or knowledge to a commercial business in response to a request to progress their innovation activities (e.g. product or process development).

EMPIR's Support for Impact Projects have a clear focus on dissemination and exploitation of the outputs of previous iMERA-Plus, EMRP or EMPIR research projects. To ensure impact will be achieved, a key requirement is for an external request for the work from an organization ready to take up the outputs of the project and move them on to impact outside the metrology community. To provide a faster, more timely response to address stakeholder requirements, Support for Impact Projects should be relatively small and of short duration.

The key outcomes of such projects, aimed at increasing the impact of prior research, are expected to include:

- Improved International Standards achieved more timely, thus having greater impact.
- Improved International Regulations founded on robust and rigorous science.
- Adopted knowledge and technology leading to innovation and enhanced economic activity.

6 Glossary

(to be completed at final drafting stage)

AC	Alternating Current
ACES	Atomic Clock Ensemble in Space
AGT	Acoustic gas thermometry
BIPM	International Bureau of Weights and Measures (Bureau International des Poids et Mesures)
BSRN	Baseline Surface Radiation Network
CB	Capacity Building
CCI	Commission for Climatology of WMO
CERN	European Organization for Nuclear Research (Conseil Européen pour la Recherche Nucléaire)
CCL	Consultative Committee for Length
CCM	Consultative Committee for Mass and Related Quantities
CCQM	Consultative Committee for Amount of Substance: Metrology in Chemistry and Biology
CC	Consultative Committee (CIPM)
CEN	European Committee for Standardization (Comité Européen de Normalisation)
CENELEC	European Committee for Electrotechnical Standardization.
CEOS	
CERN	European Organization for Nuclear Research (Conseil Européen pour la Recherche Nucléaire)
CGPM	General Conference on Weights and Measures
CIESM	Hydrochanges Program for Mediterranean deep water
CIMO	Commission for Instrument and Methods of Observation (WMO)
CIPM	International Committee for Weights and Measures (Comité International des Poids et Mesures)
CLIC	Compact Linear Collider
CMC	Calibration and Measurement Capabilities
CMM	Coordinate Measurement Machine
CNSS	
CTE	Coefficient of Thermal Expansion
DC	Direct Current
DCGT	Dielectric-constant gas thermometry
DI	Designated Institute
DTR	Day Temperature Range
EAP	Environment Action Programme
EARS	EMRP HLT01 (EARS)
ECV	Essential Climate Variables
EDM	Electronic distance meter
EEA	European Environment Agency
E-ELT	European Extremely Large Telescope
ELI-NP	Extreme Light Infrastructure - Nuclear Physics
EM	
EMF	Electromagnetic Field
EMPA	Swiss Federal Laboratories for Materials Testing and Research, Dübendorf
EMPIR	European Metrology Programme for Innovation and Research
EMRP	European Metrology Research Programme
ENV	Environment Call (EMRP)
E-PRTR	European Pollutant Release and Transfer Register
ERB	Earth Radiation Budget
ESS	European Spallation Source
ETRS89	European Terrestrial Reference System 1989
ETSI	European Telecommunications Standards Institute
ETSI-ISG	European Telecommunications Standards Institute’s Industry Standards Group
EURAMET	European Association of National Metrology Institutes
EUV	Extreme Ultraviolet

