

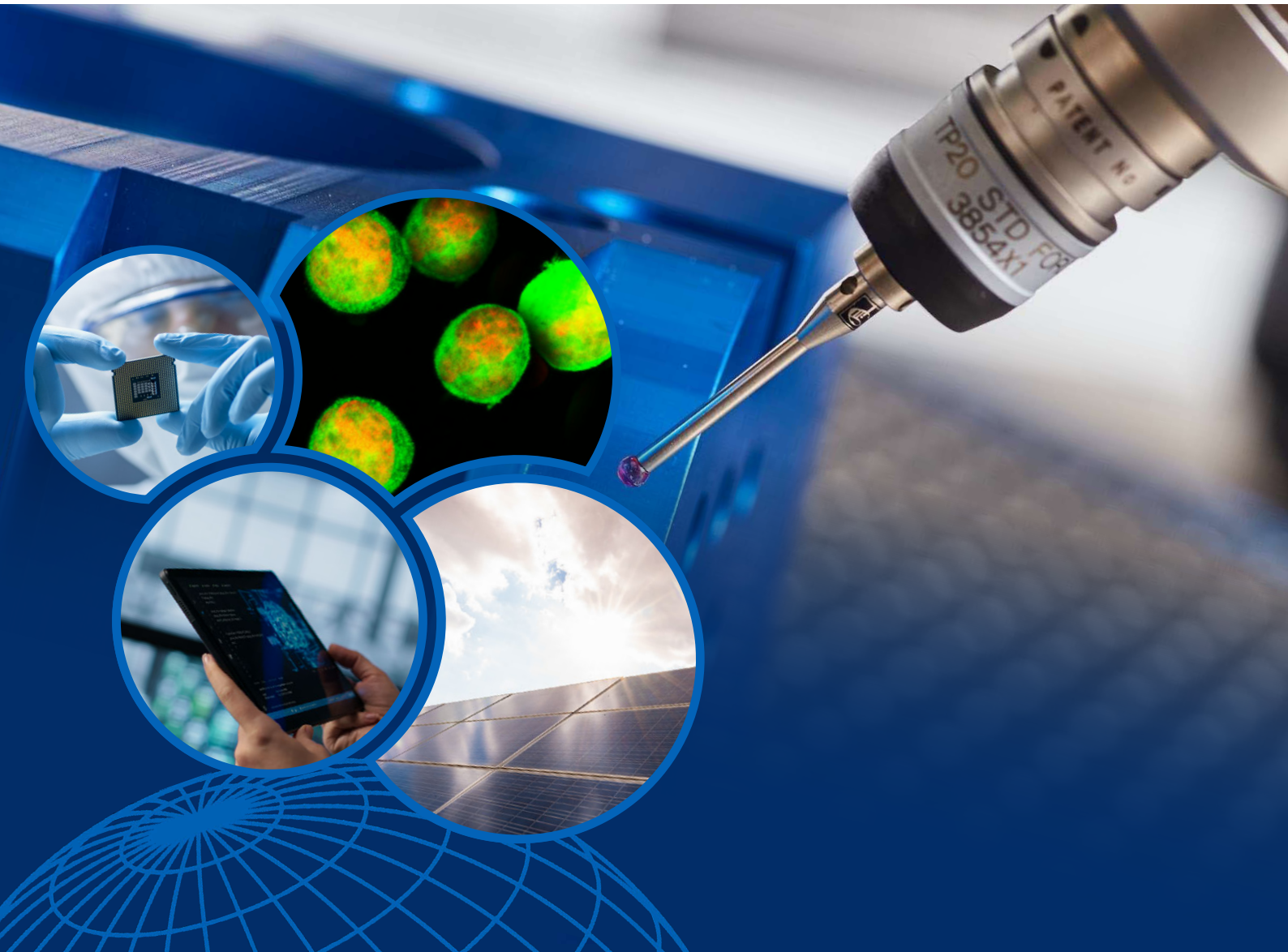


UNITED NATIONS
INDUSTRIAL DEVELOPMENT ORGANIZATION

Bureau
International des
Poids et
Mesures



SUSTAINABLE
DEVELOPMENT
GOALS



Metrology Matters: Accurate Measurements are Essential for a Better World

A collection of case studies showcasing how metrology is the silent backbone of the United Nations Sustainable Development Goals

Metrology Matters: Accurate Measurements are Essential for a Better World

A collection of case studies showcasing how metrology is the silent backbone of the United Nations Sustainable Development Goals

A joint publication prepared by the International Bureau of Weights and Measures (BIPM) and the United Nations Industrial Development Organization (UNIDO), and with contributions from the International Organization of Legal Metrology (OIML)

Table of Contents



Abbreviations, Acronyms, and Initialisms	5
Preface	9
Part I. Introduction	12
Context and Rationale	12
Global Measurement Framework	13
Strategic Role of the BIPM – OIML – UNIDO Collaboration	17
Challenges for Metrology	19
Metrology and the UN Sustainable Development Goals (SDGs)	20
Part II. Metrology to Support the SDGs	24
SDG 1 No Poverty	24
SDG 2 Zero Hunger	26
SDG 3 Good Health and Well-Being	28
SDG 4 Quality Education	32
SDG 5 Gender Equality	34
SDG 6 Clean Water and Sanitation	36
SDG 7 Affordable and Clean Energy	38
SDG 8 Decent Work and Economic Growth	40
SDG 9 Industry, Innovation and Infrastructure	42
SDG 10 Reduced Inequalities	46
SDG 11 Sustainable Cities and Communities	48
SDG 12 Responsible Consumption and Production	50
SDG 13 Climate Action	52
SDG 14 Life Below Water	54
SDG 15 Life on Land	56
SDG 16 Peace, Justice and Strong Institutions	58
SDG 17 Partnerships for the Goals	58
Part III. Reflections	64
Key Takeaways and Opportunities	64
Continued Activities through 2030	65
Acknowledgements	66
Annex. 12 Featured Case Studies	67

Abbreviations, Acronyms, and Initialisms



AfCFTA	African Continental Free Trade Area
AM	Additive Manufacturing
AFRIMETS	Intra-Africa Metrology System
APMP	Asia Pacific Metrology Programme
ASEAN	Association of Southeast Asian Nations
AzMI	Azerbaijan Institute of Metrology
BIPM	International Bureau of Weights and Measures
BMKG	Meteorology, Climatology, and Geophysical Agency of Indonesia
BSN	National Standardization Agency of Indonesia
CBKT	Capacity Building and Knowledge Transfer Programme
CCU	Carbon Capture and Utilization
CENAMEP AIP	National Metrology Center of Panama
CGPM	General Conference on Weights and Measures
CIPM	International Committee for Weights and Measures
CMCs	Calibration and Measurement Capabilities
CMI	Czech Metrology Institute
CMMs	Coordinate Measuring Machines
CMS/ITRI	Center for Measurement Standards in the Industrial Technology Research Institute of Chinese Taipei
CNES	French Space Agency
COOMET	Euro-Asian Cooperation of National Metrological Institutions
CRM	Certified Reference Material
CSIR-NPL	Council of Scientific and Industrial Research–National Physical Laboratory of India
DCC	Digital Calibration Certificate
DFM	Danish Fundamental Metrology
DI	Designated Institute
DPP	Digital Product Passport
EAC	East African Community
EAEU	Eurasian Economic Union
ECVs	Essential Climate Variables
EMNS	European Metrology Networks
EMPIR	European Metrology Programme for Innovation and Research
EMRP	European Metrology Research Programme
EURAMET	European Association of National Metrology Institutes
EV	Electric Vehicle

Global ACI	Global Accreditation Cooperation Incorporated (formerly ILAC) Global
GCOS	Climate Observing System
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GLONASS	Globalnaya Navigazionnaya Sputnikovaya Sistema (Russia's GNSS)
GNSS	Global Navigation Satellite System
GPS	Global Positioning System (US)
GULFMET	Gulf Association for Metrology
IAEA	International Atomic Energy Agency
IAQ	Indoor Air Quality
IEC	International Electrotechnical Commission
IFCC	International Federation of Clinical Chemistry and Laboratory Medicine
IGOs	Intergovernmental Organizations
ILAC	International Laboratory Accreditation Cooperation (now Global ACI)
IMO	International Maritime Organization
INetQI	International Network on Quality Infrastructure
INM	Instituto Nacional de Metrología, NMI of Colombia
INMETRO	National Institute of Metrology, Quality and Technology of Brazil
ISO	International Organization for Standardization
JCTLM	Joint Committee for Traceability in Laboratory Medicine
KATS	Korean Agency for Technology and Standards
KazStandard	Kazakhstan Institute of Standardization and Metrology
KEBS	Kenya Bureau of Standards
KCDB	BIPM Key Comparison Database
KRISS	Korea Research Institute of Standards and Science
LDCs	Least Developed Countries
LED	Light-Emitting Diode
LPBF	Laser Powder Bed Fusion
MASM	Mongolian Agency for Standardization and Metrology
METAS	Federal Institute of Metrology of Switzerland
MNPs	Micro- and nanoplastics
MOCCA	Ministry of Climate Change and Environment of the UAE
MoIAT	Ministry of Industry and Advanced Technology of the UAE
MPA	Maritime and Port Authority of Singapore
MRA	Mutual Recognition Arrangement
MRgRT	Magnetic Resonance Imaging-guided Radiotherapy

MSL	Measurement Standards Laboratory of New Zealand
NAB	National Accreditation Body
NIM	National Institute of Metrology of China
NIMT	National Institute of Metrology of Thailand
NIS	National Institute of Standards of Egypt
NISIT	National Institute of Standards and Industrial Technology of Papua New Guinea
NIST	National Institute of Standards and Technology of the United States
NIT	National Institute of Technology of India
NMC, A*STAR	National Metrology Centre, Agency for Science, Technology and Research of Singapore
NMI	National Metrology Institute
NMIJ	National Metrology Institute of Japan
NMIM	National Metrology Institute of Malaysia
NMISA	National Metrology Institute of South Africa
NML-BSTI	National Metrology Laboratory, Bangladesh Standards and Testing Institution
NOAA	National Oceanic and Atmospheric Administration of the United States
NPL	National Physical Laboratory of India
NPL	National Physical Laboratory of the United Kingdom
NPTG	National Power Transmission Grid of Mongolia
NSAI	National Standards Authority of Ireland
NSB	National Standards Body
OIML	International Organization of Legal Metrology
OIML-CS	International Organization of Legal Metrology Certification System
PT	Proficiency Testing
PTB	Physikalisch Technische Bundesanstalt, NMI of Germany
QI	Quality Infrastructure
QI4SD	Quality Infrastructure for Sustainable Development
QMS	Quality Management System
RLMO	Regional Legal Metrology Organization
RMO	Regional Metrology Organization
SAF	Sustainable Aviation Fuel
SASO	Saudi Standards, Metrology and Quality Organization of Saudi Arabia
SDGs	Sustainable Development Goals
SIDS	Small Island Developing States
SI	International System of Units
SIM	Sistema Interamericano de Metrología / Inter-American Metrology System
SLBS	Saint Lucia Bureau of Standards
SNSU-BSN	National Metrology Institute of Indonesia
SOLAS	International Convention for the Safety of Life at Sea

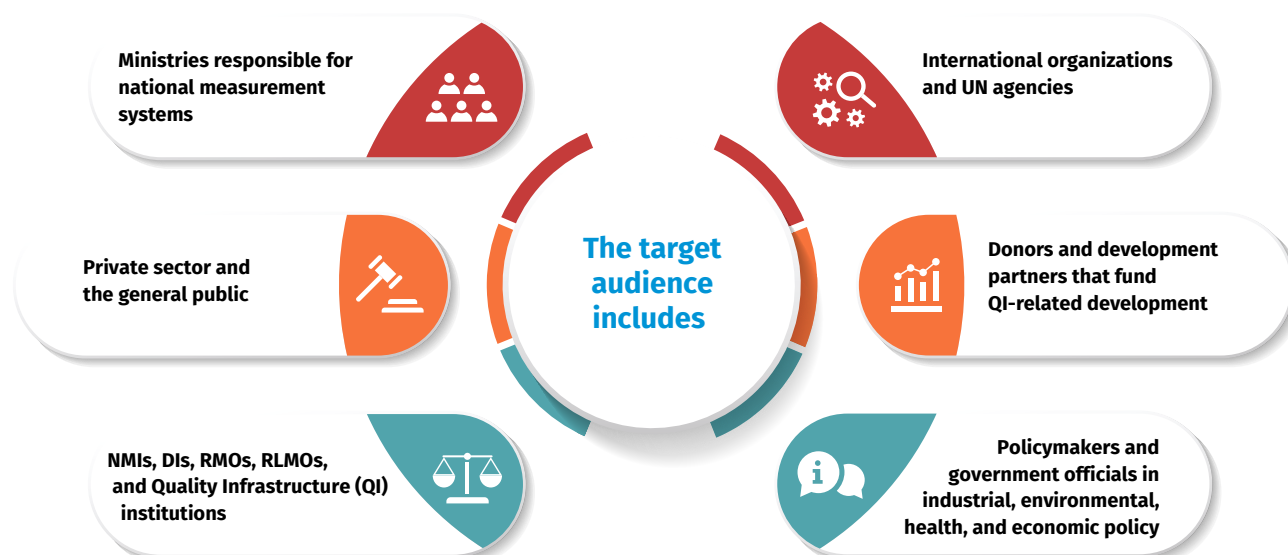
STAR	Spectroscopically Tuneable Absolute Radiance calibration and characterization Optical Ground Support Equipment (or STAR-cc-OGSE)
STEM	Science, Technology, Engineering, and Mathematics
TBT	Technical Barriers to Trade
UAE	United Arab Emirates
UAL	Underwater Acoustics Laboratory (Türkiye)
UKSA	UK Space Agency
UME	TÜBİTAK National Metrology Institute of Türkiye
UN	United Nations
UNECE	UN Economic Commission for Europe
UNIDO	United Nations Industrial Development Organization
UTC	Coordinated Universal Time
UNIIM	Ural Research Institute for Metrology
UzNIM	Uzbek National Institute of Metrology
VGM	Verified Gross Mass
VNIIM	The D.I. Mendeleev All-Russian Research Institute for Metrology
VSL	Van Swinden Laboratorium, NMI of the Netherlands
WADA	World Anti-Doping Agency
WASH	Water, Sanitation, and Hygiene (WHO)
WHO	World Health Organization
WIM	Weigh-In-Motion
WMO	World Meteorological Organization
WTO	World Trade Organization
ZMA	Zambia Metrology Agency

Thank you to the authors of the case studies from the National Metrology Institutes (NMIs), Designated Institutes (DIs), Regional Metrology Organizations (RMOs), and Regional Legal Metrology Organizations (RMLOs) for making this work possible.

Preface



This publication is a collection of case studies that showcase how accurate, reliable, and metrologically traceable measurements are the silent backbone of the United Nations Sustainable Development Goals (SDGs). Collected from National Metrology Institutes (NMIs) and Designated Institutes (DIs) worldwide, these real-world case studies present tangible, data-driven examples of how metrology contributes to specific SDGs.



These case studies can serve to strengthen awareness among policymakers, donors, and other stakeholders of metrology's role in sustainable industrial and social development. The publication presents a detailed and defensible description of the contribution of metrology to achieving the UN SDGs.

Part I. Introduction gives a brief explanation and rationale for the global measurement infrastructure, its interactions with other international organizations, a summary of metrology and its challenges, and how it supports the UN SDGs.

Part II. Metrology to Support the SDGs showcases a series of case studies that demonstrate how metrological solutions and interventions have addressed specific challenges, supported particular SDGs with quantifiable impact, and are essential to a better, more sustainable world.

The **Annex** features 12 of the case studies, two from each Regional Metrology Organization (RMO), from this collection.

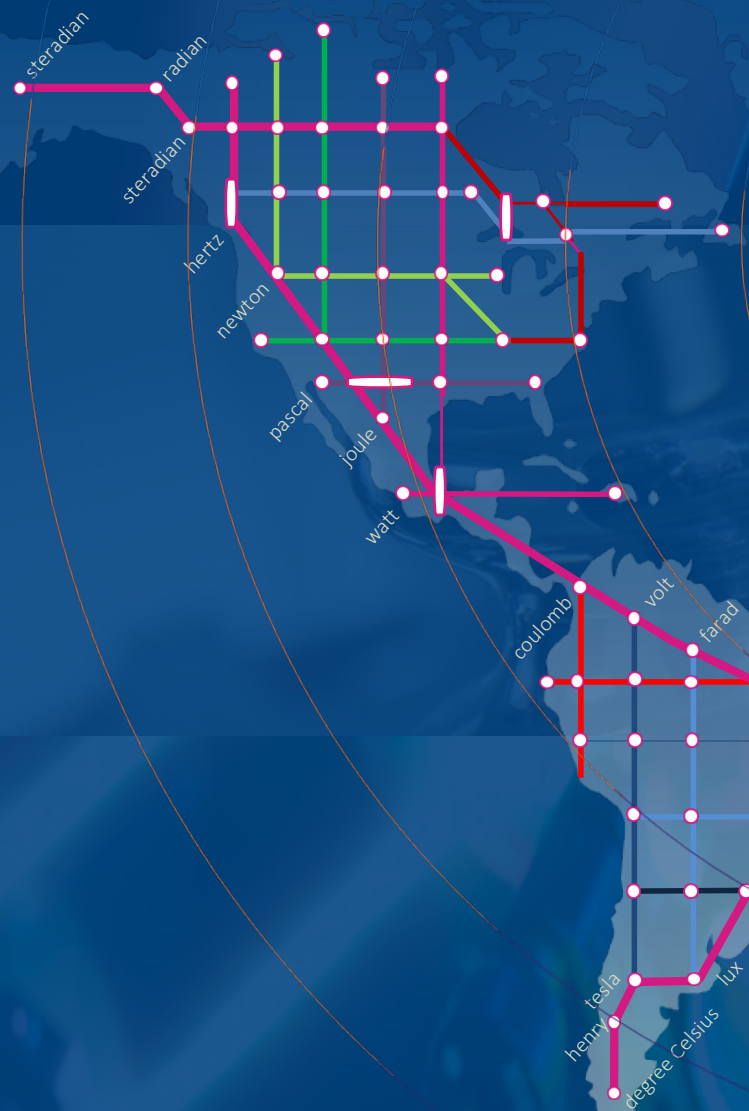
Part III. Reflections summarizes the key takeaways and metrology opportunities that were gleaned from this study. It describes ongoing efforts to highlight, promote, and evolve the case studies in various sectors, while continuing to collect new ones through to 2030.



The anticipated outcome of this publication is to enhance global recognition of metrology as a key enabler of the UN SDGs. In addition, it will promote a shared understanding of metrology and how international harmonized measurement systems contribute to national development priorities and global goals.

This is intended to lead to stronger integration of measurement systems into sustainable development, industrial, environmental, and health policies that support national and regional economies. The content of this publication and the resources developed by the BIPM, the OIML, and UNIDO will also serve as a communication and advocacy resource for the global metrology and quality infrastructure (QI) community.

Part I. Introduction





Part I. Introduction



Context and Rationale

While the impact of metrology on people's day-to-day lives may not be obvious, we all rely on accurate measurements to support even the most basic human functions, such as ensuring access to clean drinking water and safe food. Accurate measurements advance societal progress in the healthcare, agriculture, and green industries, thereby improving the well-being, job opportunities, and living conditions of the global population. These measurements also support monitoring of the planet's climate, land, and ecosystems, on which the population is dependent and to which it is intrinsically linked. Human progress and prosperity also depend on accurate measurements that enable sustainable development in industry, innovation, and infrastructure. A sound measurement infrastructure thereby contributes to virtually all the UN Sustainable Development Goals (SDGs)¹ to achieve inclusive and sustainable industrial development that supports all people, the planet, and global prosperity.

Metrology, the science of measurement, underpins and benefits all sectors of the economy by providing a framework for accurate, comparable, and trusted measurement data that supports vital economic and societal decision-making. Scientific metrology establishes measurement units and ensures their metrological traceability by linking units to internationally recognized reference methods and standards; industrial (or applied) metrology applies measurements in manufacturing processes to ensure accuracy and quality control; and legal metrology applies regulatory requirements to measuring instruments to support compliance and ensure fair trade. Together, the fields of metrology enable all industry sectors to precisely measure and control processing and manufacturing, robustly evaluate products, and advance technologies towards more sustainable goods and services. This spurs more resource-efficient consumption and production, directly supporting industrial innovation, competitiveness, and economic growth. Besides industry, reliable measurements are used in fundamental scientific research and advancements that will generate the technology of the future. Indeed,

there is a circular aspect: innovative metrology enables the development of cutting-edge measuring instruments, which, in turn, enables advanced metrology and improved metrological services.

Specific areas of metrology map across several sectors of the economy. For example, ionizing radiation metrology closely aligns with the energy and nuclear power sectors but also supports healthcare applications, such as nuclear medicine for diagnostic imaging in cancer diagnosis and treatment, and environmental monitoring to identify contaminants. Time and frequency, electrical, and mass metrology are ubiquitous and used across all sectors of commerce, energy, and transportation infrastructure. For example, they support global financial markets, telecommunications and smart-city networks, navigation, renewable-energy power grids, and logistics and supply chain management. Similarly, chemical and biological metrology support advances in biotechnology and pharmaceutical production.

Policy-level decisions based on trustworthy, high-quality data support public and government policies that satisfy national economic directives and ensure national security and prosperity. Accurate and reliable measurements are essential for policymakers to balance risk and reward and to make sound decisions. Examples include monitoring local and global emissions for air quality and climate change modelling, ensuring food safety for global markets, and making data-driven decisions in advanced manufacturing sectors such as aerospace and aviation production. To achieve these benefits, governments need to support and invest in their national metrology system and align it with current policy priorities and long-term strategic goals. They also need to provide the resources required to maintain and develop their capabilities.

Building metrological infrastructure into a national economy creates opportunities for economic growth and can add direct value to a country's Gross Domestic Product (GDP). This is vital

¹ UNIDO's contribution to the Sustainable Development Goals (SDGs) of the 2030 Agenda for Sustainable Development.

for developing nations; a basic framework of metrological infrastructure is needed to begin producing and exporting refined goods rather than commodities, while also ensuring marketplace equity between businesses and consumers. A metrology framework will generate more stable, value-added revenue while also developing local industry, fostering economic diversification, and creating jobs. International trade also relies on a harmonized global metrology infrastructure to ensure that product specifications, testing results, and certifications are recognized across borders. This preserves the resources of individual economies, minimizes technical barriers to collaboration, and builds confidence between global trading partners.

All successful economies depend on the “silent infrastructure” of metrology that operates in the background yet supports many functions fundamental to modern society. As this system is largely unseen, we might take for granted the trust that metrology protects: the water is safe to drink, the food is safe to eat, and it is safe to fly across the world. If the global measurement framework was to degrade, measurement errors would result, eroding public confidence and jeopardizing safety in trusted systems, such as financial services, transportation networks, and industrial processes.

Global Measurement Framework

Overview

At the global level, the metrology system is comprised of two principal intergovernmental organizations that collectively strengthen national and international metrology systems to work towards inclusive and sustainable industrial development. As established by the Metre Convention, the International Bureau of Weights and Measures (BIPM) coordinates international comparability and traceability of measurements and serves as an international centre for collaboration between Member States, RMOs and strategic partners to advance scientific metrology. A second intergovernmental treaty organization, the International Organization of Legal Metrology (OIML), coordinates legal metro-

logy infrastructures and develops model regulations and mutual recognition systems for legally controlled measuring instruments, measurements, and processes, helping to ensure consumer protection and fair trade. In support of the BIPM and the OIML, the United Nations Industrial Development Organization (UNIDO) assists countries in building quality infrastructure and institutional capacity for standards, metrology, testing, accreditation, and conformity assessment bodies/institutions to improve industrial competitiveness and market access. These organizations work together to provide a foundational framework that enables globally recognized, reliable, and harmonized measurement systems to support the UN Sustainable Development Goals (SDGs). In turn, the global measurement framework, together with documentary standards and laboratory accreditation systems, provide an integrated global quality infrastructure.

The CIPM MRA

The CIPM Mutual Recognition Arrangement (CIPM MRA) established by the International Committee for Weights and Measures (CIPM), provides a global framework for establishing the equivalence of national measurement standards and facilitating the mutual recognition of calibration and measurement certificates issued by the national laboratories. Confidence in international measurements is built on peer-reviewed, metrologically rigorous interlaboratory measurement comparisons conducted by the CIPM Consultative Committees (CCs) and regionally approved quality systems of the national laboratories. This process is designed to provide statements of measurement capabilities of each laboratory, as summarized by the calibration and measurement capabilities (CMCs) published in the BIPM Key Comparison Database (KCDB), as recognized by other participating institutions. In general, the technical capabilities reflect the industrial development and measurement needs of its national economy, and the quality of the CMCs is what matters, rather than the overall number of them.

The impartial scientific comparison of international measurement standards is the backbone that ensures the veracity of metrology systems worldwide. Access to and knowledge of national capabilities fosters transparency and confidence

among regulators, accreditation bodies, industry, and other laboratories that rely on this competency for global trade. For example, under the CIPM MRA, manufacturers can place confidence in “already tested” components from their multifaceted yet streamlined manufacturing supply chains and airlines can utilize repair shops around the world during aircraft operation and maintenance.

The CIPM MRA also strongly supports the terms adopted by the World Trade Organization (WTO) in its Agreement on Technical Barriers to Trade (TBT) for industrial and agricultural products, such as electrical appliances, vehicle components, and bulk or packaged food items. The agreement promotes recognition of conformity assessment results from other countries, provided they are based on positive assurance of conformity with technical regulations or standards. While not itself a conformity assessment activity, metrology remains a vital pillar of such assessments. This harmonization applies even when regulations differ and supports the concept of “*tested once, accepted everywhere.*”

CIPM MRA provides governments and other parties with a secure technical foundation for wider agreements related to international trade, commerce, and regulatory affairs. With over 25 years of success, the CIPM MRA allows decision-makers to select appropriate calibration and measurement services for use within their economy and internationally.

OIML Certification System

International measurements are also integral to the legal metrology infrastructure, which harmonizes regulations for measuring instruments used in trade and commerce, provides guidelines for medical equipment, and supports environmental monitoring and the enforcement of public safety laws. This infrastructure is reliant on accurate data and a sound measurement system. The OIML Certification System (OIML-CS) is a voluntary international framework for issuing, registering, and using OIML type evaluation and test reports and (OIML-CS-issued) certificates for measuring instruments used in legal trade and commerce. Based on the uniform technical requirements in OIML Recommendations, the OIML-CS aims to globally harmonize and accelerate national type approval processes by eliminating the duplication of testing across borders. As partici-

pating economies and signatories of the OIML-CS, OIML members can build confidence in the conformity of instruments under legal metrology control for global trade. This confidence is supported by reliable measurements, and facilitates international trade through clearly defined rules, including accreditation and peer assessments, and the mutual acceptance of test results and certificates.

When marketplace agreements become imbalanced, governments are often obliged to impose legal and/or regulatory requirements on measuring instruments. Examples might include fuel dispensers, electricity meters, and non-automatic weighing instruments, where a consumer has no way to verify the accuracy of the measurement. Many measurements and tests that support manufacturing and interoperability of measuring instruments are not subject to regulatory control. In these cases, the arrangements are laid out in individual contracts. However, they usually require the use of the metrology infrastructure, either directly or by reference via manufacturing and quality management standards, to ensure their appropriateness and technical reliability.

The Role of NMIs

At the national level laboratories nominated as National Metrology Institutes (NMIs) maintain national measurement standards and have the specific responsibility of disseminating measurements traceable to the International System of Units (SI) via their calibration and other measurement services. They establish metrological traceability to the SI either by directly realizing the units or by linking their national standards to those maintained by other institutes, through the CIPM MRA. In many countries, the NMI responsibility is delivered by more than one national laboratory, and Designated Institutes (DIs) are established to cover specific metrology areas (e.g., ionizing radiation).

The NMIs and DIs represent the apex of the national measurement system and, through the realization of the SI, directly connect to and support the metrological traceability of testing capabilities throughout their countries. A relatively small number of standards and services underpin countless calibrations that support industry measurements, and guarantee the quality of goods, products, and services across the globe. Furthermore, NMI and DI engagement in CIPM MRA ensures global comparability of their standards and services, ultimately building trust with the stakeholders they serve.

Decision-makers and policymakers need to maintain a clear vision of how their national metrology system, including the NMI and DIs, is intended to serve their nation's economic and societal needs. An existing metrology system for one nation may not be an appropriate model for another. Decision-makers should consider which other public and private enterprises can be used to

sustainably build the metrology functions needed to achieve the Sustainable Development Goals. Metrology systems should be built with the flexibility to respond to a nation's changing needs, while considering the interplay with the country's legislative arrangements, enforcement authorities, and available metrology expertise within the relevant technical sectors.²



RMOs and RMLOs

For many developing economies, the Regional Metrology Organizations (RMOs) and Regional Legal Metrology Organizations (RMLOs) serve as a launch point to participate in the global metrology system (**Figure 1**). Engagement brings additional benefit as the RMOs and RMLOs in turn engage with their relevant regional economic block (where they exist). The more developed States within RMOs and RMLOs also have a unique opportunity to support and bolster neighbouring economies through cooperation on shared metrological practices and services across borders.

Integral to the CIPM MRA, the six current RMOs play a critical role in supporting the objectives of the CIPM MRA and worldwide harmonization and coordination for global metrology. They are the organizations that review and monitor the Quality Management Systems (QMS) of the NMIs and DIs participating in the CIPM MRA.

The Joint Committee of the Regional Metrology Organizations and the BIPM oversees the operation of the CIPM MRA. In four of the six regions, the scientific and legal metrology organizations are combined; though not in the Asia Pacific or Europe. See **Figure 2**.

² National metrology systems - Developing the institutional and legislative framework" (OIML D 1:2020)

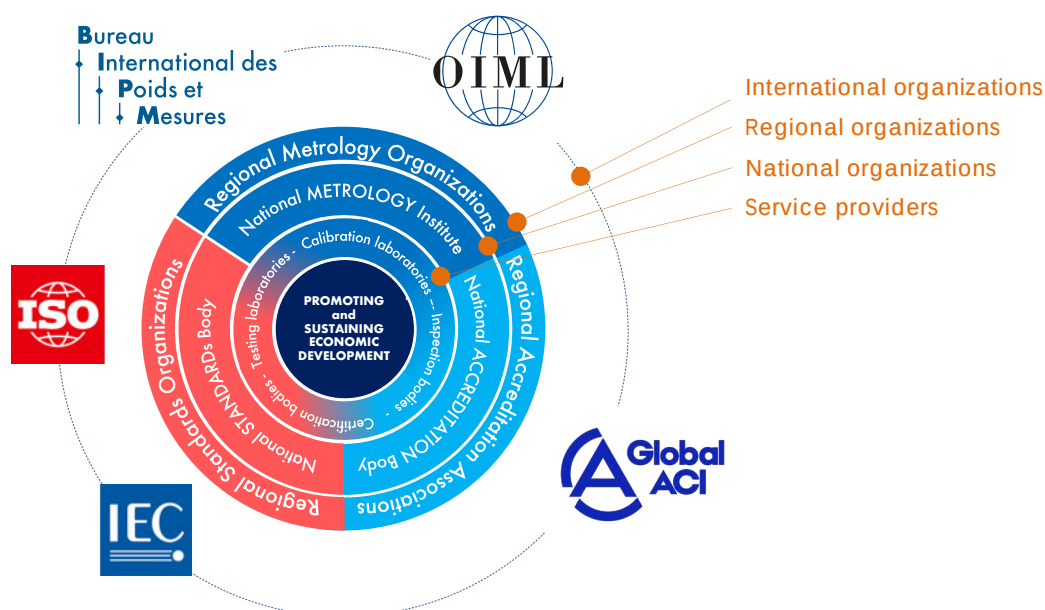


Figure 1. The role of NMIs and Regional Metrology Organizations (RMOs) within the international quality infrastructure.

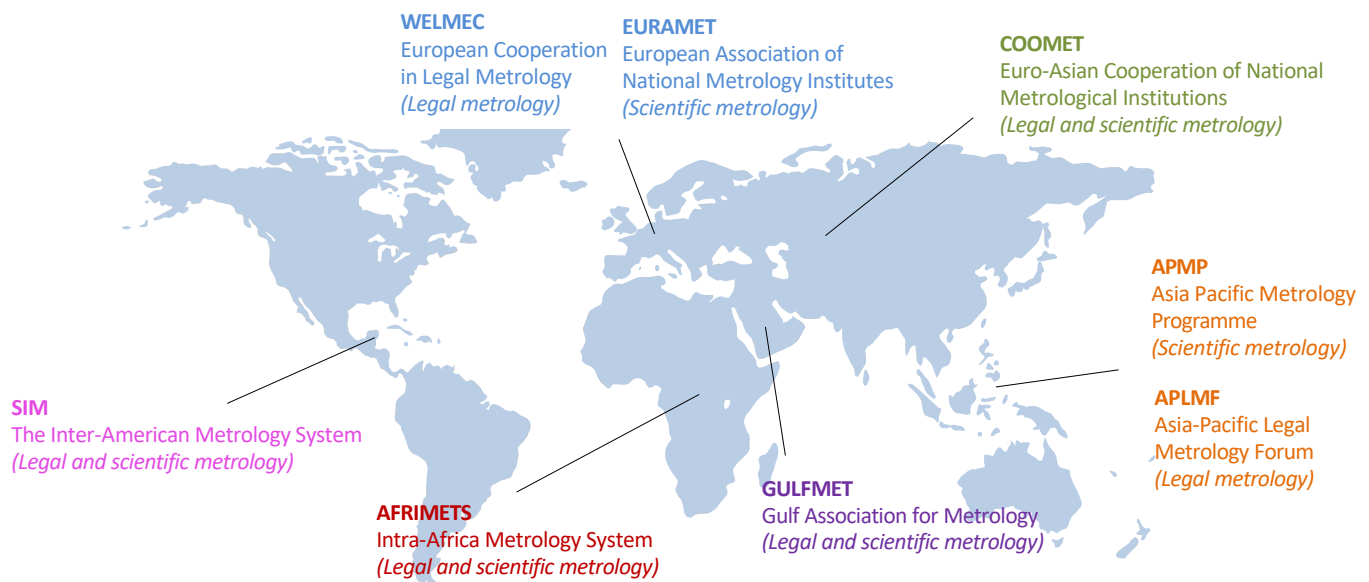


Figure 2. Regional scientific and legal metrology organizations.

RMOs and RLMOs also collaborate with the other regional organizations representing documentary standards and accreditation, collectively stimulating the development of regionally relevant quality infrastructure.

Quality Infrastructure and Industry

The challenge of inclusive and sustainable industrial development is best met by an economy with a high-functioning quality infrastructure. Quality Infrastructure (QI) is a necessary concept that decision-makers can use to support the effective operation of national economies and their recognition and access to global markets. It is made up of “organizations (public and private) together with the policies, relevant legal and regulatory framework, and practices needed to support and enhance the quality, safety and environmental soundness of goods, services and processes.”³ Through this international network, regional and national quality infrastructure organizations provide a forum to discuss matters of common interest. This network also connects metrology players with National Standards Bodies (NSBs), National Accreditation Bodies (NABs), and development partners.

As noted earlier, the small set of high level services provided by the NMIs and DIs enable a multitude of services to be provided by commercial laboratories that account for the vast majority of calibrations and tests used in

industry and commerce. Many of these commercial laboratories are accredited to ISO/IEC 17025 by bodies recognized by Global Accreditation Cooperation Incorporated (Global ACI), which ensures consistency amongst accreditation bodies, assuring the quality of over 115 000 laboratories worldwide. Global ACI is a vital component of the global quality infrastructure that ensures that testing data from one country is recognized in another. Global ACI collaborates with both the BIPM and the OIML and recognizes the role of the CIPM MRA and KCDB in verifying acceptable metrological traceability routes, usually to the SI.

Figure 3 shows the position of the NMIs or DIs, who serve as primary sources of metrological traceability, and illustrates how it is extended to industry through a network of accredited calibration laboratories. In some economies, local and regional authorities provide select calibration services. Industry then calibrates measuring instruments used in manufacturing, testing laboratories, or in commercial transactions under legal control.

³ [INetQI - Quality Infrastructure Definition](#)

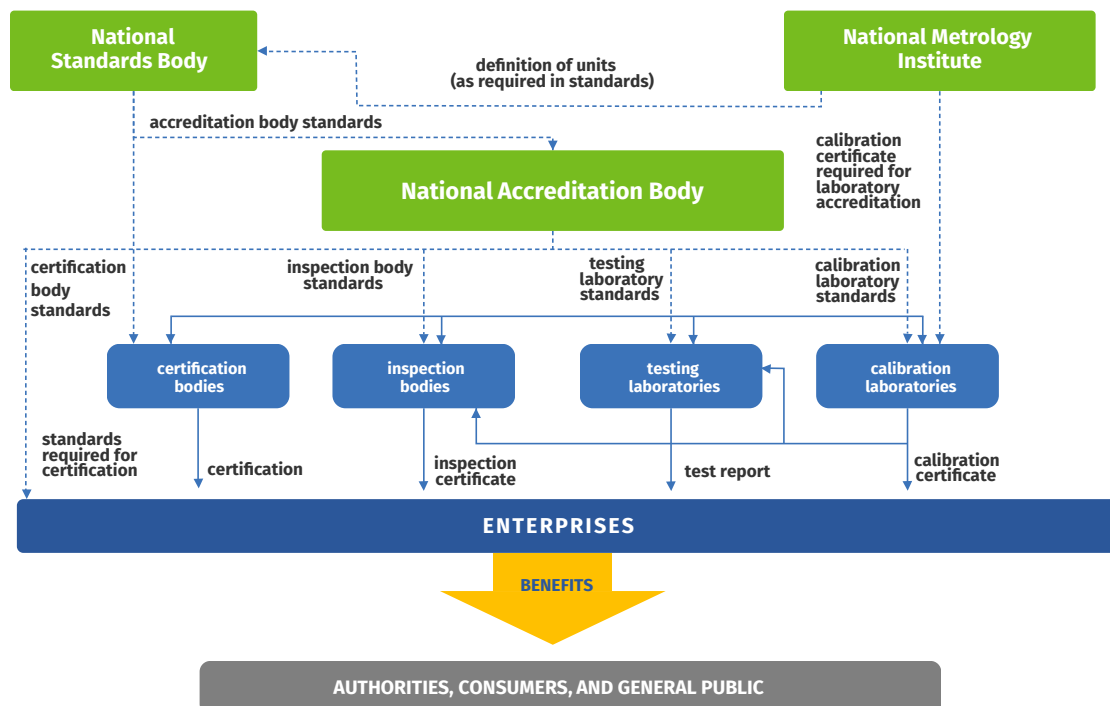


Figure 3. Elements of the quality infrastructure. Source: World Bank.⁶¹

The cost of maintaining accurate measurements typically accounts for a significant portion of industrial production and manufacturing overheads. Often classified under failure prevention and appraisal expenses within the broader cost of quality framework, this depends greatly on the development stage and the technological demands of each industry and can vary widely across companies relative to their total revenue. Although the numbers vary over time and differ across economies, the number of routine calibrations, inspections, or tests conducted daily in industrial production environments by accredited laboratories is substantial and critical to their success.

International Organizations as Partners

The institutional landscape of international metrology involves close collaboration with other international organizations that rely on accurate, reliable measurements to support their mission-based decisions. Other global organizations represent specific sectors of metrology, such as the International Atomic Energy Agency (IAEA) and the World Meteorological Organization (WMO). They connect to national measurement standards through cooperation with the BIPM and, in some limited cases, participate directly in the CIPM MRA.⁴ Similarly, the OIML liaises with numerous international organizations involved in trade, health, agriculture, and public safety, which are major stakeholders in the standards devel-

oped by their technical committees.⁵ Both the BIPM and the OIML closely with Global ACI, ISO and International Electrotechnical Commission (IEC) to advance the common goal of accreditation and standardization worldwide.

Through this nexus of national metrology institutes, calibration networks, international and regional metrology organizations, standards development organizations, and accreditation bodies, a robust, uniform metrology infrastructure ensures globally comparable, SI-traceable measurements across all countries.

Strategic Role of the BIPM – OIML – UNIDO Collaboration

Tripartite Partnership

The collaboration between the BIPM, the OIML, and UNIDO reflects a strategic alignment of mandates that gives science, regulation, and international development a beneficial unified voice, especially for developing countries. UNIDO relies on its active liaison with the BIPM and the OIML, as international metrology organizations, to fulfil its unique mission of promoting inclusive and sustainable industrial development and advancing the UN Sustainable Development Goals (SDGs).⁶

⁴<https://www.bipm.org/en/institutional-liaison>

⁵https://www.oiml.org/en/about/organizations-in-liaison/choiceorganization_view

⁶UNIDO's contribution to the Sustainable Development Goals (SDGs) of the 2030 Agenda for Sustainable Development.

⁶¹J. Luis Guasch, J.-L. Racine, I. Sanchez, and M. Diop. Quality Systems and Standards for a Competitive Edge. The World Bank, 6 2007.

Currently, not all UN Member States are members of the three organizations, creating gaps in access to the global measurement system. Currently, of the 193 UN countries, 111 participate in the activities of the BIPM and around 130 in the OIML. Those that do not yet participate in BIPM activities represent only about 2 % of global GDP despite accounting for around 15 % of the world's population, with many of these countries being Least Developed Countries (LDCs) and Small Island Developing States (SIDS). At the same time, several developed economies are not members of UNIDO, including the United States of America, Canada, and Australia. This situation underscores the strategic importance of the BIPM – OIML – UNIDO collaboration, as it allows the three organizations to extend beyond their individual memberships and collectively reach all countries, providing access to technical assistance, capacity building and international cooperation in metrology. When combined, these roles create a complete system that enables countries to obtain accurate measurements, apply them in practice, and use them to support economic and social progress and protect the environment.

The partnership between UNIDO, the BIPM, and the OIML is longstanding. This partnership recognizes that strengthening measurement systems is essential to economic growth, to reducing technical barriers to trade, and to supporting the integration of developing countries into the global economy. It also provides a basis for joint programmes, knowledge exchange, data sharing, and coordinated support to developing countries, ensuring that efforts across the three organizations are aligned and mutually reinforcing. Over time, this collaboration has expanded through joint initiatives and global platforms to promote a shared understanding of quality infrastructure and to coordinate support to countries. Efforts include the UNIDO Guidance Document on the OIML-CS and the Quality Infrastructure for Sustainable Development (QI4SD) Index,⁷ to which BIPM and OIML data and expertise contributed to assessing and benchmarking national quality infrastructure systems.

Strategy of Publication

This current publication is another instance of collaboration between the three organizations, building on their long-standing partnership to jointly promote the role of metrology in achieving the 2030 Sustainable Development

Agenda. It serves three strategic functions.

1. It strengthens advocacy by demonstrating, in practical terms, how international harmonized measurement systems contribute to national development priorities and global goals. By linking metrology to tangible outcomes such as improved health services, environmental monitoring, and trade competitiveness, it helps decision-makers recognize metrology as a critical enabler rather than a purely technical field.
2. It supports policy dialogue by providing a common reference point for governments, development partners, and technical institutions. The collaboration among the BIPM, the OIML, and UNIDO ensures that perspectives from science, regulation, and international development are brought together, enabling more coherent and informed discussions on strengthening national quality infrastructure systems.
3. It contributes to knowledge sharing across the global metrology and quality infrastructure communities. By drawing on the combined expertise of the three organizations, as well as the experiences of national and regional institutions worldwide, this publication helps bridge gaps among stakeholder groups, from policymakers to technical experts, and promotes a shared understanding of priorities, challenges, and solutions.

Through this integrated approach, the tripartite collaboration between the BIPM, the OIML, and UNIDO provides a strategic platform that connects the global measurement system with national development priorities and societal needs, ensuring that all countries, regardless of their current BIPM and OIML membership status, can benefit from accurate, metrologically traceable, and internationally recognized measurements.

The goals of this publication include:

- 1 **Advocacy for metrology** as part of the critical infrastructure in national, regional, and global development success
- 2 **Building a shared language for policymakers** to enable effective dialogue and impactful decisions
- 3 **Identifying and connecting stakeholders** to cooperatively and successfully achieve the SDGs

⁷ <https://hub.unido.org/qi4sd/2years2024>

Challenges for Metrology

Hidden by Design

Metrology systems are pervasive and seamless across the public and private sectors and are thus often overlooked; however, they have inherent value as the “silent infrastructure” upon which modern society depends. Their true value may only be recognized through the disruption caused when absent. Therefore, raising of awareness is an important step in making the case for investment of limited resources in a well-integrated national measurement system, especially in developing economies.

Metrology is utilitarian by nature and is often built into its tools of trade (i.e., measuring instruments) through their intrinsic design and operations, and thus, its impact may not be obvious. For example, in legal metrology, devices and measuring instruments, such as electricity meters and dynamic measuring systems (e.g., petroleum fuel dispensers) are generally “sealed” and may only be adjusted and calibrated by appropriate bodies. The test devices used to ensure the accuracy of measuring instruments in routine commercial transactions or commodity inspections are themselves calibrated, thus maintaining metrological traceability.

The indirect impact of metrology can pose a challenge in communicating to both policymakers and the public its role in supporting the routine day-to-day transactions in our society. Success in metrology is something that you do not have to think about. Its contributions are embedded within more recognizable outcomes, such as technological innovations, manufacturing efficiency, reduced waste, and enhanced data for clinicians or climate modelers. This makes it difficult to identify metrology as a primary driver of such progress. Furthermore, the impact of a particular metrological capability is often spread out across many economic sectors. Consequently, the costs of supporting the infrastructure are often not borne by the ministry or ministries responsible for the sectors impacted.

Infrastructure and Resources

Establishing a national measurement system with specialized laboratory functions requires substantial capital, with costs highly dependent on the metrological scope and the required measurement precision to deliver the services.

This may include the development or procurement of primary standards and advanced measurement instrumentation, as well as construction costs for high-precision laboratories with appropriate environmental controls. Additional maintenance and operational costs may also be significant, including the investment in obtaining a skilled technical workforce that is adequately trained, and maintaining the laboratory through appropriate accreditation activities (e.g., ISO/IEC 17025).

A particular challenge is that the national metrology system should support many different areas, ranging from industrial and economic activity to environmental monitoring and healthcare. Therefore, finding a successful funding model for the NMI and aligning it with the horizontal needs across many sectors is not easy.

It is also important that scientific, industrial, and legal metrology priorities are updated as national needs evolve and that independent assessments are conducted to ensure good alignment between future requirements and metrological capability. If an economy is focused on delivering routine services to industry and the broader community, the highest level of uncertainty may not be warranted. There is a risk that developing economies will overinvest in unnecessarily high-precision capabilities, incurring costs that far exceed their practical realization and overall benefits. The existence of the CIPM MRA helps manage these risks. Economies may collaborate, where appropriate, with neighbouring metrology systems to provide metrological traceability rather than independently maintaining all, or indeed any, primary standards, provided such arrangements adequately support national economic and industrial development requirements.

Career Entry and Opportunities

A further challenge is that developing a robust metrology system requires staff expertise that takes years to develop and relies on skills not taught in traditional Science, Technology, Engineering, and Mathematics educational programmes. Often, metrologists come from adjacent technical sectors, and unlike the traditional science-based professions, it may not be an obvious career choice. There is almost always a shortage of people with the necessary skills and experience in metrology. National metrology

laboratories must compete for talent that may have other more glamorous and lucrative opportunities. Those who choose a career in metrology, however, find it rewarding, motivated by its technical challenges, meaningful purpose, and societal contribution.

The growing needs of the technical private sector have also led to increased demand for scientific and industrial metrologists. This is especially important for the emerging technologies areas, but also for the established transportation, aerospace, and electronics industries. In some economies, retaining existing NMI and DI staff, who constitute a small and highly specialized workforce, may be challenging.

Metrology and the UN Sustainable Development Goals (SDGs)

Metrology, the science and practice of measurement, serves as a foundational infrastructure for achieving the SDGs by enabling accurate, reliable, and internationally comparable measurements across health, environment, energy, industry, trade, and public safety. This includes fostering development to sustainably support **People** to reduce poverty and promote gender equality through good health practices,

An effective metrology system provides **three essential factors**:

1 Traceability to the SI, or to internationally agreed reference materials or procedures

2 Regulated measurements and measuring instruments

3 Confidence via certification, standardization, accreditation, and calibration.

high-quality food and education, protect the **Planet** by ensuring clean water, sustainable production, and preserving life below water and on land, and increase societal **Prosperity** by promoting clean energy, innovative industries and sustainable cities and communities, resulting in reduced inequalities, and facilitating decent work and economic growth. These are unified global tasks that must be undertaken together internationally, regionally, and nationally.

Effective national metrology systems are critical enablers of sustainable development, supporting governments and industries in measuring, managing, and advancing towards the SDGs. Achieving the SDGs as part of the UNIDO 2030 Agenda is only possible through strategic partnerships and technical cooperation that are interwoven into robust, harmonized metrology systems. The overarching goal is to enhance the impact of industrial development on economic growth and to minimize technical barriers to trade between all countries.

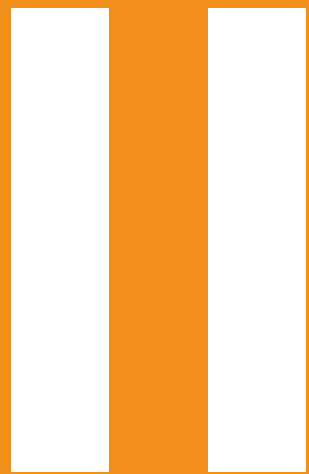
It is hoped that this document will inspire decision-makers in countries with emerging metrology systems by providing examples from around the world that illustrate the value of a well-integrated metrology infrastructure. Specifically, the study aims to highlight the foundational aspects, benefits, challenges, and quantifiable impacts of metrology through a series of illustrative case studies in scientific, industrial, and legal metrology that underpin the SDGs. Here, only a small subset of examples are presented from the vast possibilities across the RMOs, NMIs, and DIs. It is also befitting that this study coincides with the 2026 World Metrology Day theme: “Metrology: Building Trust in Policy Making”⁸ as these case studies highlight the essential role of accurate, metrologically traceable measurements as the basis for sound, transparent policymaking, regulations, and public trust.

⁸ <https://www.bipm.org/en/-/2026-02-13-world-metrology-day-2026-theme-announcement-1>



SUSTAINABLE DEVELOPMENT GOALS





Part II. Metrology to Support the SDGs





Part II. Metrology to Support the SDGs



The following compendium presents a series of short excerpts from over 60 case studies obtained from NMIs, DIs, and their partnering organizations that demonstrate how accurate measurements – from local to global – are essential to a better, more sustainable world. This collection is further supported by additional content drawn from NMI, DI, RMO, and RLMO websites and other informational sources to complement the extracts from the case studies. It aims to balance scientific, industrial, and legal metrology topics, RMO representation, and each of the individual SDGs. It is, however, far from an exhaustive collection.