EUVL	Extreme Ultraviolet Lithography
FAO	Food and Agriculture Organization
FG-FNMID	Focus Group on Facilitating National Metrology Infrastructure Development (EURAMET)
GALILEO	European Global Navigation Satellite System
GAW	Global Atmosphere Watch
GCOS	Global Climate Observing System
GDP	Gross Domestic Product
GEO	Group on Earth Observations
GES	Good Environmental Status
GHz	Gigahertz
GLONASS	Globalnaya Navigatsionnaya Sputnikovaya Sistema (Global Navigation Satellite System)
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GRUAN	GCOS Reference Upper-Air Network
HI-CB	Human and Institutional Capacity Building
HIFU	High Intensity Focused Ultrasound
HITU	High Intensity Therapy Ultrasound
IACT	International Association of Chemical Thermodynamics
IAEA	International Atomic Energy Agency
ICP-MS	Inductively Coupled Plasma - Mass Spectrometry
ICT	Information and Communications Technology
ICTAC	International Confederation for Thermal Analysis and Calorimetry
ID-MD	Interdisciplinary - Multidisciplinary
ILC	International Linear Collider
IMERA-Plus	Implementing Metrology in the European Research Area (programme preceding EMRP)
INRIM	Istituto Nazionale di Ricerca Metrologica
IPCC	Intergovernmental Panel on Climate Change
IR	Infra-red
IRS	
ISO	International Standards Organization
ISTI	International Surface Temperature Initiative
ITER	International Thermonuclear Experimental Reactor
ITRS	International Technology Semiconductor Roadmap
ITS-90	International Temperature Scale of 1990
IUPAC	International Union of Pure and Applied Chemistry
IVD	In Vitro Diagnostics
JCGM	Joint Committee for Guides in Metrology
JRP	Joint Research Project (R&D projects in EMRP and EMPIR)
KCDB	Key Comparison Database
KET	Key Enabling Technology
LED	Light Emitting Diode
LHC	Large Hadron Collider
MEMS	Micro Electro Mechanical System
MeP	Mise-en-Pratique
MHz	Megahertz
MRA	Mutual Recognition Agreement
MRI	Magnetic Resonance Imaging
NEA	Nuclear Energy Agency
NMI	National Metrology Institute
NMR	Nuclear Magnetic Resonance
NOAA/ESRL	NOAA Earth System Research Laboratory, Boulder
OIML	International Organization of Legal Metrology (Organisation Internationale de Métrologie Légale)
oVOC	Oxygenated Volatile Organic Compound
PET	Positron Emission Tomography / Privacy Enhancing Technologies
PLTS-2000	Provisional Low Temperature Scale of 2000
PMOD/WRC	Physikalisch-Meteorologisches Obseratorium Davos / World Radiation Center
Pt-Ir	Platinum-Iridium

QKD	Quantum Key Distribution
QMS	Quality Management System
RBE	Relative biological effectiveness
REACH	Registration, Evaluation, Authorisation & Restriction of Chemicals
RF	Radiofrequency
RMO	Regional Metrology Organization / Regional Meteorological Office
RPot	Research Potential (EMPIR Call)
SDO	Standards Developing Organization
SET	Single Electron Transistor
SI	International System of Units (Système International d'Unités)
SIP	Support for Impact (EMPIR Call)
SPD	Single Photon Detectors
SPECT	Single Photon Emission Computed Tomography
SPS	Single Photon Sources
SQL	Standard Quantum Limit
SRA	Strategic Research Agenda
T&F	Time and frequency
TAI	International Atomic Time (Temps Atomique International)
TC	Technical Committee (EURAMET, SDOs)
TC-AUV	Technical Committee of Acoustics, Ultrasound and Vibration (EURAMET)
TC-EM	Technical Committee for Electricity and Magnetism (EURAMET)
TC-F	Technical Committee for Flow (EURAMET)
TC-IR	Technical Committee for Ionising Radiation (EURAMET)
TC-L	Technical Committee of Length (EURAMET)
TC-M	Technical Committee of Mass and Related Quantities (EURAMET)
TC-MC	Technical Committee of Metrology in Chemistry (EURAMET)
TC-PR	Technical Committee of Photometry and Radiometry (EURAMET)
TC-Q	Technical Committee for Quality (EURAMET)
TC-T	Technical Committee of Thermometry (EURAMET)
TC-TF	Technical Committee for Time and Frequency (EURAMET)
TEM	Transmission electron microscopy
TFT	Time and Frequency Transfer
TG	Task Group (EURAMET)
THz	Terahertz (300 GHz to 3 THz)
TLEP	Future Circular Collider e+e (FCC-ee -formerly known as TLEP)
TP	Targeted Programme (EMPIR)
TSEM	Transmission Scanning Electron Microscopy
TWSTFT	Two-Way Satellite Time and Frequency Transfer
UTC	Coordinated Universal Time
UV	Ultraviolet
VOC	Volatile Organic Compound
VUV	Vacuum Ultraviolet
WCRP	World Climate Research Programme
WG	Working Groups (EURAMET, SDOs)
WHO	World Health Organization
WMO	World Meteorological Organization
XRCD	X-ray Crystal Density
XRI	X-ray Interferometry

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