Some of the case studies and metrological examples summarized herein support the objectives of a single SDG. Others contribute to more than one SDG. This collection is intended to represent not only the breadth of activities but also to reflect different stages of growth and evolution in the metrological programmes of many NMIs and DIs. A few case studies address the evolving metrology infrastructure itself, with significant downstream benefits for their economies and regions just emerging. More detail on each case study developed during this project is available on the BIPM website.⁹

Many of the NMIs and DIs work within their own national QI and metrology systems to enable sustainable industrial development for their own economies. They strive to build capacity that clearly aligns with the UN's inclusive and sustainable industrial development goals, and many have illustrated multifaceted approaches in achieving this objective. However, no single organization can achieve these goals alone, and benefits could be realized by working together towards these goals. The potential for further aligning individual scientific, industrial, and legal metrology activities to advance common interests are immense.

It can be seen too, that these independent, parallel activities from the NMIs and DIs also represent an “unintended collaboration” in the simultaneous development of solutions towards sustainable development goals.

Here we enumerate the SDGs and pull examples from the full set of over 60 case studies collected so far. A selection of 12 of these case studies are featured in the **Annex**. They balance scientific, industrial, and legal metrology topics, RMO representation, and cross-sections of the individual SDGs.

*The work undertaken by these NMIs and DIs exemplifies the contribution of accurate, metrologically traceable measurements and impactful measurement services and programmes that have demonstrated clear, discernible effects that support **People**, protect the **Planet**, and encourage societal **Prosperity**.*



SDG 1 No Poverty

Fair measurements in commerce help reduce poverty by building trust in commercial transactions across the marketplace – from local street markets to interstate commerce ports. The accurate calibration of measuring devices that are used to dispense commodities, such as fuel pumps, water meters or electricity meters, ensures that citizens pay only for what they consume. In many developing countries, these protections prevent vulnerable populations from being overcharged for basic public or essential services.

A combination of accurate measurement systems, legal metrology laws and enforcement protects low-income populations from economic losses in daily transactions. For example, in Kenyan markets, the Weights and Measures Department in the Ministry of Investments, Trade and Industry routinely inspects and certifies market weighing scales that are used to sell products such as meat, vegetables, and cereal grains. The Kenya Bureau of Standards (KEBS) ensures that the nation's mass metrology standards are traceable to the International System of Units (SI).¹⁰ Together, these agencies ensure that scales used in market and other commercial transactions are tested and correctly verified. This protects small farmers – often living at or below the poverty line – who could lose income due to incorrect sales or faulty scales. This also creates a level playing field for businesses and supports the growth of small businesses, enabling them to compete equitably in the marketplace.

Government-driven development of legal metrology legislation was crucial to the initial establishment of fundamental capacity building in many developing economies. Modern legal metrology programmes have been critical in correcting inaccuracies in the marketplace (e.g., fuel measurement discrepancies and net quantity in prepackaged products).

¹⁰ <https://www.bipm.org/bipm-unido-impact-study>

¹¹ Draft Kenya Quality Policy 2023, Section 2.2.2 Metrology.
<https://www.industrialization.go.ke/downloads>

This is vital to restoring trust and enabling fair economic transactions across multiple market sectors.

The result is a high-functioning national industry network that provides reliable products and services, reduces waste and inefficiencies at the production stage, and enables long-term, sustainable economic growth by enabling industries to scale faster and compete more effectively in global markets.

Several legal metrology case studies presented herein that support industrial growth illustrate that fundamental capacity building not only strengthens the infrastructure supporting a nation's economy and its global impact but also ensures that the general population can participate in a fair and equitable marketplace. For example, Saint Lucia has built metrology infrastructure over several years, which has now earned its citizens' trust in the government's regulatory oversight of commercial transactions, such as fuel dispensers.¹¹ Indonesia has developed and recently instituted a randomized-sampling inspection method for prepackaged goods,¹² which has both improved business performance and increased consumers' confidence in the marketplace.

In Zambia, the agricultural sector accounts for nearly 50 % of the workforce and around 7 % of national GDP. With the appropriate legal metrology framework and certification schemes for grain measuring instruments, the Zambia Metrology Agency (ZMA) has begun effective management across the agriculture sector.¹³ The Agency also manages weighing instruments for large-scale farmers (e.g., weighbridges, hoppers, and platform scales) and supports the agricultural industry in creating employment and achieving food security to advance national-level poverty reduction.

¹² 058-SIM-LC. Development of Metrology in the Small Island Developing State of Saint Lucia (SLBS)

¹³ 053-APLMF-ID. Regional Challenges on Prepackaged Goods for Strengthening the Economy, Industry, and Consumer Protection (APLMF)

¹⁴ 052-AFRIMETS-ZM. Strengthening Measurement Systems in Zambia's Agriculture through Standardized Trade Instruments and Quality Assurance (ZMA)



SDG 2 Zero Hunger

The production of high-quality food not only makes possible the export of food products but also supplies a nation's population with food that is fit for consumption. This is critical for the fight against hunger. In global food markets, grain moisture content determines crop pricing and storage safety. This directly affects food security and the income of farmers and customers. Metrological products and services ensure the calibration of moisture meters used across East Africa, Asia, and Central America, where incorrect readings can lead to farmers receiving unfairly low prices for rice, maize, sorghum, or wheat. NIMT, the National Institute of Metrology, Thailand, produces Certified Reference Materials (CRMs) of Thai 'rice' (without shell) and 'paddy' (with shell) with a well-established moisture content (ranging from 10 % to 18 %), and can accurately validate rice moisture meters well within the target requirement of 0.5 %.¹⁴

Chemical metrology has direct applications in global food sustainability, ensuring adequate agricultural output and reducing post-harvest losses. Precise chemical measurements ensure fertilizer nutrient concentrations are accurate, helping farmers avoid over-application that damages soil or under-application that reduces yields. For example, in South American countries, such as Brazil and Colombia, accredited laboratories including Centro de Qualidade Analítica (CQA) and the Instituto Agronomico de Campinas (IAC) in Brazil, and AGRILAB Laboratorios S.A.S. in Colombia, provide ISO/IEC 17025-compliant testing services for fertilizer composition, helping to support regulatory compliance and ultimately protect agricultural productivity.

With its use of CRMs, Proficiency Testing (PT) schemes, and capacity building across African food and feed testing laboratories, the National Metrology Institute of South Africa (NMISA) Mycotoxin Reference Material Programme¹⁵ has demonstrated a significant reduction in mycotoxin contamination in grain and nut exports over a 4-year time frame. This has provided a sustainable

transformation of the analytical foundation to reduce post-harvest losses, in addition to underpinning food safety capabilities for many NMIs and DIs. It has secured access to safe, high-quality staple foods for people across Africa, and reduced rejected export shipments, particularly to customers in highly-developed nations.

In addition to preventing food spoilage and enabling high-quality exports to global markets, adequate measurement services in food quality and food safety testing ensure that people have access to ample supplies of nutritious, safe food. This metrology capacity is multifaceted, as it supports Good Health and Well-Being (SDG 3) and enhances food security for many rural communities through sustainable agribusinesses.

Many new services are being developed across NMIs and DIs to address their nations' needs for food safety testing. A newly enacted PT scheme for "Basic Yellow 2" dye and cadmium in durian fruit has been shown to improve the capability of Thai food testing laboratories.¹⁶ The National Institute of Standards (NIS) in Egypt is developing RMs specifically for veterinary drug residues in animal products to meet the nation's food safety requirements.¹⁷ The Instituto Nacional de Metrología de Colombia (INM) maintains its own CRMs and PTs to support contaminant testing in cocoa¹⁸ and tilapia,¹⁹ two significant exports for Colombia. These examples may seem narrow in scope; however, they represent a positive trend among NMIs and DIs developing national-level metrology capabilities and specific measurement services that directly serve their economies' needs.

Many of the well-established NMIs and DIs from AFRIMETS, APMP, COOMET, EURAMET, and SIM have developed and continue to maintain robust measurement services in food safety and nutritional assessment. This includes the development of calibration standards and services, matrix-based CRMs and reference materials, as well as PT programmes and materials to support testing laboratories. While not an exhaustive list, the KCDB indicates that over 30 NMIs and DIs have capabilities in this area.²⁰ Over the past decade, the

the metrology community has hosted numerous food safety workshops and RMO-based focus and working groups to advance the capabilities of NMIs and DIs related to food safety and better align their services with stakeholders' needs.



¹⁰¹⁵APMP-TH. Food Security and Economic Stability for Thailand: Moisture Content in Rice (NIMT)

¹⁰⁵¹AFRIMETS-ZA. The Multiplier Effect: NMISA's Mycotoxin Reference Material Programme (NMISA)

¹⁰²³APMP-TH. Building Capacity for the Measurement of Contaminants in Durian Exports (TISTR)

¹⁰³⁰AFRIMETS-EG. Veterinary Drug-residue Monitoring to Ensure Egypt's Food Safety and Support Healthy Lives (NIS)

¹⁰⁰³SIM-CO. Metrology for Sustainable Competitiveness in Cocoa: Advancing Industrial Innovation and Inclusive Economic Growth (INM)

¹⁰⁰⁴SIM-CO. Promoting Competitiveness in Colombian Aquaculture: Metrological Traceability for the Control of Inorganic Contaminants in Tilapia (INM)

¹⁰BIPM Key Comparison Database (KCDB). Calibration and Measurement Capabilities (CMCs). <https://www.bipm.org/kcdb/>

SDG 3 Good Health and Well Being

It is well established that accurate medical measurements save lives. Many developed NMIs and DIs have developed ionizing radiation metrological reference standards for radiation dose calibration used in cancer radiotherapy. When hospitals calibrate their equipment to these standards, patients receive the correct radiation dose—neither too weak to treat the tumour nor too strong to damage healthy tissue. There is clinical evidence that the difference between under-treatment and over-treatment is approximately 2.5 %.²¹ Some clinical diagnostic standards in developing economies have been less consistent and less trustworthy. As an unfortunate example, machine errors in radiation dose have claimed the lives of patients, which occurred in Panama, where a 2001 International Atomic Energy Agency (IAEA) report²² indicated that at least five of a list of 28 pelvic cancer patients died due to an overdose caused by a machine error. Many NMIs now participate in the BIPM ionizing radiation programme to maintain metrological traceability of their nation's primary standards, while also ensuring the traceability of the IAEA dosimetry standards and the proper calibration of numerous medical devices used in clinical treatments.

Within the EMPIR project *Metrology for MR guided radiotherapy*, the National Metrology Institute in the Netherlands (VSL) demonstrated the potential of a newly-designed portable water calorimeter as a primary standard for a prototype magnetic resonance imaging-guided radiotherapy (MRgRT) system.²³ This device improved the dosimetry capability to deliver accurate absolute doses in patients with spine cancer, demonstrating the clinical feasibility of MRgRT. The results of the research enabled clinical trials using the prototype MR-linac device to proceed. For selected patient groups with renal cancer, the effectiveness of MRgRT was demonstrated to be on the same level as invasive treatments, thereby offering a non-invasive alternative to treatments such as surgery.

Thermometry measurements play a vital role in the health and safety of the population and in research applications. An important application is the refrigeration of vaccines, which depends on precise temperature measurement. During the COVID-19 pandemic and vaccine deployment, thermometers and cold chain data loggers were calibrated in local laboratories using NMI and DI standards. This ensured that vaccines remained within safe temperature limits, typically 2–8 °C.²⁴ Accurate measurements of this nature are vitally important despite being carried out routinely.

INM of Colombia also developed a qualitative molecular biology PT scheme for SARS-CoV-2 detection, the first of its kind in Colombia.²⁵ This included over 119 laboratories reporting results and covered more than 80 % of Colombia's provinces. The technical capabilities and coordination processes developed at INM and its partner health institutes in Colombia remain relevant today; similar PT exercises covering new respiratory viruses (for example Influenza A, Influenza B, and others) are underway. Through a coordinated regional response during the SARS-CoV-2 pandemic, NIM in China, led an APMP regional metrology effort focused on training, capacity building, and inter-laboratory testing to ensure the accurate performance of medical ventilators used in patient treatment.²⁶ In 2021, a group of NMIs demonstrated the high-accuracy quantification of biological reference standards for SI-traceable RNA measurement procedures used in COVID-19 diagnostic testing through a CIPM interlaboratory study.²⁷ The direct impact was timely support for diagnostic manufacturers in developing test kits and ensuring the quality of routine testing as it expanded across hospitals and laboratories worldwide.

Advances in cell and gene-based therapeutics, as well as other regenerative medicine products, rely on accurate cell characterization in complex biological diagnostic samples and materials. Flow cytometry has been used as a routine method for detecting and characterizing highly heterogeneous cells and other biological entities. The lack of comparability across cytometry instruments and methods prompted NIST to form the

²¹Consultative Committee for Ionizing Radiation (CCRI) Strategic Plan Strategy 2030+. 3rd edition. <https://www.bipm.org/en/committees/cc/ccli>

²²International Atomic Energy Agency (IAEA) 2001, "Investigation of an accidental exposure of radiotherapy patients in Panama", Report of a Team of Experts, 26 May–1 June 2001

²³036-EURAMET-NL. Improved Dosimetry Enables Online MRI-guided Radiotherapy (VSL)

NIST Flow Cytometry Standards Consortium²⁸ with regenerative medicine experts and stakeholders from industry, academia, and government. The initial results are promising, including the development of calibration microspheres for cytometry measurements based on metrologically traceable fluorescence intensity values. The consortium is also taking steps towards standardizing flow cytometry methods and harmonizing instrumentation operations.

NMIs and DIs may have the resources to establish and maintain extensive consortia with industry and stakeholders to develop new metrology capability and services for healthcare applications. However, their national healthcare needs require their metrology infrastructure to maintain a broad portfolio of measurement services that support a wide range of clinical diagnostics. International consortia, such as the Joint Committee for Traceability in Laboratory Medicine (JCTLM)²⁹ and the International Federation of Clinical Chemistry and Laboratory Medicine (IFCC),³⁰ serve as fora to facilitate and promote global standardization of clinical measurement capabilities. Membership of the JCTLM and contributions to its database on higher-order reference materials, methods, and services illustrate the extensive participation of NMIs and DIs with metrology and measurement service capabilities in laboratory medicine and healthcare applications.

Many NMIs and DIs continue to develop specialized measurement services to meet the healthcare needs of their populations and their national economies. Together with a European metrology research consortium, the Czech Metrology Institute (CMI) established a competency centre in 2020 for intraocular pressure metrology (IOP) to provide hundreds of eye tonometry calibrations per year.³¹ The project focused on developing expertise and knowledge within the central European region, an

²⁸Biswas, K., Muthukumarasamy, V., Bai, G. et al. A reliable vaccine tracking and monitoring system for health clinics using blockchain. *Sci Rep* 13, 570 (2023). <https://doi.org/10.1038/s41598-022-26029-w>

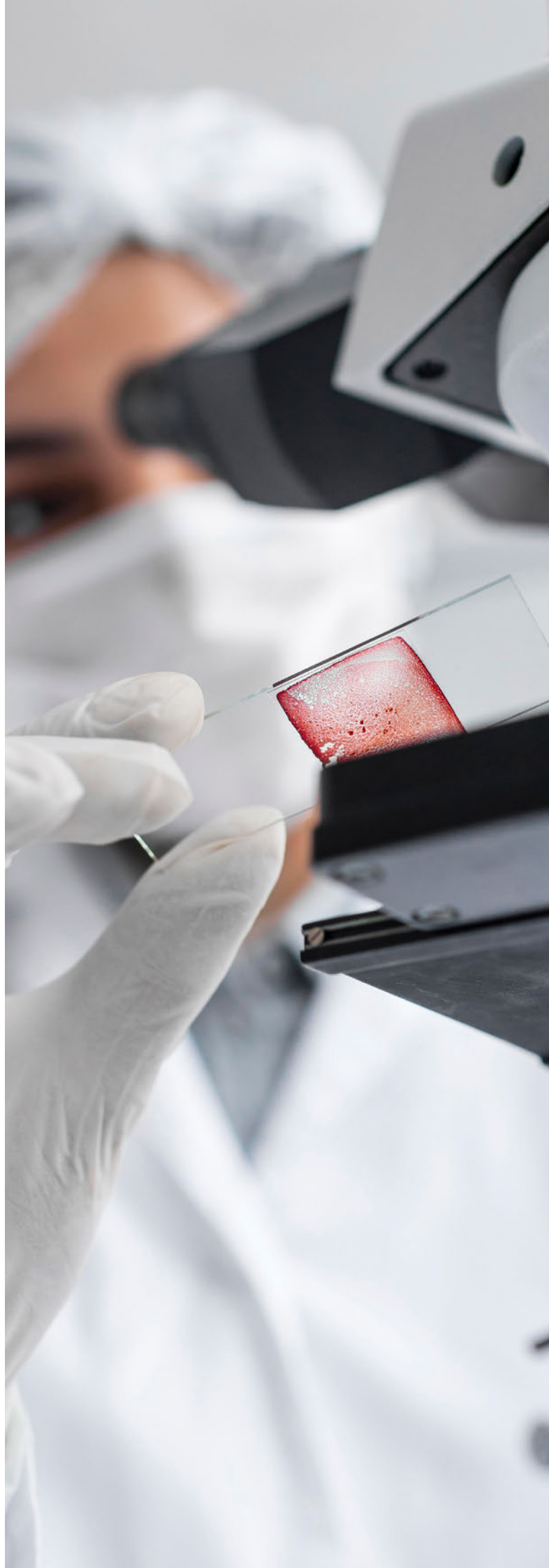
²⁹021-SIM-CO. Quality Assurance Tools to Improve SARS-CoV-2 Detection in Colombia (INM)

³⁰001-APMP-CN. Pilot Comparison and Capacity Building for Medical Ventilator Testers (NIM)

³¹Milayec, M. et al. (2021) 'Metrological framework to support accurate, reliable, and reproducible nucleic acid measurements', *Analytical and Bioanalytical Chemistry* <https://doi.org/10.1007/s00216-021-03712-x>

³²060-SIM-US. Metrology to Harmonize Cell and Particle Measurements and Advance Modern Medicine and Biotechnology (NIST)

²⁹The Joint Committee for Traceability in Laboratory Medicine (JCTLM) <https://jctlm.org/about-us/>



area that previously lacked adequate calibration capabilities to support routine equipment used in ocular hypertension screening. As part of the project, an 'artificial' eye for tonometer calibration was designed, manufactured, and validated in an international metrological comparison. KazStandard also maintains a range of metrological services,³² including testing of measuring instruments for type approval, metrological certification, verification, and calibration to ensure measurement reliability across Kazakhstan's healthcare sector.

Acoustic measurements are critical in many industries, and they also directly impact the health and well-being of the population. According to the World Health Organization (WHO),³³ listening to music at 80 dBA SPL or higher for 8 hours, or its equivalent, may cause permanent hearing damage. Sound and vibration measurements also influence the quality of products and services and the performance and reliability of equipment, thereby guiding industry innovations to safeguard people's well-being and safety. The Russian Metrological Institute of Technical Physics and Radio Engineering has developed a primary standard for the power, intensity, and pressure of ultrasound in water. This is then used to calibrate high-frequency hydrophones and to test the acoustic output of ultrasound medical equipment, ensuring the safety of diagnostic ultrasound procedures.³⁴

³²The International Federation of Clinical Chemistry and Laboratory Medicine (IFCC) <https://ifcc.org/>

³³043-EURAMET-CZ. Metrology in the Fight Against Glaucoma (CMI)

³⁴019-COOMET-KZ. Development of Physical Metrology Infrastructure to Support Healthcare, Environmental Monitoring, and Industry (KazStandard)

Air quality and environmental conditions significantly impact human health and well-being. In the United Arab Emirates (UAE), rapid urbanization and industrial growth have heightened the need for reliable, accurate air quality data to support effective environmental and health policies. The Ministry of Industry and Advanced Technology (MoIAT), the Ministry of Climate Change and Environment (MOCCA), and the National Center of Meteorology of the UAE worked with local environmental monitoring authorities to develop a nationwide air monitoring programme that included the mandatory calibration of the air-quality testing instrumentation for over 70 monitoring stations across the UAE.³⁵ At the start of the programme in 2023, it was determined that only approximately 75 % of the measuring instruments used in laboratories to measure indoor and outdoor air quality were properly calibrated. Since the start of this initiative, it has been verified that 100 % of instruments are now fully calibrated using metrologically traceable national standards and procedures under the new national quality system.

³⁵World Health Organization and International Telecommunication Union (2019) Safe listening devices and systems: a WHO-ITU standard. Geneva: World Health Organization. <https://apps.who.int/iris/handle/10665/280085>

³⁶Ultrasound Methods for Clinical and Healthcare Diagnostics. Case Study 031. COOMET/RU

³⁷Enhancing Air Quality Measurement Accuracy to Support Public Health and Climate Action. Case Study 056. GULFMET/AE

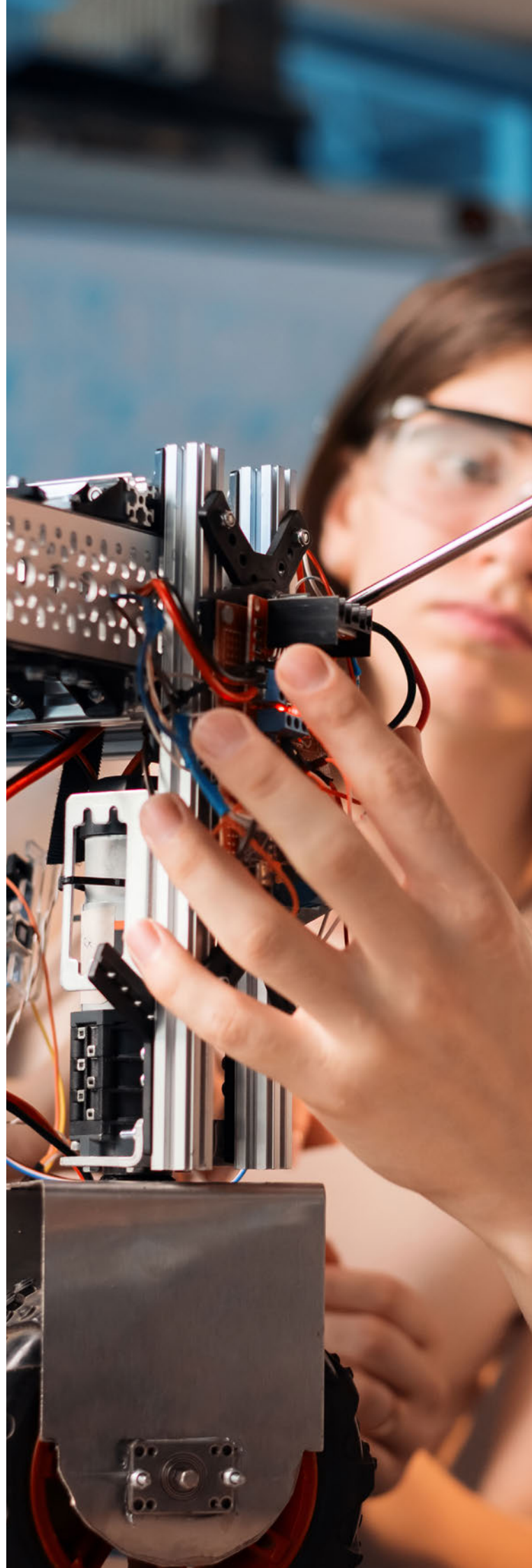


SDG 4 Quality Education

Many NMIs strengthen science and metrology education by transferring knowledge to the STEM-based vocational programmes and other private laboratories, and by providing measurement science “best practices” and standards to industry, universities, and technical schools within their individual economies. In Thailand, NMIT is part of a nationwide network of educators to “train the trainer” in the value of metrology and measurement science practices.³⁶ Measurement Standards Laboratory (MSL) of New Zealand maintains an ‘Earn-While-You-Learn’ apprentice scheme for metrologists,³⁷ priming the next generation of industry technologists and metrologists in New Zealand and beyond.

Some NMIs extend metrology training to other NMIs, DIs, and additional metrology-based organizations. For example, NIST trains early-career metrologists³⁸ across the United States and the Inter-American Metrology System / Sistema Interamericano de Metrología (SIM) region; the National Metrology Institute of Germany, Physikalisch Technische Bundesanstalt (PTB) supports metrology training programmes in the Caribbean and Asia regions; and the BIPM and the TÜBİTAK Ulusal Metroloji Enstitüsü (UME) in Türkiye support young metrologists from all the RMOs through specialized workshops and laboratory internships.³⁹

These metrology-based educational programmes help both professionals and students to learn and appreciate the importance of precision measurements in physics, chemistry and engineering. Ideally, this knowledge is transferred to academia and/or industry, providing technologists and up-and-coming metrologists with hands-on access to high-quality equipment and preparing them for careers in industry or research. These collaborations also allow universities to maintain accredited laboratories that meet international standards and are metrologically traceable to the International System of Units (SI).





*Metrology Asia Pacific. Bringing metrology into the classroom. <https://metrologyasiapacific.com/metrology-resources/bringing-metrology-into-the-classroom/>

**Measurement Standards Laboratory (MSL) of New Zealand Apprenticeship Programme <https://www.measurement.govt.nz/consultancy/msl-apprenticeship-programme>

***National Institute of Standards and Technology (NIST) Office of Weights and Measures, Laboratory Metrology Training Program. <https://www.nist.gov/pml/owm/laboratory-metrology/metrology-training>

***BIPM-TUBITAK UME Project Placements. <https://www.bipm.org/en/-/2025-02-14-bipm-tubitak-ume-project-placements>





SDG 5 Gender Equality

The field of metrology promotes gender equality by providing equal access to technical and scientific careers. For instance, the Asia Pacific Metrology Programme (APMP) runs initiatives that encourage women scientists to take on leadership roles, participate in research projects, and serve on technical committees.⁴⁰ The government of Canada actively supports and promotes equity, diversity, and inclusion, including gender equality, through the strategic plans of its metrology institutes and participation in the 50-30 Challenge programme, which is designed to promote gender parity within leadership roles.⁴¹ These efforts help increase female representation in STEM fields and empower women to contribute to high-tech sectors such as nanotechnology, medical metrology, and renewable energy measurement systems.

As chemical and biological metrology has grown in recent years, metrology overall appears to have shifted towards a more equitable gender balance across its various sectors. However, disparities persist across metrology fields, as evidenced by a recent study of Latin American women in metrology.⁴² Metrology offers many rewarding career opportunities for women,⁴³ and the future of metrology will depend on contributions from all people from diverse backgrounds, a range of STEM education and professions, and other social positions.

⁴⁰Asia-Pacific Economic Cooperation (APEC) Project Database. <https://pdb.apec.org>

⁴¹The 50 – 30 Challenge: Your Diversity Advantage. <https://ised-isde.canada.ca/site/ised/en/50-30-challenge-your-diversity-advantage>

⁴²López-Canchola, C-C. et al. Participation of Latin American women in metrology: Challenges and opportunities in industry and research/academia, Measurement: Sensors. 2025. <https://doi.org/10.1016/j.measen.2024.101324>

In some cases, the development of testing methods and measurement systems may not fully account for the impact of gender and, unintentionally, may compromise the reliability and accuracy of the outcomes. For example, personal protective equipment (PPE) sizing systems are often based on male body proportions, and medical devices or biometric systems may be calibrated using gender-specific or unbalanced reference data, unbeknownst to the user. The UN Economic Commission for Europe (UNECE)'s Working Party on Regulatory Cooperation and Standardization Policies (WP.6)⁴⁴ has been working to develop gender-responsive standards and quality infrastructure that underpin metrological advancements. These, in turn, support inclusive and sustainable industrial development. The UNECE has developed guidance and training materials for metrology institutions on how best to ensure a gender-responsive approach to their existing technical activities, from the initial research phase to measurement system validation.

Germany's PTB hosted an information and exchange event on "ISO 53800 - Guidelines for the promotion and implementation of gender equality and women's empowerment", in January 2026.⁴⁵ The event was designed to provide information to NMI and DI staff interested in fostering more gender equality and women's empowerment in the workplace. On its website, PTB maintains information on gender equality and provides its equality and strategy plans through 2028, accessible to all.

⁴⁴BIPM, Celebrating Women in Metrology: Lessons from the field, <https://www.bipm.org/en/-/2025-02-11-international-day-of-women-and-girls-in-science>

⁴⁵UN Economic Commission for Europe (UNECE), Gender-Responsive Standards. <https://unece.org/trade/wp6/gender-responsive-standards>

⁴⁶Gender Equality in National Metrology Institutes – Information and Exchange. <https://www.ptb.de/cms/ptb/fachabteilungen/abt1/gruppe-n3/veranstaltungen/gender-equality-in-national-metrology-institutes-information-and-exchange.html>



SDG 6 Clean Water and Sanitation

As described by the WHO's Water, Sanitation, and Hygiene (WASH) initiative, access to clean water and sanitation infrastructure is vital to preventing diseases and thus ensuring the basic human need for health and well-being.⁴⁶ Metrology underpins many of the operational and maintenance aspects of WASH. For example, accurate flow measurements in water distribution systems are required to minimize leaks and optimize raw water treatment processes for drinking water treatment plants. Calibrated flow meters across municipalities help detect inefficiencies in water distribution networks and reduce waste.

In Uzbekistan, water management and irrigation infrastructure are currently being modernized through the development of a measurement-based "smart water" system, aiming to increase the efficiency of irrigation networks by 15 % by 2030. This will include the real-time measurement of water levels and discharge in irrigation systems and water channels, integrated into a Geographic Information Systems (GIS)-based framework for regional and national water resource management. In support of these national objectives, the Uzbek National Institute of Metrology (UzNIM) is expanding its contribution to developing the measurement infrastructure needed to support the country's emerging smart water system, helping ensure reliable, comparable, and fit-for-purpose measurements for future water resource management.⁴⁷

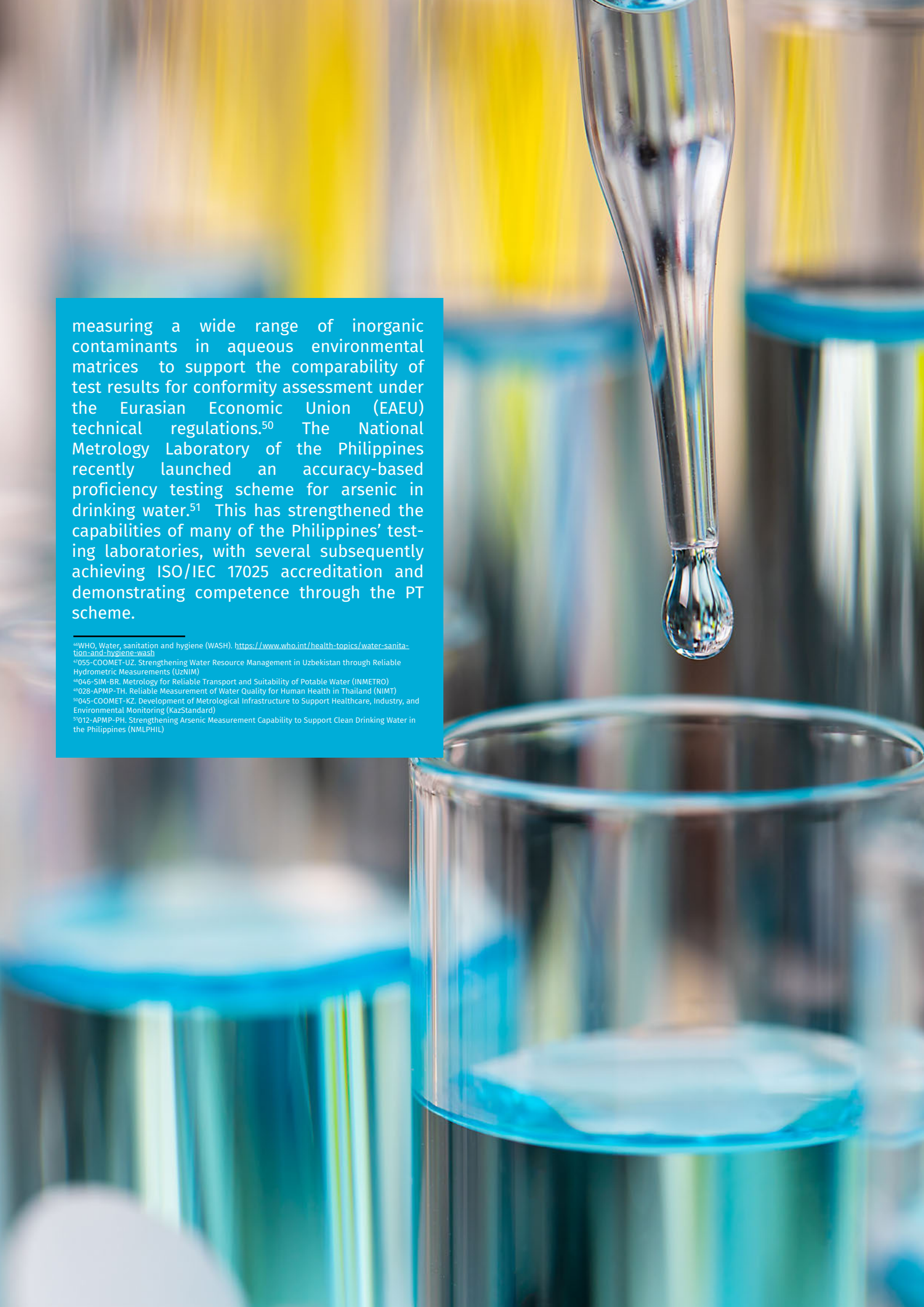
The physical infrastructure of the water transportation system is also vital to delivering clean and potable water and managing sanitation systems across municipalities. The National Institute of Metrology, Quality and Technology (INMETRO) in Brazil is developing complementary measurement services to safeguard infrastructure and water quality, including PT schemes and reference materials for measuring the hardness of pipe materials, as well as turbidity to ensure water potability through the infrastructure.⁴⁸

Water management and the sustainable provision of clean water in developing economies are not limited to physical infrastructure alone. In addition, accurate measurements obtained through metrologically traceable methods and measurement services enable local municipalities to produce clean drinking water, improve treatment efficiency of effluents, and, ultimately, support evidence-based policy and operational decisions for sustainable water management and productivity.

Modern water treatment and public water distribution systems rely on accurate monitoring of chemical and biological contaminants, including heavy metals, bacteria and turbidity. This helps municipalities ensure their drinking water meets safety limits. Many NMIs and DIs with mature chemical and biological metrology programmes have a long history of providing reference materials and measurement services (e.g., PT schemes) that enable routine testing of water quality and evaluation of industrial effluents to ensure compliance with existing regulations.

These CIPM MRA-based measurement services, along with the data they generate, build trust in the use of data for national-level policy decisions. The more nascent metrology programmes in developing NMIs can use existing programmes as models to build their metrology capability; however, this must still be developed within the institute. Each economy can make use of its own "local" metrology infrastructure to verify any new capabilities within its own national metrology systems. This enables the best available technologies and capabilities to become operationally practical for what is currently needed in their own economy.

NIMT (Thailand) recently demonstrated the impact of establishing metrology services through CRMs and PT programmes to validate measurements of bacterial levels, dissolved oxygen concentration, and turbidity, a key indicator of drinking water safety.⁴⁹ This national-level metrology infrastructure has saved the Thai economy up to 1.5 million USD each year across multiple measurement sectors. KazStandard recently developed a series of methods for



measuring a wide range of inorganic contaminants in aqueous environmental matrices to support the comparability of test results for conformity assessment under the Eurasian Economic Union (EAEU) technical regulations.⁵⁰ The National Metrology Laboratory of the Philippines recently launched an accuracy-based proficiency testing scheme for arsenic in drinking water.⁵¹ This has strengthened the capabilities of many of the Philippines' testing laboratories, with several subsequently achieving ISO/IEC 17025 accreditation and demonstrating competence through the PT scheme.

⁵⁰WHO, Water, sanitation and hygiene (WASH). <https://www.who.int/health-topics/water-sanitation-and-hygiene-wash>

⁵¹055-COOMET-UZ. Strengthening Water Resource Management in Uzbekistan through Reliable Hydrometric Measurements (UzNIM)

⁵²046-SIM-BR. Metrology for Reliable Transport and Suitability of Potable Water (INMETRO)

⁵³028-APMP-TH. Reliable Measurement of Water Quality for Human Health in Thailand (NIMT)

⁵⁴045-COOMET-KZ. Development of Metrological Infrastructure to Support Healthcare, Industry, and Environmental Monitoring (KazStandard)

⁵⁵012-APMP-PH. Strengthening Arsenic Measurement Capability to Support Clean Drinking Water in the Philippines (NMLPHIL)



SDG 7 Affordable and Clean Energy

Metrology-enabled innovations serve as a foundation for energy efficiency policies, clean energy technologies, and affordable access to renewable energy. This supports developing economies in their transition toward low-carbon, low-emission growth pathways, while stimulating local economies and bolstering both national and global markets.

Germany's PTB established metrologically traceable purity standards that enable producers to certify the high purity of hydrogen used as a vehicle and industrial fuel, accelerating the clean energy transition.⁵² Several collaborating NMIs across Europe have also developed new calibration standards and reference material services to improve the calibration and verification of hydrogen refueling stations.⁵³ The French DI for flow measurements (CESAME-EXADEBIT) integrated these standards into a calibration service that provides flow rate measurements for both light- and heavy-duty hydrogen refueling stations, enabling the industry to meet the accuracy requirements of applicable regulations and conduct verification tests twice as fast as previously.

In Brazil, INMETRO has ensured that only compliant solar panels enter the market by integrating calibration of reference solar cells and power quality instruments with technical support for accredited testing laboratories into a comprehensive photovoltaic (PV) metrology programme.⁵⁴ Compared to uncertified imports, the use of certified panels increased average system efficiency and saved consumers, who used distributed generation as their energy source, up to 10 %. This project also consolidated the national testing and certification chain for PV inverters and provides a primary reference for flickermeters, reducing flicker grid interference from non-compliance equipment and preserving grid stability for Brazil's green energy expansion.

⁵²PTB's Hydrogen Strategy, https://www.ptb.de/cms/fileadmin/internet/forschung_entwicklung/Innovationscluster_der_PT/Innovationscluster_Energie/Hydrogenstrategy_PT_2024_eng.pdf

⁵³002-EURAMET-UK. Accurate Quantity and Quality of Hydrogen Fuel Delivered at Hydrogen Refueling Stations (HRS) across Europe (NPL)

Mongolia had a specific need to develop national standards for high-voltage and high-current equipment to ensure the technical reliability of its power grid. A joint project was thus formed involving the Mongolian Agency for Standardization and Metrology (MASM), the Ministry of Energy, the National Power Transmission Grid (NPTG) company, and with support from PTB, to build electrical metrology capacity for MASM and to establish NPTG as a DI for electrical standards.⁵⁵ This case also demonstrates the effectiveness of utilizing the "Designated Institute" model in meeting the evolving industrial needs of a developing nation.

Accurate electrical metering enables equitable access to energy for both businesses and the general population. However, a meter's performance can change over time, and many require periodic testing to ensure accuracy is maintained. To give consumers greater control over their energy use, millions of smart meters are being installed across Europe. A past European Metrology Research Programme (EMRP) project⁵⁶ developed a new probability-based approach to model the performance of meter batches, thus enabling energy supply companies to better plan cost-effective meter replacements. The National Metrology Center of Panama (CENAMEP AIP) designed and implemented a national programme in Panama for the metrological verification of in-service electric energy meters,⁵⁷ enabling the determination of the meters' compliance with their accuracy class. This reduced the maximum permissible measurement error by up to 75 % (from ± 2 % to ± 0.5 %), resulting in a 5 % to 10 % reduction in billing errors.

As demonstrated by INMETRO in Brazil,^{58,59} the localization of calibration services for critical solar and wind energy measuring instruments, such as pyranometers and laser-based anemometry systems, eliminates reliance on international service providers for high-level calibration, reducing costs, logistical complexity, and turnaround times. Similar benefits are applied to luminous flux output relative to electrical power input for LED products in Brazil. This will reduce overall costs for national-level operations and reduce entry barriers to the global market.

⁵⁴050-SIM-BR. Accurate and Traceable Measurements for Photovoltaic (PV) Systems: Ensuring Electrical and Power Performance and Quality (INMETRO)

NIS in Egypt ensures that lighting products meet energy efficiency standards by improving photometric measurements, enabling regulators to enforce efficiency policies effectively.⁶⁰ INMETRO also supports a national labelling programme to verify luminous efficacy, further supporting a high-quality marketplace and reducing energy waste.⁶¹ By broadening the operational ranges for single-phase harmonic measurements, underpinned by a new metrologically traceable calibration service for voltage flicker, INMETRO in Brazil aims to ensure that nationwide renewable deployment will not compromise grid reliability. The development of new carbon capture and utilization technology by Brazil may also stimulate innovation in low-carbon fuels and promote industrial decarbonization pathways for the manufacturing sectors.

INMETRO has recently demonstrated⁶² that metrology plays a pivotal role in the successful application of heterogeneous catalytic hydrogenation of CO₂ with green hydrogen (H₂) for carbon capture and utilization (CCU) technology. A wide range of valuable chemicals and fuels can be produced, including methanol, dimethyl ether, higher alcohols, gasoline, diesel, and

sustainable aviation fuel (SAF), all of which are considered low-carbon or “green” when synthesized from renewable hydrogen. The CO₂-to-fuel production process used reference materials for mass determinations, laboratory environmental monitoring, instrument calibrations, and a series of analytical quality assurance processes. These metrology-based tools enable accurate measurement of the calorific value of synthetic fuels, ensuring that a litre delivers the promised energy and makes them a reliable and affordable alternative to fossil fuels.

The A*STAR – National Metrology Centre (NMC) of Singapore has developed regional and interregional training and capability-building activities for stable isotope-based chemical profiling and country-specific source attribution of low-carbon fuels.⁶³ With this new analytical capability, metrology laboratories can now distinguish between fossil-based, biogenic, and low-carbon energy sources (e.g., green vs blue hydrogen, bio vs fossil methane), providing an independent basis for verification. Such differentiation supports fair market pricing, prevents mislabelling or greenwashing, and incentivizes sustainable production and responsible consumption practices.



⁶⁰016-APMP-MN. Powering Mongolia's Grid through Metrology: Extending Electrical Standards via International Collaboration (MASM)

⁶¹EMRP Project NEW04 Uncertainty, “Novel mathematical and statistical approaches to uncertainty evaluation.” <https://www.ptb.de/emrp/new04.html>

⁶²013-SIM-PA. Strengthening and Transparency in Electricity Billing in Panama Through Metrological Verification (CENAMEP AIP)

⁶³026-SIM-BR. National Wind Speed Traceability for Enhancing Brazil's Wind Energy Infrastructure (INMETRO)

⁶⁴050-SIM-BR. Accurate and Traceable Measurements for Photovoltaic (PV) Systems: Ensuring Electrical and Power Performance and Quality (INMETRO)

⁶⁵029-AFRIMETS-EG. Building Egypt's Photometric and Radiometric Measurement Capability to Support Energy Efficiency and Climate Action (NIS)

⁶⁶048-SIM-BR. Metrology for Sustainable, Safe and Energy-Efficient LED Lighting in Brazil (INMETRO)

⁶⁷007-SIM-BR. Nanometrological Characterization of Heterogeneous Catalysts for the Conversion of CO₂ to High-Value Products (INMETRO)

⁶⁸027-APMP-SG. Isotope Fingerprinting for Trusted Low-Carbon Fuels: Enabling Climate Action, Fair Trade, and Transparency (NMC, A*STAR)



SDG 8 Decent Work and Economic Growth

Accurate measurement systems strengthen economies by enabling quality manufacturing and fair trade. Legal metrology programmes, as administered by NMIs, DIs, or other organizations under the trade and commerce ministries, are responsible for routinely verifying hundreds of weighing instruments and measuring devices, such as fuel dispensers, truck scales, and taximeters, across the whole of their nations. This ensures a consistent quality and quantity of goods and services and ensures that both consumers and businesses operate in an environment of trust, which is essential for strong economic growth.

CENAMEP AIP has developed fundamental capacity in weighbridges and legal metrology infrastructure,⁶⁴ enabling Panama to serve as a global logistics hub, providing an interconnected infrastructure for the Canal, ports, railways, highways, and airports for containerized cargo transport. This has made this economic activity one of the most important for Panama, supporting countless high-quality jobs. Notably, it ensures that Panama can comply with the International Maritime Organization (IMO) International Convention for the Safety of Life at Sea (SOLAS) Verified Gross Mass (VGM) declarations for containers.

Manufacturing industries also rely on precision measurements to improve productivity. Calibrated instruments enable factories to reduce defects, meet international standards, obtain accreditation, scientifically demonstrate product quality, and export these high-quality products to neighbouring markets. The EURAMET-administered research programmes, EMRP and EMPIR, have clearly demonstrated a boost to industrial production⁶⁵ by the inclusion of metrology research and accurate validation of new technology that has supported the development of innovative products and services. It is estimated that sales from products influenced by these metrology-accelerator programmes amount to over 1.6 billion euros.

Advances in nationwide metrology programmes also serve as a gateway to new job opportunities as well as economic growth. A clear example is the Saudi Standards, Metrology and Quality Organization (SASO)'s scaling up of its initial scientific metrology capabilities to foster the development of new measurement services (e.g., PT schemes) in Saudi Arabia, while training hundreds of the next generation of metrologists and technical experts to work in private sector entities.⁶⁶ Qatar has also developed national-level capability in temperature, humidity, mass, electrical, and dimensional metrology,⁶⁷ thereby creating new jobs, and with plans to expand through 2027. By providing internal calibration services within the country, they have also observed a significant reduction in the need for calibration services abroad.

Driven by AI and cloud computing, economies of all sizes and types are embracing digitalization. Many NMIs and DIs, whether mature or still developing, large or small, have embraced, or are embracing, digital transformation efforts in their metrology programmes and measurement services. These represent significant new job opportunities for the metrologists themselves and for the industries that will be underpinned by the metrological advancements. The Azerbaijan Institute of Metrology (AzMi) initiated a phased digital transformation of its calibration and certification processes. This not only improved metrological traceability for calibration services and accelerated verification but also directly supported the outgrowth of the local industry's digitalization efforts.⁶⁸ Furthermore, the Metrology Division of the National Institute of Standards and Industrial Technology (NISIT) of Papua New Guinea has partnered with its national telecommunications and ICT provider to collaboratively develop and deploy a Digital Calibration Certificate (DCC) system and associated secure digital infrastructure.⁶⁹

Another example of economic transformation via digitalization is SASO's recent development and implementation of the legal metrology programme (Taqqees) aligned with the Saudi Vision 2030 national initiative.⁷⁰



This consisted of a highly coordinated development of a seamless platform that connected manufacturers, importers, service providers, verification bodies, and regulatory inspectors within a single digital legal metrology network. Integrated workflows have improved compliance monitoring and strengthened the national quality infrastructure, enabling sustainable industrial development and diversification beyond a singular export economy.

Colombia has demonstrated the value of metrologically driven initiatives (i.e., reference materials, PT schemes) to ensure the quality of and the sustainable competitiveness of cocoa, currently the country's second-most valued export product after coffee.⁷¹ Cocoa production is now considered a viable alternative to illicit crops for many farmers, thereby generating a strong source of rural employment. With government support, the promotion of environmental sustainability through forest management arrangements involves enterprises of all sizes across the country. In cocoa processing and chocolate manufacturing, large companies and smaller processors play prominent roles. In the marketing of processed products and market access, the domestic industry and other private importers and exporters are involved.

⁷⁰059-SIM-PA. Optimization of Multimodal Transport and Preservation of Road Infrastructure in Panamá through Metrological Traceability in Weighbridges (CENAMEP AIP)

⁷¹EURAMET Delivering Social, Economic, and Scientific Impact. <https://www.euramet.org/metrology-for-societys-challenges/impact/>

⁷²041-GULFMET-SA. Scaling Up Scientific Metrology in Saudi Arabia (SASO)

⁷³040-GULFMET-QA. Strengthening Qatar's National Metrology Capabilities to Directly Support Industry (QGOS)

⁷⁴034-COOMET-AZ. Digital Transformation of Azerbaijan's Metrology Services (AzMI)

⁷⁵011-APMP-PG. Establishing Digital Infrastructure and Industrial Digitalization in Papua New Guinea (NISIT)

⁷⁶057-GULFMET-SA. Digital Transformation of Legal Metrology in Saudi Arabia (SASO)

⁷⁷003-SIM-CO. Metrology for Sustainable Competitiveness in Cocoa: Advancing Industrial Innovation and Inclusive Economic Growth (INM)



SDG 9 Industry, Innovation and Infrastructure

In the scientific and innovative technology industries, nanometre-level accuracy is required for precision manufacturing tools and processes. Innovative 3D printer technology used in advanced manufacturing is applied in traditional industries and increasingly in semiconductor fabrication and biomedical applications for its ability to rapidly fabricate geometric shapes with precise dimensions. NMIs have developed nanometrology instruments that allow semiconductor manufacturers to measure tiny features on microchips with atomic-scale accuracy. This also supports innovation in electronics, telecommunications, and AI.

The semiconductor industry in Chinese Taipei produces high-quality chips, resulting in a global market share of 70 %. A national metrology framework at the Center for Measurement Standards in the Industrial Technology Research Institute (CMS/ITRI) in Chinese Taipei has been established to ensure accuracy, consistency, and metrological traceability across the semiconductor manufacturing ecosystem.⁷² Using this framework, consisting of particle-size reference materials and SI-traceable gas and nanoparticle standards for impurity analysis and incoming quality checks of semiconductor process gases, the current manufacturing process is capable of producing beyond the cutting-edge 3 nm technology node. This has also significantly improved production yields of semiconductor materials from 75 % to approximately 99 %.

Electricity is ubiquitous in everyday life, and electrical metrology spans a wide field encompassing many quantities and requiring numerous derived standards, such as voltage, power, and magnetic field strength. As significant drivers of industrial evolution and with many derived units, electricity and magnetism are key enablers of industrial revolutions. With the first exploitation of electrical energy for telephones, power, and lighting over 150 years ago, more recent discoveries have stimulated innovations in advanced electronics and information technology to automate industrial production.

Photometry and radiometry measurements are used across a wide range of industries, as well as in emerging areas such as biomedicine, quantum-based information, quantum photonics, terahertz power, climate monitoring, and photovoltaics. A practical example is the characterization of the light sources and spectral distributions of traditional and LED lighting products. As illustrated by prior clean energy examples from NIS⁷³ and INMETRO,⁷⁴ the application of LEDs for general illumination also contributes to other SDGs, as it delivers enormous social benefits by saving energy and reducing costs, and serves as a model for innovative urban and industrial zones.

Time and frequency measurements are critical for telecommunications and financial transactions and serve as the foundation of radio engineering. The Global Navigation Satellite Systems (GNSS), including GPS (US), Galileo (EU), GLONASS (Russia), and BeiDou (China), rely on accurate time and frequency measurements. The evolution of these global positioning systems has driven technological revolutions in highly accurate navigation, positioning, and timekeeping, which are vital to civilian, military, and scientific applications. The National Metrology Laboratory (NML), Bangladesh Standards and Testing Institution (BSTI), has recently established its own primary national time scale – UTC(BD).⁷⁵ NML-BSTI has achieved a self-described “digital heartbeat” for its 5G infrastructure, achieving a timing accuracy of less than 1 microsecond ($<1 \mu\text{s}$) and underpinning millions of mobile financial transactions per day. KazStandard has also modernized the national primary standard for time and frequency for Kazakhstan based on three new passive hydrogen masers with automated UTC-based steering.⁷⁶

Metrology also supports national infrastructure through material testing and structural monitoring. Accurate measurement of concrete strength, steel composition, and vibration data ensures safer buildings, bridges, and roads. The prime application of metrology in mass and related quantities (e.g., force, torque, hardness, pressure, and vacuum) enables the sustainable production of goods and services across the aerospace, construction, automotive, electronics, manufacturing, mining, energy, pharmaceutical, and health-care sectors.

Vacuum chambers are an important tool in the manufacture of many high-tech, high-value products, such as semiconductors, photovoltaics, and LED lighting. A consortium of seven European NMIs and five private companies collaborated to develop a new vacuum gauge calibration facility⁷⁷ capable of providing a well-defined, very rapid pressure drop for SI-traceable dynamic pressure calibrations under conditions encountered by sensors in industrial applications. Utilizing this new facility, the development of a commercial ultra-fast pressure measurement gauge has enabled rapid analysis of vacuum chambers used in production, thereby improving productivity and process efficiency for customers in the semiconductor industry.

Accurate fluid metering is essential for measuring flow in the delivery of fuel, oil, and gas products, as well as in water treatment and other liquid-handling and manufacturing processes in many industries. NIST in the US maintains the accuracy of flow meters through mass- and volume-calibrated field test procedures, ensuring the efficiency and integrity of US pipelines spanning thousands of miles and transporting over 100 million gallons of refined fuels per day.⁷⁸ A*STAR NMC in Singapore, working in conjunction with the Maritime and Port Authority (MPA) of Singapore, suppliers, ship operators, and meter manufacturers, has developed a quantity measurement assurance process through a real-time, tamper-proof, fully digital bunkering system using mass flow meters.⁷⁹ This framework has reduced variability caused by two-phase and transient flows, resulting in a 25 % reduction in fuel bunkering time. Beyond petroleum products, milk is a vital liquid-based product underpinning Ireland's national economy, which also critically relies on accurate fluid metering. The National Standards Authority of Ireland (NSAI) Legal Metrology oversees a private industry verifier, ensuring that all milk tankers deliver an accurate amount of product from farm and dairy suppliers through verified milk meters.⁸⁰

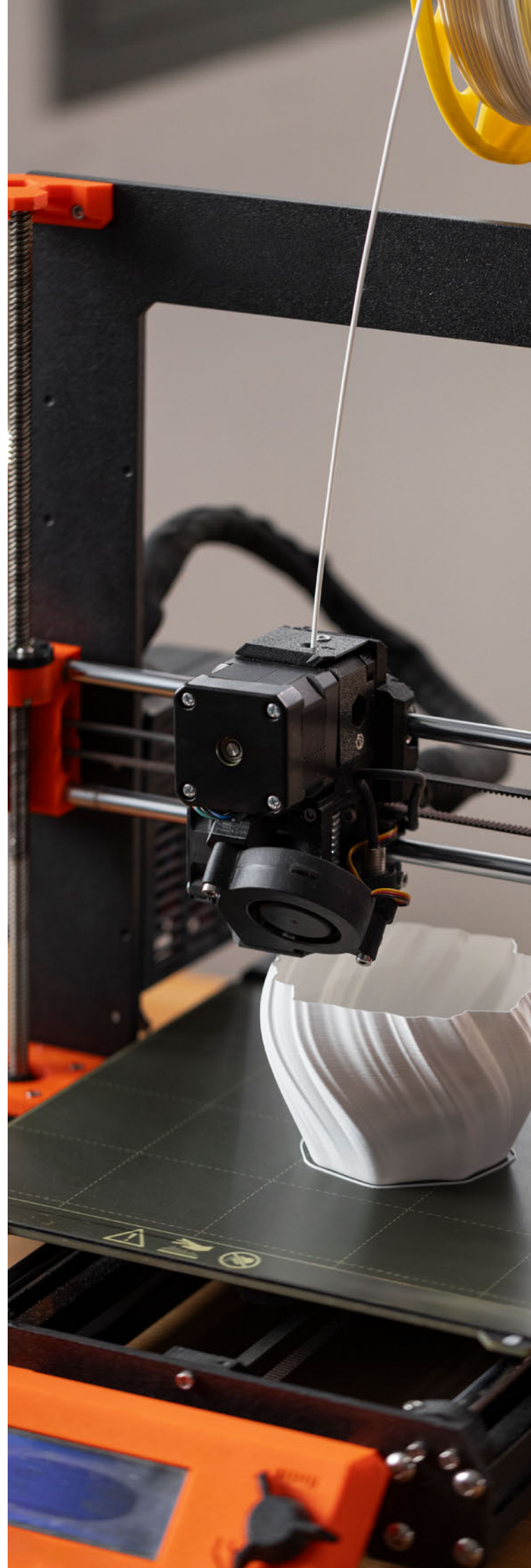
Industrial production and logistics rely on accurate weighing of raw materials, semi-finished products, and finished products. The

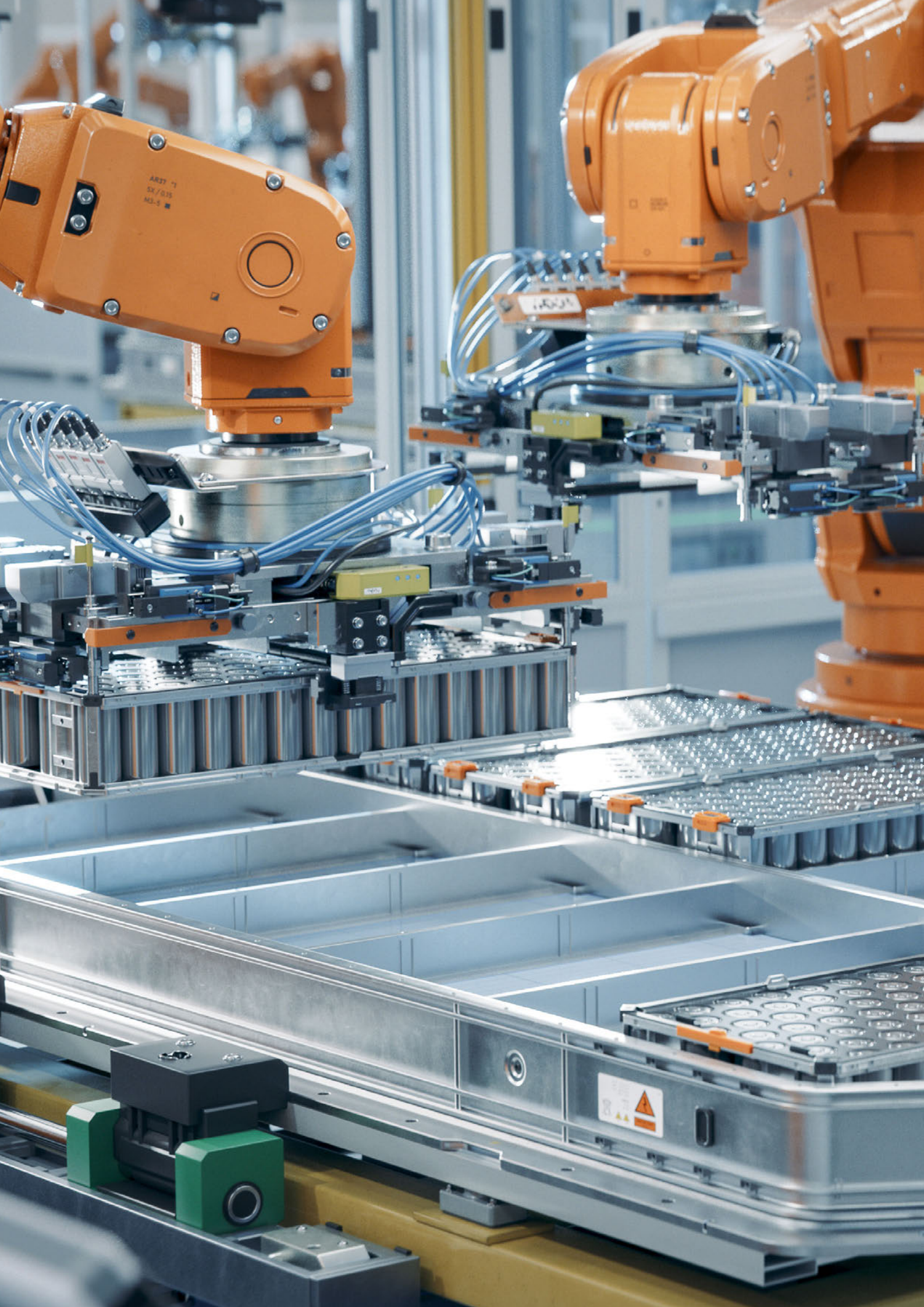
⁷⁷054-APMP-TW. Metrology for Sustainable Semiconductor Manufacturing: Enabling Quality, Precision, and Efficiency (CMS/ITRI)

⁷⁸029-AFRIMETS-EG. Building Egypt's Photometric and Radiometric Measurement Capability to Support Energy Efficiency and Climate Action (NIS)

⁷⁹048-SIM-BR. Metrology for Sustainable, Safe and Energy-Efficient LED Lighting in Brazil (INMETRO)

⁸⁰047-APMP-BD. Securing National Time Sovereignty for a Resilient New Bangladesh (NML-BSTI)







National Metrology Institute of Russia, D. I. Mendeleyev Institute for Metrology (VNIIM), developed and maintains national mass standards and verification schemes for high-capacity weighing instruments, including truck and rail weighbridges and industrial automatic weighing systems.⁸¹ VNIIM introduced new calibration and verification services for large capacity load cells and weighing instruments, updated national verification procedures in line with international recommendations (e.g., OIML R 76, R 106, R 60), and organized training for verification laboratories and industrial users. As in many other countries, adopting international standards aligns national practices with global norms, facilitating seamless trade. This will also minimize the need for redundant testing across borders through the OIML-CS.

The fundamental metrology capabilities of NMIs and DIs directly support a wide range of industries through their measurement services. KazStandard has reported⁸² that the development of its physical metrology infrastructure is specifically designed to support its national industry and enhance its industrial competitiveness. This includes calibration services for dew-point temperature standards, mass standards, and harness reference blocks, as well as standards and measuring instruments used in environmental measurements and healthcare applications. Examination of their industrial

quality management system has indicated that these metrological improvements have reduced defect rates by approximately 10 % to 30 %, depending on the industry and production process.

Belarus has recently strengthened its export competitiveness by expanding national measurement standards and metrological traceability in high-temperature and radiation metrology for the energy, manufacturing, and petrochemical sectors.⁸³ As a specific example for nuclear power and radiometry, the Belarusian State Institute of Metrology (BelGIM) annually verifies about 12 000 units of radiation and dosimetric monitoring instruments using their national standards. This not only eliminates the need to export equipment outside the Republic of Belarus for metrological evaluation but facilitates the country's export potential for BelGIM's products and services.

⁸¹017-COOMET-KZ. Ensuring a Reliable National Time Scale UTC(KZ) as Critical Infrastructure of Kazakhstan (KazStandard)

⁸²042-EURAMET-DE. Faster Production and High-quality End-products with Faster Vacuum Gauges (PTB)

⁸³038-SIM-US. How Liquid Volume Metrology Services Underpin the Oil and Gas Industry (NIST)

⁸⁴018-APMP-SG. Transparency and Trust for Bunkering Custody Transfer in Singapore's High-value Maritime Supply Chain (NMC, A*STAR)

⁸⁵009-EURAMET-IE. Accurate Milk Metering to Support Ireland's Dairy Industry (NSAI)

⁸⁶033-COOMET-RU. Metrology for Fair Trade and Resource Efficiency: Accurate Mass Measurements in Industrial Weighing Systems (VNIIM)

⁸⁷019-COOMET-KZ. Development of Physical Metrology Infrastructure to Support Healthcare, Environmental Monitoring, and Industry (KazStandard)

⁸⁸020-COOMET-BY. Metrological Traceability for Strengthening National Industrial Innovation and Export Potential for Belarus (BelGIM)

SDG 10 Reduced Inequalities

Countries with developing metrology systems might face Technical Barriers to Trade (TBT) when exporting goods because their standardization, accreditation, and measurement systems may not be internationally recognized. Central American countries received support to create a competent network of NMIs, accredit their test and calibrations laboratories and align their practices with global standards through international support projects such as PRACAMS-SIECA, a quality and application of health and phytosanitary measures project from the UN, the Quality Infrastructure For Circular Economy (QI4CE) Project from the PTB and RMOs like SIM.⁸⁴ This allows public and private laboratories and enterprises in smaller economies to improve their competence and technical capabilities, enabling them to participate in international trade on fair terms.

Robust QI systems support governments, industries, and public health systems, but also protect consumers and ensure a fair and equitable marketplace. As described in a recent PTB-UNIDO publication,⁸⁵ a QI legal framework that supports the establishment of accurate testing and calibration services, accreditation and conformity assessments, and national metrology programme works to secure equal access to safe and reliable products and services for the entire population. This, in turn, helps to reduce socio-economic inequalities. Indeed, UNIDO considers quality infrastructure so important for development and addressing inequalities that they have established a Sustainable Development Index⁸⁶ to allow countries to understand how much progress they have made in establishing a national QI.

On a regional scale, the Asia-Pacific Legal Metrology Forum (APLMF) worked with the OIML and local legal metrology authorities to develop a randomized sampling inspection method for prepackaged goods, based on OIML R 87, using an average-quantity system and a statistical methods framework.⁸⁷

These coordinated inspection programmes, underpinned by harmonized measurement standards and the OIML-CS for prepackages, now provide APLMF member economies (e.g., Indonesia) with new international and regional trade opportunities by providing economies that import their products with greater assurance that the products meet declared quantity requirements. This reduces the need for duplicate testing and inspections, lowers TBT, and streamlines market access. These straightforward legal metrology practices reduce the inequalities or technical gaps between industrialized, well-developed nations and developing industries in smaller countries.

⁸⁴Report of PTB International Cooperation. SIM General Assembly 2024. https://sim-metrologia.org/wp-content/uploads/2024/12/5_4_2024-11-PTB-en-SIM.pdf

⁸⁵UNIDO-PTB 2024. Fostering Sustainability and Responsible Social and Economic Action. Building legal frameworks for a future-proof Quality Infrastructure. https://hub.unido.org/sites/default/files/publications/online_PT_B_UNIDO.pdf

⁸⁶UNIDO 2022. Quality Infrastructure for Sustainable Development Index (QI4SD). Supporting Sustainable Development Goals with Quality Infrastructure. https://hub.unido.org/qi4sd/pdfs/QI4SD_Index_MAIN_REPORT.pdf

⁸⁷053-APLMF-ID. Regional Challenges on Prepackaged Goods for Strengthening the Economy, Industry, and Consumer Protection (APLMF)





SDG 11 Sustainable Cities and Communities

Sustainable cities and communities develop smart industries that use advanced technology clusters, which in turn require access to specific measurement technologies. Smart cities also depend on accurate environmental measurements to keep their population healthy. Noise and air quality sensors in many cities are calibrated using reference standards developed by NMIs and DIs, ensuring reliable data for pollution, health, and noise control.⁸⁸

Indoor air quality (IAQ) monitoring is essential for infectious disease control and serves as the basis for promoting sustainable cities and communities and the well-being of their populations. A*STAR's NMC in Singapore has developed a data-driven calibration method to achieve autonomous calibration of sensing data to be used in the control of fresh air ventilation systems.⁸⁹ This system has been demonstrated in a Green Mark Platinum building in Singapore and has shown a 20 % energy-saving in ventilation while maintaining the IAQ target. Outdoor air quality can also have a significant impact on human health and well-being. In the UAE, rapid urbanization and industrial growth have heightened the need for reliable, accurate air quality data to support effective environmental and health policies for its population. As illustrated by a prior good health example,⁹⁰ MOCCA and the National Center of Meteorology of the UAE developed a nationwide air-quality monitoring network comprising over 70 stations equipped with air-quality testing instrumentation.

In Brazil, a specialized national metrology capacity that focused on luminous efficacy measurement and the characterization of luminous intensity and light distribution has been implemented and applied to public and indoor lighting.⁹¹ INMETRO has developed new measurement and testing services for solid-state LED lighting, focusing on blue-light content and stroboscopic assessments to verify compliance with health and safety thresholds in schools, hospitals, workplaces,

and public infrastructure (e.g., roadways). INMETRO has recently contributed to two national regulations (road lighting and LED light sources), which are expected to establish measurable requirements for luminous efficacy, light distribution, and blue light content, as well as mandatory requirements for the declaration and measurement of flicker and stroboscopic effect parameters. This is driving the development of corresponding measurement and testing services to support testing laboratory capacity and conformity assessment activities in line with forthcoming Brazilian technical regulations.

Metrology also supports the maintenance, safety, and preservation of transportation infrastructure, such as bridges and roadways. Therefore, SASO in Saudi Arabia is currently developing a unified legal metrology framework for truck scales, bridge weighing scales, and weigh-in-motion (WIM) systems, with verification services for truck scales to launch in 2026. This enhancement is anticipated to significantly reduce the use of overweight vehicles, which accelerate the deterioration of road infrastructure and increase maintenance costs.⁹² Furthermore, in rail, aviation, and ground transportation infrastructure, precise measurements and sensors of braking forces, engine performance, cruise control, autopilot, and structural integrity ensure safer mobility systems for private and public transportation.

In Panama, sustainable industrial competitiveness is highly dependent on reliable, interconnected roads, bridges, Atlantic and Pacific ports, and logistics infrastructure, including the shipping containers that move through the Panama Canal. Overweight vehicles directly contribute to premature infrastructure degradation, reduced road safety, reduced urban and suburban (peri-urban) mobility, and increased emissions from unnecessary overloads. As was alluded to earlier, CENAMEP AIP developed a high-capacity weighbridge calibration service,⁹³ based on OIML R 76 and a methodology developed within the SIM, which was used for the weight enforcement under the International

⁸⁸European Metrology Network for Pollution Monitoring. <https://www.euramet.org/european-metrology-networks/pollution-monitoring>



Convention for the SOLAS VGM requirements, and ultimately maintained vehicles within legal weights limits.

Successfully integrating technology into smart industrial clusters in urban zones requires access to specific measurement technology. Larger-scale length-based measurement applications, such as using 3D scanner technology, accurately measure transport vehicle dimensions. In Malaysia, the government-appointed company, PUSPAKOM, conducts mandatory inspections of more than 3 million commercial, public, and private vehicles per year. They use the National Metrology Institute of Malaysia (NMIM) physical artefact standards – metrologically traceable to a primary NMIM length standard – as in situ calibration standards to verify the field-based 3D laser scanners.⁹⁴ These routine yet accurate measurements are trusted by both businesses and customers, protecting Malaysia's critical transportation infrastructure while ensuring the safety of all road users.

⁹⁴See Digital Metrology for Digital Health Policy Brief, Metrology Asia Pacific. <https://metrologyasia-pacific.com/metrology-resources/digital-metrology-for-digital-health/>

⁹⁵056-GULFMET-AE. Enhancing Air Quality Measurement Accuracy to Support Public Health and Climate Action (MoIAT)

⁹⁶048-SIM-BR. Metrology for Sustainable, Safe and Energy-Efficient LED Lighting in Brazil (INMETRO)

⁹⁷006-GULFMET-SA. Truck Weighing Instruments under Legal Metrology Control in Saudi Arabia (SASO)

⁹⁸059-SIM-PA. Optimization of Multimodal Transport and Preservation of Road Infrastructure in Panamá through Metrological Traceability in Weighbridges (CENAMEP AIP)

⁹⁹Metrology Asia Pacific Case Study: Putting length metrology into 3D laser scanning. <https://metrologyasiapacific.com/metrology-resources/putting-length-metrology-into-3d-laser-scanning/>



SDG 12 Responsible Consumption and Production

Industries use metrology to control material consumption and reduce waste. In the chemical and pharmaceutical sectors, precise weighing and volumetric measurements ensure efficient use of raw materials and compliance with quality standards and national regulations. In a very straightforward example, Qatar has demonstrated that by providing its own instrument calibrations within its own economy, it can reduce international shipments for about 175 of its measuring instruments. This has resulted in a demonstrable reduction in associated carbon emissions of approximately 7.9 tons of CO₂ annually, directly supporting responsible consumption and production in industry.⁹⁵ Although this is a small amount in absolute terms, this demonstrates how a single concerted effort can control excessive consumption and reduce waste overall.

Accurate dimensional measurements are vital across many industries to ensure product quality control and assurance and enable the development of more advanced products. This reduces product defects, minimizes rejection rates, reduces waste, and leads to improved productivity. Modern factories use coordinate measuring machines (CMMs) calibrated to metrology standards to produce high-precision components for the automotive, aerospace, and electronics sectors, and with minimal waste. This also ensures that a product manufactured in Asia can be easily used in Europe, Africa, or America. The EMRP project *Traceability for computationally-intensive metrology (TraCIM)*⁹⁶ developed a software verification system (SVS) that is used to process the vast amount of data generated from CMMs. The TraCIM SVS uses a “gold standard” dataset based on a certified reference object to complete software validation and provide confidence in the accuracy of CMMs along the production line.

Additive Manufacturing (AM) via Laser Powder Bed Fusion (LPBF), in which a laser beam fuses metal powder into a 3D shape, is commonly used in the aerospace, biomedical, and automotive sectors to fabricate intricate metallic parts while minimizing material waste. However, multivariable process vari-

ability may have compromised the reliability of manufactured components, reducing industry trust and limiting the adoption of AM techniques. The Council of Scientific and Industrial Research (CSIR)–National Physical Laboratory (NPL) India and the National Institute of Technology (NIT) Delhi have conducted a detailed metrological characterization of the stability and dimensional accuracy of 3D-printed components with a full evaluation of measurement uncertainty analysis of various process variables (i.e., laser power, scan speed, and hatch spacing).⁹⁷ After process parameter optimization and instrument calibration, significant improvements in dimensional accuracy were observed using the LPBF manufacturing technique, resulting in components produced well within specified tolerances. The results are 3D-printed parts produced with accurate dimensions. This increases process repeatability and reduces rejections or the need for post-machining treatments, thereby reducing overall waste and enhancing manufacturing efficiency.

As the testing and certification body for the Netherlands, NMI Certin is preparing for the introduction of EU Digital Battery Passports, which become mandatory in 2027 and apply to electric vehicle (EV) batteries and industrial batteries exceeding 2 kWh, and identify the source of battery raw materials, their chemistry type, manufacturing process, charging history, etc. This is part of the larger Digital Product Passport (DPP) initiative under the EU’s Ecodesign for Sustainable Products Regulation.⁹⁸ Such information can be used by recyclers with more accurate chemical and material data about each battery to support both recovery and reuse processes.⁹⁹

Through collaboration among several NMIs and the EMRP project *Ionising radiation metrology for the metallurgical industry (Metro-Metal)*, a series of certified radioactive steel calibration standards was developed to measure radioactivity levels in the material forms commonly encountered in steel recycling.¹⁰⁰ These standards enabled steel recyclers to

⁹⁵040-GULFMET-QA. Strengthening Qatar’s National Metrology Capabilities to Directly Support Industry (QGOS)

⁹⁶EMRP project NEW06 TraCIM “Traceability for computationally-intensive metrology.”

⁹⁷014-APMP-IN. Relevance of Accurate Dimensional Metrology in Smart Manufacturing (NPLI; NIT)



reliably certify their products as compliant with the EU Council Regulation 333/2011, which requires scrap metal recycling companies to provide certificates of radioactive content for each batch of steel produced. This metrological solution directly supported the scrap metal industry and a sustainable circular economy approach, while safeguarding the environment and the public.

As illustrated by INMETRO,¹⁰¹ the use of heterogeneous catalysts to produce sustainable aviation fuel (SAF) is a prime example of developing metrological infrastructure to produce low-carbon, or “green,” fuels in a more sustainable manner. Through innovations in nano-material design, new heterogeneous catalysts with nanosized structures will require metrological characterization at the atomic scale. However, the application of metrology-based tools to measure active sites with picometer precision is key to its successful development and implementation. The integration of sensors directly into hydrogenation reactors will provide real-time, metrologically traceable data. This will allow automated adjustments to production processes, reducing waste and increasing safety in industrial plants.

CMS/ITRI in Chinese Taipei¹⁰² has demonstrated that the use of SI-traceable gas and nanoparticle standards in semiconductor manufacturing has improved measurement consistency, minimized variation between validation measurement tools, accelerated process optimization and efficiency, and maximized production yields. The faster detection of critical dimensions and composition errors has significantly reduced energy-intensive rework and enabled more resource-efficient manufacturing processes, ultimately reducing waste and enabling more sustainable, efficient industrial-level production of semiconductor chips.

¹⁰¹Regulation (EU) 2024/1781 of the European Parliament and of the Council of 13 June 2024. <https://eur-lex.europa.eu/eli/reg/2024/1781/oj>

¹⁰²Centre for European Policy Studies (CEPS) 2024 Implementing the EU Digital Battery Passport. Opportunities and challenges for battery circularity. <https://www.ceps.eu/ceps-publications/implementing-the-eu-digital-battery-passport/>

¹⁰³EMPIR project IND04 MetroMetal “Ionizing Radiation Metrology for Metallurgical Industry.”

¹⁰⁴007-SIM-BR. Nanometrological Characterization of Heterogeneous Catalysts for the Conversion of CO₂ to High-Value Products (INMETRO)

¹⁰⁵054-APMP-TW. Metrology for Sustainable Semiconductor Manufacturing: Enabling Quality, Precision, and Efficiency (CMS/ITRI)



SDG 13 Climate Action

Climate monitoring depends entirely on traceable measurements. For example, the World Meteorological Organization (WMO) and the National Oceanic and Atmospheric Administration (NOAA) Global Atmosphere Watch programmes use metrologically-traceable calibration gases to monitor CO₂ and methane levels at hundreds of stations worldwide. They also gather vast amounts of trustworthy data from multiple systems to predict changes in climate. This ensures climate models receive accurate, comparable data. Satellite-based climate sensors also require precise radiometric calibration. NMIs and other meteorological organizations provide reference measurements that enable satellites to detect temperature changes, variations in ice cover, and trends in atmospheric composition with high accuracy.

Millions of measurements are made every day to cover the Essential Climate Variables (ECVs; atmospheric, oceanic, and terrestrial) identified by the Global Climate Observing System (GCOS). Using metrologically-based services to generate accurate, comparable, and trustworthy data is vital for policy makers in making climate action decisions. A demonstrable example of the involvement of measurements in climate action was illustrated by the recent 2022 Metrology for Climate Action workshop, which generated many recommendations for the metrology community to support the physical science basis of climate change and climate observations. Over a thousand on-line participants were registered, including numerous experts from the BIPM, the WMO, universities and meteorological organizations, and several NMIs, the latter of which have demonstrated the comparability of gas standards for climate change and air quality monitoring through several comparisons within the CIPM MRA framework.¹⁰³

The National Physical Laboratory (NPL) in the UK has designed and built instrumentation and methods to reduce measurement uncertainty for a variety of ECVs, for use both in space and on the ground.¹⁰⁴ These include

networks of field instruments for measuring surface reflectance and vegetation parameters, as well as transportable facilities for pre-flight calibration and characterization of satellite sensors using tuneable lasers in a new facility, the Spectroscopically Tuneable Absolute Radiance calibration and characterization Optical Ground Support Equipment (STAR-cc-OGSE, or “STAR”). The STAR facility was used to calibrate the recently launched Carbon Dioxide Monitoring Mission (Micro-Carb) by the French Space Agency, CNES, with support from the UK Space Agency (UKSA), launched in July 2025. The MicroCARB objective is to monitor greenhouse gas (GHG) and fluxes of carbon dioxide between the atmosphere, oceans, and ground-level vegetation.

Chemistry metrology is also a major contributor to environmental monitoring of GHGs, underpinning climate action goals. For example, the National Metrology Institute of Indonesia (SNSU-BSN) has recently partnered with the Meteorology, Climatology, and Geophysical Agency of Indonesia (BMKG) and PTB's Innovation Cluster for Environment and Climate programme to strengthen Indonesia's GHG monitoring capability.¹⁰⁵ The collaboration has enabled SNSU-BSN to develop national-level capability for sustaining primary GHG standards for carbon dioxide (CO₂) and methane (CH₄) at atmospheric levels in synthetic air matrices. The initiative supported Indonesia's Net Zero Emission 2060 targets, and the modernization of environmental monitoring systems and measurement infrastructure needed for carbon accounting, emissions verification, and carbon market mechanisms. In Russia, VNIIM has developed SI-traceable measurement capabilities for atmospheric CO₂ amount fraction and its isotopic composition ($\delta^{13}\text{C}$ and $\delta^{18}\text{O}$) at ambient levels. A notable fivefold improvement in their measurement capabilities followed the completion of the CCQM-K120 interlaboratory comparison for measuring CO₂ at background and urban levels.¹⁰⁶ This has enabled Russia's national greenhouse gas monitoring plan to reliably monitor and attribute GHG sources, and in alignment with WMO Global Atmosphere Watch (GAW) requirements.

¹⁰³Wielgosz, R.I. et al. (2017) 'Comparisons of gas standards for climate change and air quality monitoring', in *Metrology: from Physics Fundamentals to Quality of Life*. IOS Press, pp. 89–120

¹⁰⁴061-EURAMET-UK. Trustworthy Data to Enable Evidence-based Climate Action (NPL)

¹⁰⁵024-APMP-ID. Development of Metrological Traceable Greenhouse Gas (GHG) Standards for Indonesia (SNSU-BSN)

¹⁰⁶035-COOMET-RU. Accurate Measurements of Carbon Dioxide at Atmospheric Levels for Climate Action (VNIIM, Saint-Petersburg)

An aerial photograph of a lush green landscape. A river or stream flows through the center, bordered by dark, possibly stone or wooden, walls. Several sheep are grazing in a field on the right side. The overall scene is peaceful and rural.

The electrification of transportation infrastructure is a significant step toward supporting sustainable industrial development and promoting resource-efficient technologies in daily use. The Republic of Korea has recently identified the need for a high-speed charging network, backed by national regulations, to support its estimated 30 % EV market share by 2030. Korea Research Institute of Standards and Science (KRISS) and the Korean Agency for Technology and Standards (KATS) have formed a partnership to create a unified legal and scientific basis for high-power DC energy standards for EV fast charging.¹⁰⁷ The intervention successfully increased the national calibration capability from a 50 kW baseline to 500 kW, representing an order-of-magnitude increase in capacity while maintaining precise measurement uncertainty. This will ensure a nationwide high-speed charging network that is reliable and trustworthy, and enable the Republic of Korea's EV market to grow toward its 2030 targets.

NIM in China has developed metrological methods and tools to evaluate electric vehicle supply equipment (EVSE), combining SI-traceable EVSE testing, online performance evaluation, and risk-matched follow-up to support reliable charging services, sustainable infrastructure, clean urban transport, and the low-carbon transition.¹⁰⁸ As the largest EV charging infrastructure network in the world, this integrated metrological framework will support over 20 million charging connectors nationwide. The online EVSE infrastructure monitoring tool facilitates real-time evaluation of EVSE performance and accuracy estimation, enabling a holistic, data-driven decision process for how best to verify and inspect EVSE within municipalities across China.

¹⁰⁷008-APMP-KR. Paving the Way for Korea's Electric Vehicle (EV) Era (KRISS; KATS)

The application of metrology has widely contributed to the development and promotion of other energy-efficient technologies, such as wind- and solar-based energy generation and the standardization and usage of more efficient lighting technologies. These clean energy projects also directly reduce GHG emissions, thereby supporting the goal of climate action. Examples of metrology used to facilitate the production of low-carbon or “greener” fuels from Singapore¹⁰⁹ and Brazil¹¹⁰ also contribute to this important goal.

¹⁰⁸049-APMP-CN. Trusted and Accurate Metrology for Electric Vehicle Supply Equipment (EVSE) in China (NIM)

¹⁰⁹027-APMP-SG. Isotope Fingerprinting for Trusted Low-Carbon Fuels: Enabling Climate Action, Fair Trade, and Transparency (NMC, A*STAR)

¹¹⁰007-SIM-BR. Nanometrological Characterization of Heterogeneous Catalysts for the Conversion of CO₂ to High-Value Products (INMETRO)



SDG 14 Life Below Water

Human activities and industrial processes, such as shipping, factory discharges, and offshore operations, can have a detrimental impact on maritime habitats and ecosystems. Acoustic noise can have a significant effect on life below water; for example, noise in the frequency range of 20 Hz to 1 kHz has been demonstrated¹¹¹ to have a profound effect on marine fauna. To protect marine biodiversity and ecosystems, the EU Marine Strategy Framework Directive¹¹² has been implemented to limit human-generated noise in these frequency ranges. However, the lack of metrologically traceable standards for accurately detecting, and thus properly regulating, underwater sound prompted several NMIs and DIs, Danish Fundamental Metrology (DFM), the NPL in the UK, and the Underwater Acoustics Laboratory (UAL) in Türkiye, to cooperatively build new metrological capability to solve this problem. Together, they developed new measuring instrument technology, including 'autonomous noise recorders', which combine hydrophones, data acquisition and storage capabilities, required specification standards, and metrologically traceable calibration methods. The project developed a metrology framework to accurately measure underwater noise and enabled the use of underwater hydrophones during the 5-year construction of the Dardanelles Bridge (1915 Çanakkale Bridge) in Türkiye, with minimal disturbance to the marine ecosystem.

Micro- and nanoplastics (MNPs) are emerging contaminants of concern for both food and the environment, especially in marine environments. NMI Australia (NMIA) has been leading a collaboration with several other NMIs¹¹³ to trigger several metrology-based initiatives to establish a metrological traceability framework and standardized measurement methods for MNPs. This includes improving particle metrology measurements to develop reference materials that support comparisons of measurement capabilities.

Many established NMIs with mature chemical metrology programmes have developed

and maintained matrix-based reference materials, proficiency testing materials, or calibration services that support measurements that are vital to the fishery and aquaculture sectors. A number of NMIs and DIs have established CMCs centred on fish-based matrices under the food measurement service category in the KCDB.¹¹⁴ Accurate determination of a wide range of inorganic and organic contaminants in fishmeal, fish, and other seafood products is necessary to comply with regulatory limits for aquaculture exports. As the NMI for Colombia, INM joined a regional project led by PTB to strengthen technical capabilities to measure contaminants in fish matrices, while also conducting a metrological gap analysis with tilapia producers to identify service needs and metrological traceability challenges. As a result, INM developed its first CRM for mercury and methylmercury in fishmeal, followed by a subsequent PT scheme for mercury in fishmeal.¹¹⁵ The routine use of the nationally produced CRM provides the laboratory testing sector with significant cost savings (over 30 times cheaper) compared to using reference material products imported from countries such as Mexico, Canada, and the United States. Further, Colombia now maintains four accredited testing laboratories for measuring mercury in fish and one accredited laboratory for measuring cadmium and lead in fish.

Select NMIs develop a range of CRMs for marine toxins, improving the accuracy and reliability of monitoring efforts for cyanobacterial blooms and seafood safety assessments. These calibration standards and matrix-based reference materials allow testing and oceanographic laboratories to compare data and detect long-term changes in marine health. Oceans also absorb substantial amounts of heat and CO₂, so monitoring their chemistry is crucial. Accurate pH measurements also support studies on ocean acidification, which affects coral reefs and marine biodiversity. Many NMIs and DIs provide CRMs to support accurate pH determinations, including across a range of salinities and element and nutrient concentrations, enabling highly accurate seawater and coastal water pH measurements.

¹¹¹EMPIR project 15RPT02 UNAC-LOW "Underwater acoustic calibration standards for frequencies below 1 kHz"

¹¹²010-EURAMET-TR. New Measurement Capabilities to Support the Health of Life Below Water (MRC MI-UAL)

¹¹³005-APMP-AU. International Collaboration to Establish Pathways for Comparable Measurements of Micro- and Nanoplastics (MNPs) (NMIA)

¹¹⁴BIPM Key Comparison Database (KCDB). <https://www.bipm.org/kcdb/>

¹¹⁵004-SIM-CO. Promoting Competitiveness in Colombian Aquaculture: Metrological Traceability for the Control of Inorganic Contaminants in Tilapia (INM)





SDG 15 Life on Land

Global agriculture and much of the world's rural livelihoods are dominated by the agricultural production of staple grains and complex carbohydrate-based crops. Many economies across Asia depend on rice as their primary staple. Spoilage caused by excessive moisture poses a significant challenge to rice production and its viability as a commodity. In Thailand, NIMT developed the country's first metrologically traceable certified reference materials for rice moisture and is now achieving a 0.2 % uncertainty in moisture content measurements.¹¹⁶ This allows the industry to meet its 0.5 % target for moisture meter validation and helps mitigate a potential annual loss of 120 million USD to the Thai economy. In Zambia, ¹¹⁷ measurements related to auxiliary components (e.g., fertilizer) have also been shown to be critical to the agricultural sector, particularly for grain-based crops. An accurate application of fertilizer is vital not only for achieving high yields but also for producing high-value agricultural end products for direct consumption by the population or for export.

Soil health, biodiversity studies, and deforestation monitoring require precise environmental measurements. Chemical metrology capability and measurement services, such as reference materials and PT schemes, directly support soil testing and analysis laboratories by improving the accuracy of nutrient and pollutant measurements. This ultimately helps farmers and environmental agencies maintain healthy ecosystems. As with the food and clinical categories in the KCDB, many NMIs and DIs maintain CMCs that represent extensive portfolios of natural matrix reference materials. These are used for soil analysis method validation and to support improvements in measurement comparability for metrology institutes and organizations, as well as commercial testing laboratories. Legacy issues are well addressed by the existing measurement services, but further work is needed on measurement needs for soil health, such as

micro- and nanoplastics (MNPs) and PFAS contamination that is increasingly of public concern.

The current challenge for NMIs and DIs developing new metrology capabilities is to determine which specific environmental measurements are needed and, hence, which metrological capabilities are required to support agricultural production in a sustainable manner and to ensure sustainable soil management. The case presented by NMIA illustrates MNPs as ubiquitous contaminants across all parts of the food chain and environmental systems, including soil.¹¹⁸ To address this global issue, a group of NMIs and DIs are working together to determine the best metrological traceability framework to build the measurement capability needed to support forthcoming regulatory requirements.

In many cases, the specific needs of the national agricultural production, environmental monitoring, or economic drivers will determine the course of development of measurement services within its NMI or DI, and its access across the region. The Affiliated Branch of the D.I. Mendeleyev Institute for Metrology (UNIIM) in Russia has developed a CRM for the composition of Siberian pine (*Pinus sylvestris*) needles.¹¹⁹ This pine species is regularly monitored for pollution in both terrestrial and aquatic ecosystems due to its wide geographical distribution across Russia and its ability to rapidly change its elemental composition under worsening environmental conditions. This regionally significant CRM is also managed through a regional Register of COOMET CRMs to facilitate its use by member NMIs and DIs.

Brazil has one of the world's richest biodiversities of tree species, with approximately 16 000 species, some of which are protected under environmental regulations. Illegal logging remains a major environmental and economic concern, with a substantial share of timber production linked to unauthorized or fraudulent practices. To address this, INMETRO developed a rapid analytical methodology based on mass spectrometry chemotyping to identify the species of tree that timber came from,¹²⁰ demonstrat-



ing a classification accuracy above 95 % in validation tests that involved unknown samples. Although field deployment has not yet been formally implemented, the methodology was specifically designed to support future applications at inspection checkpoints, ports, airports, and mobile laboratory environments to improve inspection efficiency, reduce reliance on centralized laboratory analysis, and strengthen timber supply-chain verification systems.

¹⁰⁰015-APMP-TH. Food Security and Economic Stability for Thailand: Moisture Content in Rice (NIMT)

¹⁰⁰052-AFRIMETS-ZM. Strengthening Measurement Systems in Zambia's Agriculture through Standardized Trade Instruments and Quality Assurance (ZMA)

¹⁰⁰005-APMP-AU. International Collaboration to Establish Pathways for Comparable Measurements of Micro- and Nanoplastics (MNP) (NMIA)

¹⁰⁰032-COOMET-RU. Facilitating Access to Certified Reference Materials (CRMs) for Industry, Environmental Monitoring, and Healthcare Applications within the COOMET Region (UNIIM)

¹⁰⁰037-SIM-BR. Enabling Real-time Timber Identification through Low-cost Mass Spectrometry for Sustainable Forest Management and Enforcement. (INMETRO)

SDG 16 Peace, Justice and Strong Institutions

Legal metrology systems that prevent fraud in commerce also build people's trust in public institutions and the government. The Laboratorio Costarricense de Metrología (Lacomet) in Costa Rica has made the case for metrological control of evidential breath analyzers (based on OIML R 129) and traffic speed monitoring devices (based on OIML R 91) to prevent and reduce deaths and the trauma caused by road accidents.¹²¹ This has prompted greater confidence in the results used for evidentiary purposes and, thus, a decrease in court appeals.

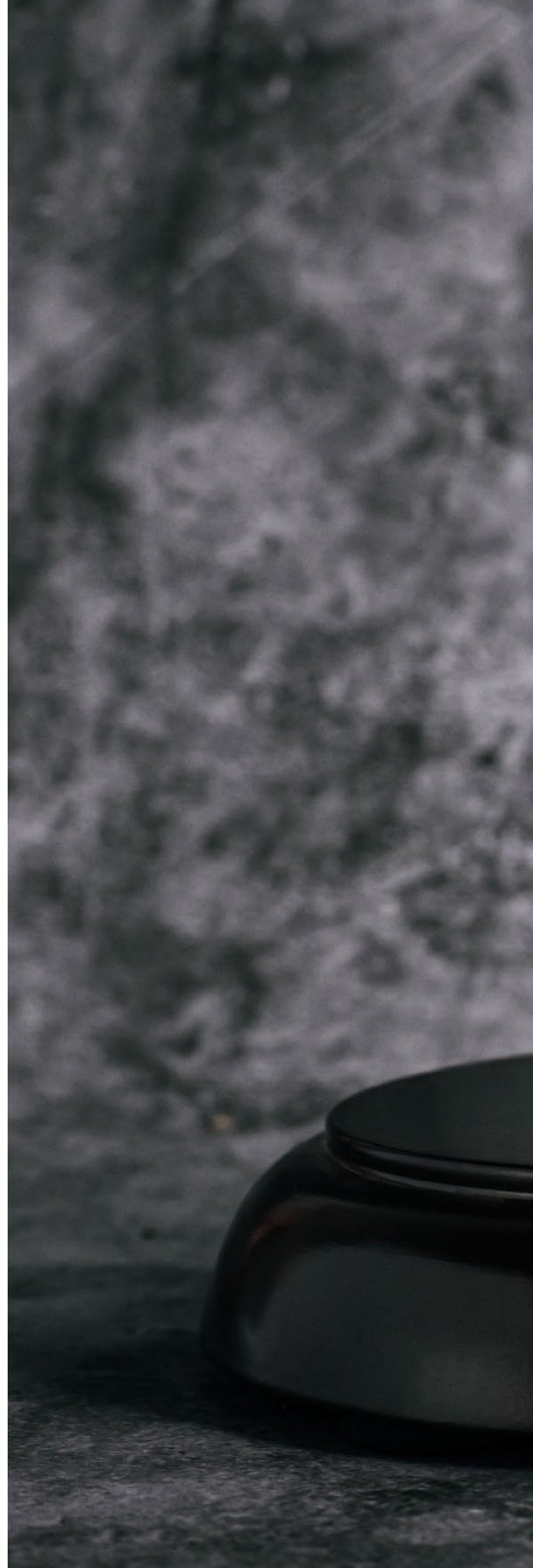
Forensic laboratories also play a critical role in the criminal justice system and in public health assessments. Reliable laboratory measurements in toxicology and drug analysis directly impact road safety policies, prevention strategies, and health-related legal decisions. Since 2020, INMETRO, supported by the National Secretariat of Public Security in Brazil, has implemented a nationwide PT scheme for forensic analysis.¹²² Through this PT programme, significant improvements in measurement comparability across Brazil's forensic testing laboratories have strengthened the scientific basis of forensic evidence, directly contributing to more reliable judicial decisions and improved public security outcomes.

Many other mature NMIs and DIs have developed and maintain metrology frameworks to support their nation's forensic science sectors that rely heavily on validated measurement methods. Calibration standards and matrix-based reference materials for DNA profiling, illicit substances, and other areas of toxicology help ensure that forensic evidence presented in court is scientifically reliable and legally defensible. Some of these initial activities have been documented in past CCQM workshops, including a symposium on Standards and Metrology in support of Anti-Doping Analysis with the World Anti-Doping Agency (WADA).¹²³

¹²¹022-SIM-CR. Metrological Controls for the Prevention and Reduction of Road Accident Trauma and Deaths in Costa Rica (LACOMET)

¹²²025-SIM-BR. Strengthening Forensic Measurement Reliability in Brazil to Support Public Health and Justice (INMETRO; Senasp)

¹²³BIPM-WADA Symposium on Standards and Metrology in support of Anti-Doping Analysis) <https://www.bipm.org/en/bipm-workshops/bipm-wada-2016>







SDG 17 Partnerships for the Goals

The field of metrology is fundamentally global and is best supported through international cooperation and multi-stakeholder partnerships. This includes policy-driven alignments as well as technical exchanges, support, and capacity building between NMIs, DIs, research and academic institutes, QI partners, standards development organizations, RMOs, RMLOs, international metrology and other organizations. Europe has an extensive history and many examples¹²⁴ of the effective use of diplomatic actions to facilitate international scientific collaboration and promote data-based decision-making in foreign and security affairs. Many economies from other regions across the globe could benefit from such relationships and endeavors to advance their sustainable development goals. The pressing need for scientific diplomacy within and between developing nations to build a knowledge-based economy of the future, rather than the provision of raw materials, is highlighted in a recent AAAS editorial.¹²⁵ All nations, developed and developing, will need to work together towards sustainable development related to emerging technologies, such as AI and the energy required for operation, as well as critical mineral supply chains. Joint metrological work is vital for cross-national and cross-disciplinary projects to tackle global issues for climate change, pandemics, and access to safe and adequate supplies of food and water.

The importance of diplomacy in metrology is clearly demonstrated by the establishment of the Metre Convention in 1875. The creation of the BIPM is one of the world's oldest international agreements. The BIPM serves as the metrological centre for scientific and technical cooperation among Member States. A key activity in this effort is international comparisons, in which national metrology institutes measure the same artefact and compare results, thereby strengthening global confidence in measurement systems. These cooperative activities allow countries

of all sizes to participate equally in global trade, technology, and science, ultimately ensuring worldwide uniformity of metrology practice. The BIPM also coordinates with numerous other international organizations; the list of liaisons on its website identifies almost 40 and establishes meaningful connections with Member States and the RMOs. The BIPM Capacity Building and Knowledge Transfer Programme (CBKT)¹²⁶ exemplifies such engagement through its workshops, laboratory placements, and remote-learning activities on the BIPM e-learning platform, which also hosts knowledge transfer materials from RMOs.

The RMOs and RMLOs provide extensive capability building activities, research exchange, and associateship programmes to enhance metrology-based partnerships and facilitate international cooperation towards sustainable development goals. An example are the EURAMET European Metrology Networks (EMNs),¹²⁷ which are comprised of NMIs and DIs focusing on horizontal metrology subjects of economic and social relevance with the aim of addressing stakeholder needs in a coordinated manner. Twelve EMNs have been established, setting collaborative research agendas and engaging in stakeholder outreach on subjects ranging from advanced manufacturing and laboratory medicine to quantum technologies. For example, the EMN for Safe and Sustainable Food¹²⁸ helps connect NMIs and DIs with stakeholders to build new collaborations and advance the comparability of food-related measurements in Europe and the world. Nearly all of these EMN activities directly underpin many of the UN SDGs.

When a country invests in metrology, it strengthens not only its own regulatory, industrial, and quality infrastructure systems but also supports the development of other NMIs and DIs, as well as regional and global trade capacity. Metrology capability building is often developed through NMI-specific initiatives or even through project-level bilateral NMI or DI engagements. Mature NMIs can provide support and knowledge transfer of existing fundamental capabilities to a developing NMI or DI and there are innumerable examples of this.

¹²⁴European Union External Action (EEAU) What is Science Diplomacy? https://www.eeas.europa.eu/eeas/what-science-diplomacy_en

¹²⁵AAAS Center for Science Diplomacy. The Imperative for World-Class Research Infrastructure in Africa: A Strategic Lever for Equitable Science Diplomacy. <https://www.sciencediplomacy.org/editorial/2026/imperative-for-world-class-research-infrastructure-in-africa-strategic-lever-for>

For nascent metrology areas, however, such partnerships can be advantageous for stimulating new economic activity for all those involved. It has also been demonstrated that multilateral engagements can be more effective and efficient^{129,130} than numerous bilateral arrangements, which are often independent and can become segregated within the metrology community. A few examples (though far from a complete list) of these partnership types for building metrological capability are provided herein; many other NMIs support such endeavours.

KEBS has recently leveraged its technical infrastructure to strengthen metrology capacity at metrology institutes across the East African Community (EAC) and the wider African Continental Free Trade Area (AfCFTA) region.¹³¹ KEBS has supported the institutions directly through technical training, laboratory visits, and calibration services that provide pathways to metrological traceability. The services covered measurement scopes in AC/DC electrical quantities, mass, force, pressure, time, temperature, density, dosimetry, volume, photometry, and acoustics. Ultimately, these activities improved the technical skills of the partner countries while building metrologically traceable measurement capability and strengthening quality infrastructure, thereby supporting confidence in measurements and conformity assessment. This case study demonstrates the long-term value of sustained investment in national metrology capability, which can support neighbouring institutions and advance a broader regional purpose.

To return the support it received during its own growth, NIM (China) has, since 2015, launched assistance programmes for several developing countries. With the support of China's Ministry of Foreign Affairs and Ministry of Science and Technology, and coupled with its own institutional funds, NIM has conducted "full chain" activities, including the establishment of measurement standards, personnel training, calibration services, and the provision of technical regulations. These efforts have bene-

fited more than 30 economies, especially those in the Association of Southeast Asian Nations (ASEAN) and Eurasia regions. At the same time, NIM has become a constructive contributor to capacity-building activities within APMP and COOMET.

PTB also operates a prolific International Cooperation programme, contracted by the German Federal Ministry for Economic Cooperation and Development, which provides financial support to numerous countries, regions, and global efforts in capacity building for metrology and quality infrastructure.¹³² PTB provided support to several NMIs to facilitate their work, as highlighted in several recent case studies within this publication. Projects range from metrology capacity building to supporting PT testing and accreditation efforts.

As part of a strategic effort to facilitate international cooperation and build global metrology capacity, the US NMI, NIST, is collaborating with Centro Nacional de Metrología in Mexico (CENAM) and KEBS to refine the tabletop Kibble balance as a scalable, transferable primary standard.¹³³ This work not only advances cutting-edge instrumentation to improve reliability and metrological traceability across many industrial sectors but also encourages and fosters equal participation at all levels of the economy, ultimately ensuring worldwide uniformity in metrological practice.

¹²⁹BIPM-TÜBİTAK UME Project Placements. <https://www.bipm.org/en/-/2025-02-14-bipm-tubitak-ume-project-placements>

¹³⁰044-AFRIMETS-KE. Kenya-led Regional Quality Infrastructure Cooperation (KEBS)

¹³¹Physikalisch-Technische Bundesanstalt (PTB), International Cooperation Group <https://www.ptb.de/cms/en/ptb/fachabteilungen/abtq/gruppe-q3.html>

¹³²Q39-SIM-US. Deployment and Knowledge Transfer of Tabletop Kibble Balance Technology for SI-traceable Mass Realization (NIST)

¹²⁸BIPM Capacity Building and Knowledge Transfer Programme (CBKT) <https://www.bipm.org/en/committees/cb/cbkt>

¹²⁹EURAMET's European Metrology Networks. <https://www.euramet.org/european-metrology-networks>

¹³⁰<https://www.euramet.org/european-metrology-networks/safe-and-sustainable-food>

¹³¹051-AFRIMETS-ZA. The Multiplier Effect: NMISA's Mycotoxin Reference Material Programme (NMISA)





Part III. Reflections





Part III. Reflections



This report presents a series of over 60 illustrative case studies in scientific, industrial, and legal metrology from across the globe. These studies highlight the foundational aspects, benefits, challenges, and quantifiable impacts of metrology in achieving inclusive and sustainable industrial development, underpinning the UN's 2030 Sustainable Development Agenda. The authors of many of these case studies have clearly and openly revealed their nation's specific technological and societal challenges. Many have provided information on the thoughtful and insightful activities, interventions, and solutions used to address these metrological challenges. Others represent early-stage activities in countries with emerging metrology systems where capabilities are being established or further developed that will significantly impact sustainable industrial development in the near future. Together, this collection of studies represents a “snapshot” of metrology programmes at various stages of development and covers a wide range of metrology topics that address the UN SDGs in different ways.

Key Takeaways and Opportunities

No two NMIs or DIs experience the same journey in developing their metrological capabilities to support sustainable development goals. Many have responded to policy drivers or national needs set by their governments by developing robust, tailored metrological programmes, services, and focused interventions. Each approach is unique to the national challenge it addresses, and ranges from launching new measurement services, such as reference materials, calibration services, or proficiency testing schemes, to developing new measurement science capabilities. Several institutes have demonstrated that, with well-targeted investments, careful planning, and effective programme deployment, creative solutions can be found even within the constraints of limited resources.

Metrology has a clear, wide-ranging role in underpinning a fair and equitable marketplace and preventing fraud, from the local to the global scale. Measurement services that ensure safe food and feed in agroindustry underpin the quality of, and confidence in, high-quality goods and export products for global trade, and also directly contribute to human health and the well-being of the population.

For many metrology institutes, the development of an initial programme area, such as legal metrology, has triggered a cascade of wider positive improvements in other areas (e.g., availability of metrological traceability for measuring instruments) not originally envisaged. Priority areas for further investment were identified through an iterative process with critical, timely feedback from policymakers and other stakeholders at key decision points in the programme development. There is often a multiplier effect from metrological solutions and interventions. Not only is the immediate issue resolved, the measurement system is strengthened and others are able to benefit.

The inherent value of partnerships was evident in several NMI case studies presented here. Partnerships took the form of joint research, regional training, capacity building, and knowledge transfer engagements, as well as direct financial support. These included both informal and formally coordinated activities (e.g., comparisons, BIPM involvement), bilateral and multilateral NMI projects, and the complementary provision of services both locally and regionally, via metrology organizations and industry partnerships. Intrinsically impartial, NMIs and DIs have also demonstrated their value as metrological “shepherds,” leading and facilitating collaboration between industry partners and stakeholders towards robust and innovative technological advances, often in sectors of great importance, such as healthcare, agroindustry, and energy. Furthermore, metrology leaders work with stakeholders to advance accurate measurements of the essential climate variables needed to understand our changing planet.

A number of institutes have demonstrated how metrology can be effectively integrated into the development of innovative measurement technology, bolstering confidence in the overall processes and the resulting high-quality products. Even modest metrological improvements, when applied within high-value chains (e.g. petroleum and energy, advanced manufacturing), translate into “big wins” in terms of economic and societal impact.

Many NMIs and DIs in countries with emerging metrology systems are now exhibiting greater autonomy and operational independence in their metrological endeavours (often initiated by fiscal drivers). Secure and resilient national infrastructure contributes to recognition of success at a national level. A number of case studies highlighted the increase of national metrology services, including (certified) reference materials, proficiency testing schemes, and other quality assurance programmes. Notably, emerging economies invest resources in developing sector-specific measurement services that address their most crucial economic and societal challenges. For example, the establishment of an independent national time scale supporting time-stamped banking and GPS activities. In addition to driving economic growth and national prosperity, these new initiatives have demonstrated how expertly designed and executed metrology programmes can improve responsiveness, timeliness, and cost-effectiveness in service delivery to their customers and stakeholders.

A few institutes in developing economies have transitioned to new, modern services (e.g. digitalization of metrology), thereby bypassing the traditional route and associated (often the large) investments. In some instances, the development of emerging technologies and modern capabilities may be concurrent (or may even precede) the development of fundamental metrology capabilities

By their nature, the case studies capture very specific, identifiable examples of the contributions of metrology. What is not captured are the benefits that accrue from the day-to-day improvement in the provision of calibration and other measurement capabilities to the vast accredited calibration and testing community, which enables the accredited laboratories to offer improved services to their customers and associated sectors. Often, any consequent benefits that the end users exploit are largely invisible to the NMI and DI community.

As shown by the breadth of case studies presented here, each institute’s metrological solution to its particular challenge is unique and defined by its own current national needs, drivers, and resource constraints. Many of these serve as examples for others to adopt and modify to their own requirements and circumstances. Others may be generalized and applied widely across the ever-changing landscape of economic and societal challenges that metrology can address.

The metrology community has an opportunity to better communicate its existence and advocate for support among policymakers, funders, collaborators, and the general public. One of the many ways to achieve this goal is through such case studies that clearly demonstrate the “why” of the work. This applies to all stages of metrology enterprises, from mature programmes with clear, discernible impacts to nascent activities with the potential to grow and shape the future development of their nation’s infrastructure. Following the initial launch of this publication, the BIPM and the OIML remain committed to continuing to develop NMI and DI case studies as part of this engagement and service to the metrology community.

It is hoped that these case studies will promote a shared understanding among governments, development agencies and industry of how measurement capabilities translate into social, environmental and economic benefits. This understanding can then lead to strategic investment in this critical infrastructure. Furthermore, governments and the NMIs might be able to develop their own blueprints for actions from the lessons highlighted in the case studies.

Continued Activities through 2030

This publication represents only a small subset of the vast number of activities, projects, and programmes undertaken by the NMIs and DIs to support the UN SDGs. The BIPM, the OIML and UNIDO will continue its partnership to refine the existing case studies while collecting new NMI and DI case studies from the RMOs through to 2030, in line with the UN’s 2030 Sustainable Development Agenda. Thus, the NMIs and DIs are invited to continue contributing to the collection by submitting additional case studies.

For the global metrology infrastructure to have the maximum impact on sustainable development, participation by, and contributions from, all states is essential. At the time of writing, around 111 states participate in BIPM activities as either Member States or Associates of the CGPM, accounting for about 98 % of global GDP. The challenge is to effectively engage in metrology with the remaining 82 or so states. One initiative to grow participation is being taken by the CIPM which is proposing that the CGPM adopt a new category of “Observer” status. If adopted, this will enable countries with very limited capabilities to be involved in metrological activities, initially through no-cost observation and active capacity building collaborations. Thus, the aim is for every state to participate in the international community at a level of engagement appropriate to its state of development, economy and ambition. It will also enable the Metre Convention to be fully inclusive, as originally intended in 1875. In the sphere of legal metrology, 130 economies currently participate in OIML activities as Member States or Corresponding Members.

A number of non-members also have some awareness of, and input into, the OIML’s work through their membership of Regional Legal Metrology Organizations (RLMOs) and the activities of the OIML’s RLMO Round Table.

These case studies provide examples of metrology initiatives and collaborations by and among RMO, NMIs, DIs and other stakeholders aiming to achieve a common outcome, that is supporting the SDGs. Indeed, it is hoped that the study may inspire new initiatives and collaborations towards that goal. Continuous engagement with NMIs, RMOs, and UNIDO partners will be maintained to collect, validate and publish new case studies on the BIPM website. Thus, contributions are welcomed using the dedicated BIPM website, at least until the 2030 UN SDG agenda is revised.

Acknowledgements



This work would not be possible without the numerous and significant technical contributions of the NMIs, DIs, and their industrial and metrology organization partners. This work was also made possible by support from Federal Institute of Metrology (METAS), Switzerland, and other supporters and backers.

This study was undertaken under the auspices of the BIPM and UNIDO, with contributions from the OIML. The publication was developed, designed, and reviewed by a BIPM-UNIDO drafting team (**Katrice Lippa** (NIST); drafting lead, **Andy Henson**; lead consultant, **Chingis Kuanbayev** (BIPM); project manager, **Javier Arias** (SIM), **David Tomlinson** (UNIDO), and **Angela Rosero** (UNIDO)) and an RMO/RMLO review team (**Humphrey Nkoben**; AFRIMETS, **Angela Samuel** and **Sze Wey Chua**; APMP, **Lazizbek Saidoripov**; COOMET, **Omer Altan**; EURAMET, **Abdulelah Q. Al-Qarnas**; GULFMET, and **Ian Dunmill**; OIML).

Annex. 12 Featured Case Studies



Over 60 case studies obtained from NMIs, DIs, and their partnering organizations were developed to promote the role of metrology in achieving the UN's 2030 Sustainable Development Agenda and to strengthen policy makers' and stakeholders' awareness of how reliable measurements underpin sustainable, industrial, and social development. Collected from NMIs and DIs across the globe, these scientific, industrial, and legal metrology case studies highlight the foundational aspects, benefits, challenges, and quantifiable impacts of metrology that underpin sustainable development and make a better world.

A collection of 12 featured case studies have been selected that represent a balance between scientific, industrial, and legal metrology and from both developed and developing economies, while also spanning the diverse thematic areas and SDGs.

Representation across the six RMOs was also maintained; two case studies each from the Intra-Africa Metrology System (AFRIMETS), Asia Pacific Metrology Programme (APMP), the Euro-Asian Cooperation of National Metrological Institutions (COOMET), the European Association of National Metrology Institutes (EURAMET), the Gulf Association for Metrology (GULFMET), and the Inter-American Metrology System (SIM) are presented.

Each of the featured case studies have demonstrated clear challenges, needs, and opportunities, including national or sectoral relevance, that are being addressed by metrological interventions and/or solutions. These case studies also describe quantifiable, data-based outcomes that support SDG implementation, national policy development and/or international cooperation.

All of the case studies from this publication, including these 12 featured case studies, are available on the BIPM website.





UNITED NATIONS
INDUSTRIAL DEVELOPMENT ORGANIZATION

Bureau
International des
Poids et
Mesures



The Multiplier Effect: NMISA's Mycotoxin Reference Material Programme

NMISA led an RMO-focused pilot programme to develop mycotoxin reference materials and food safety testing laboratory capabilities, which now underpins food testing and safety across many African nations

*National Metrology Institute of South Africa (NMISA)
South Africa (ZA)*



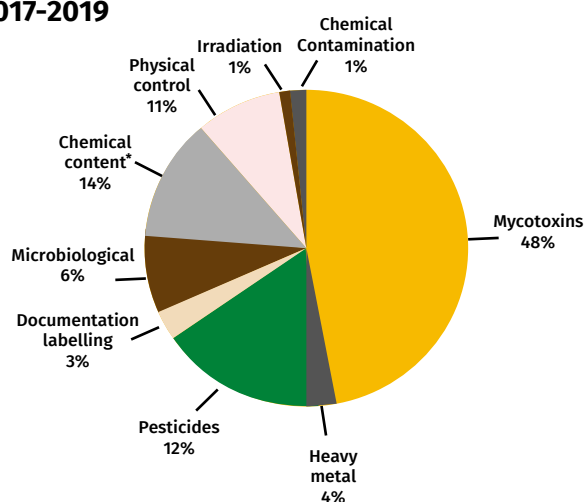
The Challenge

According to the African Union, Africa faces serious food safety and trade challenges that directly affect public health, economic development, and food security. Both acute and chronic dietary exposure to mycotoxins in staple foods like maize and groundnuts has been linked to deaths, severe illness, elevated liver cancer rates, and childhood stunting across the continent.^{1,2} The trade impact is equally significant: in 2017-2019, nearly half (48 %) of all European Union Rapid Alert System for Food and Feed (EU RASFF)³ notifications against African food exports involved mycotoxin contamination in nuts

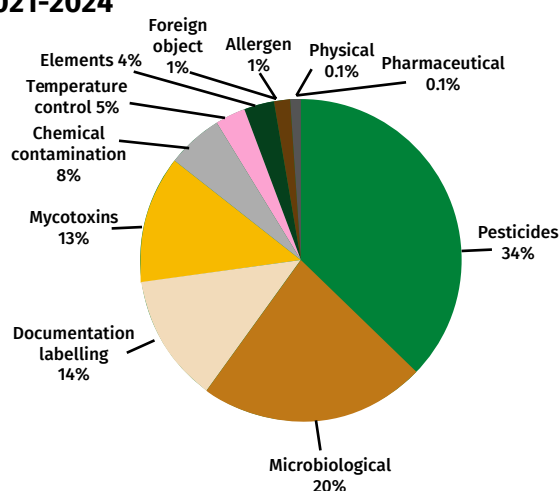
and cereals, making mycotoxins the continent's foremost barrier to international market access (Figure 1A).

Compounding these challenges was a critical measurement infrastructure gap that limited the effectiveness of broader food safety initiatives, resulting in unreliable surveillance data, weak compliance with international standards, and constrained laboratory accreditation.

A.
2017-2019



B.
2021-2024



*Chemical content is related to chemicals added to or inherent to a specific commodity. **Chemical contamination is a chemical that should not be present in a specific commodity this excludes pesticides and mycotoxins that have been grouped separately due to the number of associated alerts.

Figure 1. European Union Rapid Alert System for Food and Feed (EU RASFF) notifications, alerts, and/or rejections received by Africa during A. 2017-2019, and B. 2021-2024.⁴ The reduction in mycotoxin alerts is clearly received after multi-stakeholder global CBKT interventions.



¹Food Safety Strategy for Africa 2022-2036. AU Department of Agriculture, Rural Development, Blue Economy and Sustainable Environment. Addis Ababa: African Union – DARBE, 2022.

²Ayalew, A. "Partnership for Aflatoxin Control in Africa (PACA). Integrated Approach to Mycotoxin Control and the PACA Experience," in Africa Food Safety Workshop, Pretoria, South Africa, 2018.

³European Commission, EU RASFF portal. <https://webgate.ec.europa.eu/rasff-window/portal/>

⁴European Commission, EU RASFF portal. <https://webgate.ec.europa.eu/rasff-window/portal/>

African food testing laboratories lacked access to affordable, regionally-relevant certified reference materials (CRMs) for mycotoxin analysis, undermining the measurement foundation needed to support policy makers, regulatory authorities, and trade officials. International mycotoxin proficiency testing (PT) studies have shown that when laboratories rely solely on in-house calibration standards, measurement variability can exceed 40 %. This applies to laboratories whether or not they are ISO/IEC 17025-accredited. A significant reduction in measurement variability (to approximately 16 %) was observed when testing laboratories used a common SI-traceable calibrator.⁵ This stark difference demonstrates the impact of key metrological interventions related to calibration materials on improving measurement comparability and strengthening the evidence base required for sound decision-making.

The Solution

In 2015, NMISA established the African Food and Feed Reference Material Programme (AFFRMP), piloting indigenous mycotoxins as prioritized CRMs needed to support food and feed testing laboratories in South Africa and across the continent.

Through participation in the International Bureau for Weights and Measures (BIPM) Mycotoxin Metrology Capacity Building and Knowledge Transfer (CBKT) Programme (2016-2019),⁶ NMISA developed new analytical measurement capability (i.e., quantitative ¹H-NMR) and subsequently developed metrologically traceable mycotoxin calibration solution CRMs for aflatoxin B1, B2, G1, and G2, zearalenone, deoxynivalenol, ochratoxin-A, and patulin (**Figure 2**).

The new capability was underpinned by Calibration and Measurement Capabilities (CMCs) declared under the International Committee for Weights and Measures Mutual Recognition Arrangement (CIPM MRA). Using these calibrators, NMISA developed complementary matrix CRMs for multiple mycotoxins in white maize, peanut slurry, and peanut butter matrices.

For the first time, African food testing laboratories had access to regionally relevant, accessible, and affordable reference materials made on the continent. This sustainable, African-owned measurement infrastructure also supports innovation in industry and infrastructure, establishes long-term regional capacity, and reduces reliance on costly imports.



Figure 2 Clockwise: NMISA Mycotoxin calibration solution CRMs for aflatoxins B1, B2, G1, G2 (top left). NMISA Ochratoxin-A CRM solution (top right), and matrix CRMs for multiple mycotoxins in white maize (bottom left), and aflatoxins in peanut butter (bottom right).⁷

⁵Josephs RD, Krska, R., "International interlaboratory study for the determination of the Fusarium mycotoxins zearalenone and deoxynivalenol in agricultural commodities," Food Additives & Contaminants, vol. Volume 18, no. 5, pp. 417-430, 2001.

⁶BIPM Capacity Building and Knowledge Transfer Programme, "Metrology for Safe Food and Feed - Mycotoxins," BIPM, 2016. <https://www.bipm.org/en/committees/cb/cbkt/wg/cbkt-mm-bipm>

⁷NMISA, NMISA Reference Materials. <https://www.nmisa.org/products-and-services/reference-materials/Pages/default.aspx>

These NMISA-produced CRMs became the metrological foundation for collaborative capacity building activities across Africa, delivered jointly with multiple stakeholders through:

- BIPM Capacity Building and Knowledge Transfer Mycotoxin Metrology Programme, expanding into metrology for safe food and feed (pesticides and veterinary drug residues), enabling comparisons and CMCs for new mycotoxin and pesticide CRMs⁸
- Intra-Africa Metrology System (AFRIMETS) Food Safety Capacity Building initiatives for hands-on training and PT schemes⁹, supported by Physikalisch-Technische Bundesanstalt (PTB) Germany, alongside initiatives for fellow NMIs; Egypt's National Institute of Standards (NIS), Kenya Bureau of Standards (KEBS), and the Tunisian designated chemical metrology institute: Institut National de Recherche et d'Analyse Physico-chimique (INRAP)
- The Joint United Nations Food and Agricultural Organisation (FAO) and International Atomic Energy Agency (IAEA) Centre of Nuclear techniques in Food and Agriculture and IAEA Africa Region Technical

Cooperation projects (RAF 5067, 5078, 5084, and 5091) under the Africa Food Safety Network (AFoSaN) supporting PT schemes, spanning 30 mandated food monitoring and inspection laboratories across the continent^{10,11}

- Association of Official Analytical Collaboration (AOAC) Africa Laboratory Performance Benchmarking Programme (LPBP), which used NMISA matrix CRMs as the metrologically traceable reference materials for benchmarking laboratory performance against Standard Method Performance Requirements (SMPRs)¹²
- Pan African Quality Infrastructure (PAQI) Cassava Project, supported by PTB Germany, preparing reference materials for proficiency testing of mycotoxins and other food hazards in cassava flour.¹³

These activities encompassed workshops, proficiency testing (PT) schemes, hands-on training, and visiting scientist exchanges for mandated food monitoring and inspection laboratories, with the shared objective of expanding the number of ISO/IEC 17025 accredited food safety testing services on the continent, reinforced through the use of metrologically traceable calibrators.



Figure 3. Top row: NMISA hands-on training for AFRIMETS mycotoxin analysis (Tanzania, Malawi, Lesotho, Ethiopia), and bottom row: in-house RM production (IAEA RAF 5084 Fellowship training for Benin, Botswana, Morocco, and Nigeria).

⁸BIPM, BIPM CBKT Metrology for Safe Food and Feed - Pesticides and Veterinary Drug Residues, 2026. <https://www.bipm.org/en/committees/ch/cbkt/wg/cbkt-py-bipm>

⁹NMISA, NMISA Proficiency Testing Schemes, 2026. <https://www.nmisa.org/products-and-services/proficiency-testing-schemes/Pages/default.aspx>

¹⁰Joint IAEA-FAO, [Online]. Available: <https://www.iaea.org/newscenter/news/iaea-fao-workshop-strengthens-food-safety-network-across-africa>

¹¹IAEA AFRA Technical Cooperation, IAEA Regional Projects RAF5091, 2024. <https://www.iaea.org/projects/tc/raf5091>

¹²AOAC International - Africa Section, "AOAC Africa - Laboratory Performance Benchmarking Programme White Paper," 2021. <https://aoacsafrica.org/wp-content/uploads/2023/03/AOAC-Africa-White-Paper-LPBP.pdf>

¹³The Role of Quality Infrastructure in the Cassava Value Chain, https://www.qi-africa.ptb.de/fileadmin/Ressourcen_Downloads_Dokumente/Final_The_role_of_quality_infrastructure_in_the_cassava_value_chain_Vrs_02.pdf

A Quantifiable Impact

The intervention was grounded in nearly a decade of systematic stakeholder engagement and data collection. Surveys of South African testing laboratories in 2008-2009 first identified the absence of affordable, matrix-matched mycotoxin CRMs as a critical analytical limitation. Following the 2014-2015 launch of AFFRMP, structured stakeholder consultations with regional testing laboratories prioritized mycotoxins as the highest-priority CRMs for both calibration and food matrix measurements. In 2017, this evidence base was extended through the IAEA AFRA Technical Cooperation network (the Africa Food Safety Network), which confirmed identical priorities across participating Member States. The 2023 AFRIMETS Pan African Food Safety Testing Capacity Survey, supported by PTB Germany, provides the most recent evidence of progress and remaining gaps.¹⁴

Data quality across all NMISA-produced CRMs and PT reference values is ensured through metrological traceability to the SI, ISO/IEC 17025, ISO/IEC 17043, and ISO 17034 accreditation as RM producer, and demonstration of equivalence through participation in CCQM Key Comparisons (e.g., CCQM-K138 aflatoxins in figs, CCQM-K168 trans-Zearalenone in maize, and the CCQM K154 series for the BIPM CBKT calibration solution CRM series).

Over the past decade, the collaborative reference material and PT activities, built around NMISA's CRMs and complemented by partner contributions (Joint FAO-IAEA, AFRIMETS, BIPM CBKT, National Metrology Institute of Japan (NMIJ), National Institute of Metrology (NIM) China, Asia Pacific Metrology Programme (APMP), AOAC-Africa, and PTB Germany), have delivered measurable improvements in food safety testing capabilities across Africa. This has included demonstrable PT performance improvement for mycotoxin analysis among participating laboratories over successive PT rounds since 2018, with PT schemes covering aflatoxins in peanut slurry (2018), peanut butter, and mycotoxins in cereals (2019). **Table 1** highlights the 20-40 % improvement in food testing laboratories achieving satisfactory PT scheme performance scores over a 7-year time period.¹⁵ Continuous independent monitoring through PT participation is valuable for identifying potential bias and new measurement challenges where matrix RMs are not available (e.g., cassava).

A further benefit is the cost savings and rapid response capability for the South African food industry. For example, immediate access to NMISA patulin and aflatoxin CRM calibrators and peanut slurry and peanut butter matrix CRMs alleviated the South African Perishable Product Export Control Board (PPECB) and the wider private testing community during COVID-era testing pressures for patulin in apple and grape juice, and more recently, aflatoxin-related peanut butter product recalls. This expanded analytical scope has also qualified NMISA to offer ISO 17034 RMs and ISO/IEC 17043 accredited PT schemes that now cover priority contaminants (mycotoxins, heavy metals, pesticides) in white maize, groundnuts, almonds, macadamias, cassava, wheat, fruits, and cocoa. It is also important to acknowledge the BIPM CBKT mycotoxin metrology programme, which has enabled multiple AFRIMETS NMIs (NMISA, NIS, KEBS, INRAP) to produce mycotoxin calibration solution CRMs for the first time, with CMCs progressively published under the CIPM MRA.

Because of these multifaceted, highly coordinated activities, a significant reduction in EU-RASFF notifications of African exports for mycotoxin contamination (from 48 % to 13 %) was observed during 2021-2024 (**Figure 1B**). This significant achievement was only made possible through the collective efforts of a global community of food safety stakeholders CBKT interventions, with NMISA's metrologically traceable CRMs contributing to the measurement foundation that enabled testing laboratories to demonstrate compliance reliably. The fundamental shift, from dependency on expensive, non-matrix-matched imported reference materials to indigenous, regionally tailored measurement capacity, represents a sustainable transformation of the analytical foundation underpinning food safety in Africa.

¹⁴AFRIMETS, "Pan African Food Safety Testing Capacity Survey 2023," 2023. [http://www.afrimets.org/Lists/Events/Attachments/100/PTB FOOD SAFETY TESTING CAPACITY SURVEY REPORT FINAL Rev II Oct 2023.pdf](http://www.afrimets.org/Lists/Events/Attachments/100/PTB%20FOOD%20SAFETY%20TESTING%20CAPACITY%20SURVEY%20REPORT%20FINAL%20Rev%20II%20Oct%202023.pdf)
¹⁵NMISA, "Africa Food Safety Workshop 2022 Proceedings," in <https://www.nmisa.org/SiteAssets/AFSW%202022%20Post%20Event%20Report%20-%20Attendees.pdf>, 2022.

Table 1. Progressive improvement in Aflatoxin B1 Proficiency Test performance by selected Africa Food Safety Network laboratories for mycotoxin testing in groundnuts and cereals, 2018 – 2025.

Year	PT Study (Nuts)	No. of labs ^a	%z-score < 2	PT Study (Feed/Cereals)	No. of labs	%z-score < 2
2018	Ground nuts	33	61	---	---	---
2019	Ground nuts	12	67	Maize	54	63
2019	Ground nuts	12	100	----	---	---
2020	Ground nuts	10	90	Cassava	22	73
2021	Ground nuts (low level)	21	81	Feed (general)	14	100
2021	Ground nuts (high level)	20	80	----	---	---
2022	----	---	---	Maize	18	100
2023	Ground nuts	20	80	----	---	---
2024	Ground nuts	25	48*	Feed (general)	20	100
2025	Almonds	4	100	Wheat	16	94
2025	----	---	---	Cassava	22	40**

^aNumber of laboratories that were used in the PT scoring

*A different set of less experienced testing laboratories within the network participated in this round

** Cassava CRM for method validation was not available, additional less experienced laboratories participating in this round

The collaborative mycotoxin metrology initiatives led by NMISA and fellow African NMIs (NIS, KEBS, and INRAP), complemented by PTB, BIPM-CBKT, IAEA, Joint FAO-IAEA, and AOAC partners, have collectively informed continental policy by providing the technical foundation that enables African countries to implement indigenous food safety standards and engage meaningfully within the African Continental Free Trade Area (AfCFTA).

The current “Pan African Project for Upgrading of Quality Infrastructure in Africa”, supported by PTB Germany,¹⁶ also builds directly on this approach, supporting at least 10 additional food testing laboratories to expand their ISO/IEC 17025 accredited testing services through CRMs, PT, and targeted training. Within the Pan African Quality Infrastructure (PAQI) framework, encompassing the Intra-Africa Metrology System (AFRIMETS), African Organisation for Standardisation (ARSO), African Accreditation Cooperation (AFRAC), and African Electrotechnical Standardization Commission (AFSEC), these activities continue with new reference materials and PT schemes for emerging Africa CODEX standards, most recently including chemical hazards in the indigenous cassava-based foodstuffs.¹⁷ This programme serves as an exemplar of regional and global cooperation and partnership to achieve the UN SDGs.

The case demonstrates that sustained, coordinated investment in regional metrology—rather than isolated national efforts—generates institutional capacity that transcends borders, supports evidence-based policy, and positions African institutions as active collaborative contributors to global food safety governance, rather than passive recipients of external standards.

Acknowledgments

The authors acknowledge the foundational role of the South African Department of Trade, Industry, and Competition, the BIPM CBKT Programme, the collaborative partnerships with PTB Germany, IAEA Regional Technical Cooperation, Joint FAO-IAEA, AOAC-Africa, and AFRIMETS member NMIs, and the participating food testing laboratories across the Africa Food Safety Network.

POC: Maria Fernandes-Whaley,
MFWhaley@nmisa.org

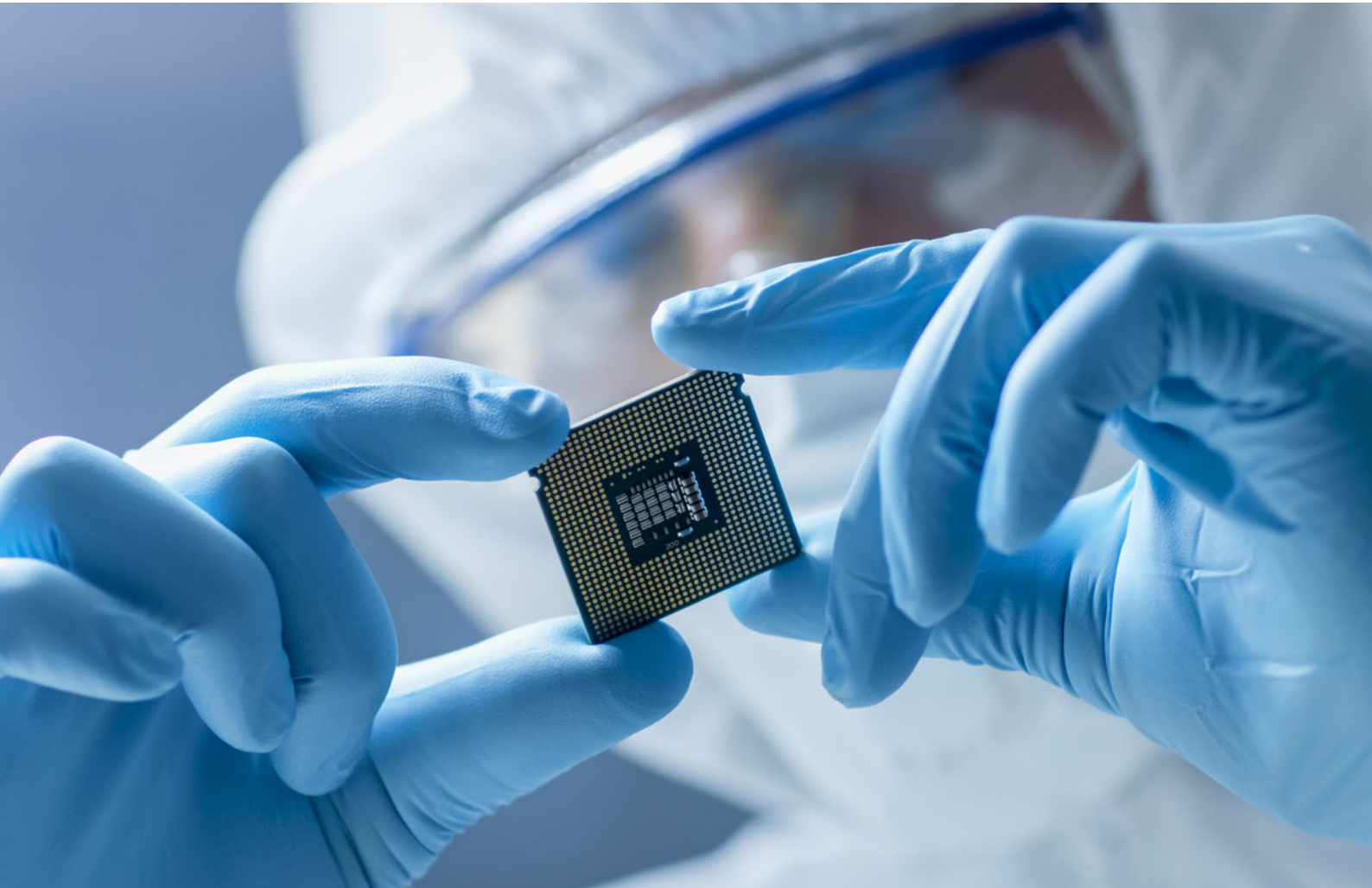
¹⁶Physikalisch-Technische Bundesanstalt, “The Pan-African Project “Upgrading Quality Infrastructure in Africa””, 2024, <https://www.qi-africa.ptb.de/our-efforts-in-africa-1>

¹⁷Physikalisch-Technische Bundesanstalt, “Pan-African Quality Infrastructure (PAQI) - Celebrating 10 Years of Success,” 2023, https://www.qi-africa.ptb.de/fileadmin/Ressourcen_Downloads_Dokumente/PAQI_Commemorative_publication_10Y_WEB.pdf



UNITED NATIONS
INDUSTRIAL DEVELOPMENT ORGANIZATION

Bureau
International des
Poids et
Mesures



Metrology for Sustainable Semiconductor Manufacturing: Enabling Quality, Precision, and Efficiency

The enhanced yield of high-quality microchip production has been enabled through the use of advanced metrology and SI-traceable standards

*Center for Measurement Standards in the Industrial Technology Research Institute (CMS/ITRI)
Chinese Taipei (TW)*



The Challenge

Microchips are ubiquitous and used in electronic devices that underpin our daily life, from communications and mobile phones to medical devices and automotive technology. Driven by surging demand for AI-related chips, the global semiconductor industry is rapidly advancing beyond the 2 nm technology node and progressing toward a 3D package of multiple chips to achieve higher performance, lower power consumption, and reduced costs.

To meet the semiconductor industry's demands for sustainability and innovation, this advancement requires extremely precise control over nanoscale device geometry and material composition, posing significant challenges for manufacturing metrology. These challenges include measuring complex nanoscale critical dimensions (CDs) and film thickness, detecting particle contamination below 10 nm with densities $< 10^2 \text{ cm}^{-2}$, and characterizing $\approx 100 \text{ }\mu\text{m}$ warpage with micrometre accuracy. Furthermore, with the transition to sub-nanometre components, the tolerance for impurities in the raw materials used to make chips is becoming more stringent. Reliable and SI-traceable measurement capabilities help reduce process deviations, thereby minimizing wafer scrap, rework, material losses, and energy-intensive reprocessing, making the advanced metrology essential for both manufacturing efficiency and sustainable production.

Addressing these challenges requires both innovative metrology solutions for characterizing buried 3D structures and reliable reference standards to ensure measurement accuracy and precision, thereby improving tool-to-tool measurement consistency. These efforts are essential for improving semiconductor manufacturing precision and yield, thereby enabling the stable production of advanced chips that underpin next-generation digital applications such as AI, cloud computing, high-performance computing, and 5G/6G communication technology.

The Solution

To address the aforementioned metrology requirements, a national metrology framework at the Center for Measurement Standards in the Industrial Technology Research Institute (CMS/ITRI) has been established to ensure accuracy, consistency, and metrological traceability across the semiconductor manufacturing ecosystem. The framework is built on the following two key metrological pillars: 1) development of advanced metrological techniques to characterize microchips and 2) the development of reference materials to ensure that important instruments and sensors used throughout the semiconductor production are adequately calibrated.

X-ray-based techniques (CD-SAXS, 2.5D/3D XCT) are used to provide non-destructive, high-resolution measurements of buried structures ($< 0.5 \text{ }\mu\text{m}$ resolution) in 3D packaging, complex geometries (CD with precision $< 0.1 \text{ nm}$) in front-end processes, and material compositions ($\text{Si}_{1-x}\text{Ge}_x$) for Gate-All-Around (GAA) nanosheets.

Reference materials (RMs) for iron oxide nanoparticles (15 nm and 30 nm) are developed to calibrate and validate measurements of particle size and particle number concentration in solution (shown on the left of **Figure 1**). In addition, gas RMs (shown on the right of **Figure 1**) consisting of impurity gas mixtures covering concentration ranges from sub-ppm to percent levels are developed to calibrate analytical instruments used for impurity analysis and incoming quality checks of semiconductor process gases. All RMs are prepared from high-concentration source materials and diluted with ultra-clean gases or matrix-matched solvents to achieve the target concentration. These RMs also provide metrologically traceable calibrations for particle and contamination measurements in microchip manufacturing processes and throughout the supply chain.



Figure 1. Reference Materials for iron oxide nanoparticles (left) and a Certified Reference Gas Mixture containing carbon monoxide, carbon dioxide, and propane in nitrogen (right).

A Quantifiable Impact

Implementing this metrological framework has enabled high-precision, metrologically traceable measurements that improve process control, resulting in higher yields, reduced variability, and enhanced microchip manufacturing productivity. Advanced 3D XCT imaging enables the non-destructive detection of dimensional defects in buried structures of 3D packaging at a spatial resolution of less than 0.5 μm .

Figure 2 shows a typical image of defects in micro-bumps measured using 3D XCT. By integrating this metrology into statistical process control, process quality can be improved at an early stage, helping manufacturers maintain product yields above 90 %. Together with a precision of $< 0.1 \text{ nm}$ in CD metrology for front-end GAA and CFET fabrication, the metrological framework supports reliable manufacturing of advanced integrated circuits while reducing rework rate by approximately 0.1 %.



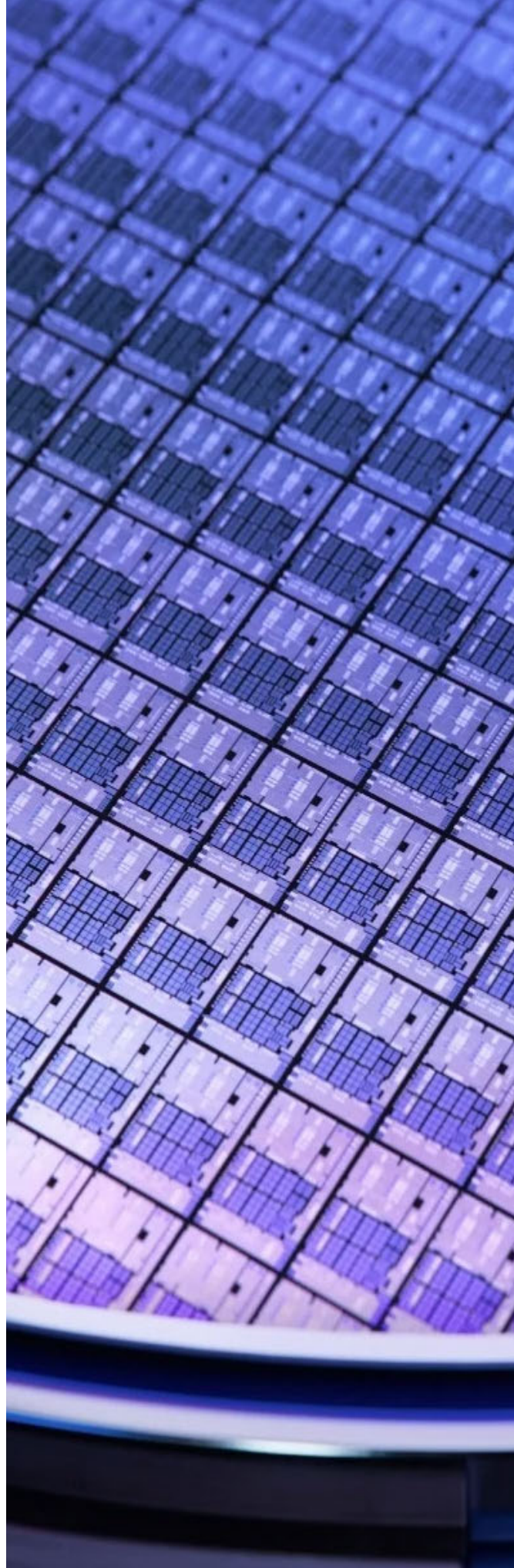
Figure 2. A typical 3D XCT image of defects and micro-bumps on silicon substrate.

The 15 nm and 30 nm nanoparticle RMs have been used as validation standards for particle inspection and new analytical instruments in semiconductor manufacturing. Applications included wafer surface scanners, scanning mobility particle sizers, and single-particle Inductively Coupled Plasma Mass Spectrometry (ICP-MS) to detect nanoscale contaminants < 10 nm. These nanoparticle RMs help ensure metrological traceable measurements and support the ultra-clean environments required for reliable production at 2 nm nodes and beyond.

The use of SI-traceable gas and nanoparticle standards has directly improved measurement consistency, minimized variation across measurement tools, and accelerated process optimization and efficiency. In a practical industrial case, the developed nanoparticle RMs were used to validate a new DMA-CPC system for contamination analysis in semiconductor raw materials, thereby improving the semiconductor materials supplier's production yield from approximately 75 % to 99 %.

The high-quality chips produced by the semiconductor industry in Chinese Taipei have resulted in a global market share of 70 %.¹ The metrological intervention described herein has also been developed in alignment with international metrology frameworks (e.g. CIPM MRA) to ensure that measurement results of the underlying metrological capabilities used in production are globally recognized and products are globally accepted. This has eliminated redundant testing and accelerated time-to-market for next-generation semiconductor products.

POC: Fang-Hsin Lin, itriA40317@itri.org.tw



¹Taipei Times. TSMC nets nearly 70% of 2025 foundry market. 14 March 2026. <https://www.taipetimes.com/News/biz/archives/2026/03/14/2003853777>



UNITED NATIONS
INDUSTRIAL DEVELOPMENT ORGANIZATION

Bureau
International des
Poids et
Mesures



Ensuring a Reliable National Time Scale UTC(KZ) as Critical Infrastructure of Kazakhstan

KazStandard modernized the state primary standard of the units of time and frequency and of the national time scale of the Republic of Kazakhstan, based on three passive hydrogen masers with automated UTCr-based steering

*KazStandard
Kazakhstan (KZ)*



The Challenge

Kazakhstan's critical infrastructure – telecommunications, energy grids, financial transactions, and transport systems – depends on precise time synchronization traceable to Coordinated Universal Time (UTC). As GNSS timing signals grow increasingly vulnerable to jamming and spoofing, a sovereign and resilient national time scale has become a strategic necessity. As a member of COOMET and a participant in the CCTF-K001.UTC key comparison, Kazakhstan needed a cost-effective solution to maintain UTC(KZ) within single-digit nanoseconds of UTC.

During an earlier period (2008–2018) in Kazakhstan's time metrology history, the national time scale UTC(KZ) relied on aging cesium clocks and deviated from UTC with an RMS of 832 ns and peak excursions exceeding 2.5 μ s. In December 2018, a power cable fire disabled the standard entirely, forcing Kazakhstan to suspend its contribution to international comparisons and data submissions to the International Bureau of Weights and Measures (BIPM). This compromised Kazakhstan's ability to provide a reliable national time reference, affecting sectors that require sub-100-nanosecond synchronization: 5G/LTE base stations (ITU 5G target: ± 30 ns), power-grid phasor measurement, GNSS validation, and financial timestamping.

The Solution

After 3 years of suspension of its time metrology activities, in 2021, the state primary standard of the units of time and frequency and of the national time scale of the Republic of Kazakhstan (hereafter, the Kazakhstan standard) was updated with a new time-and-frequency reference complex based on three passive hydrogen masers, including VCH-1008 (manufactured by Vremya-CH, Russia), thereby realizing the national time scale UTC(KZ). A novel automatic steering algorithm – a proportional-integral (PI) controller that approximates optimal linear-quadratic-Gaussian (LQG) control at a fraction of the computational cost – was developed and implemented to correct UTC(KZ) on a weekly basis using Rapid UTC (UTC_r) data published by the BIPM. The system is illustrated in **Figure 1**. This includes: (1) continuous phase comparison via the VCH-315M comparator at 1 Hz; (2) daily CGGTTS / RINEX data transmission to the BIPM via the GTR-55 multi-GNSS receiver; (3) automated weekly frequency correction of the VCH-317 synthesizer; (4) a custom monitoring software stack (UTC(KZ) Monitoring System v3.4) providing a real-time web dashboard, Telegram bot alerts, automated climate journals and PDF reporting. UTC(KZ) is the first national time scale fully based on passive hydrogen masers with automated UTC_r-based steering.

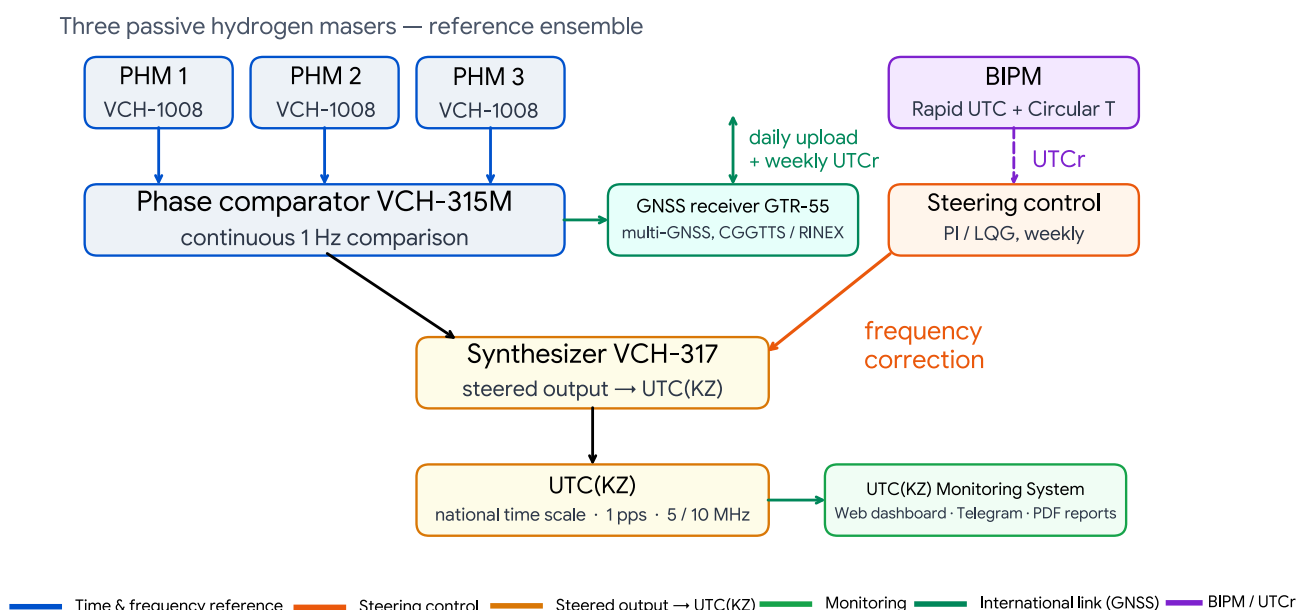


Figure 1. Functional schematic of the Kazakhstan standard for the realization of UTC(KZ).

This passive-maser configuration is unique. Out of 91 laboratories that contribute clocks to TAI (BIPM clock database, 2026), only two operate a passive H-maser as their sole primary reference – KazStandard (KZ) and the Danish Fundamental Metrology Institute (DFM, Denmark).

Of these, KZ is the only one whose national time scale is realized by an ensemble of three passive masers with automated weekly UTCr-based steering (**Figure 2**).

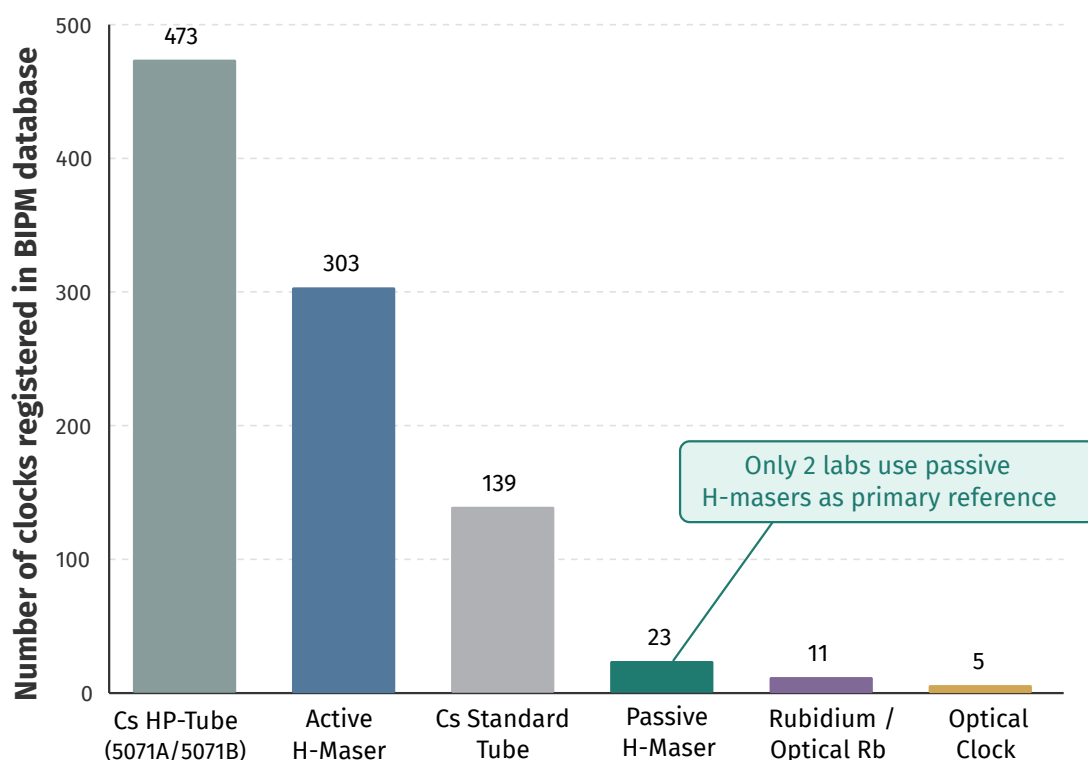


Figure 2. Clock inventory across 91 TAI contributing laboratories (BIPM clock database, 2026). Only two laboratories use passive H-masers as their sole primary reference: KazStandard (KZ, 3 × VCH-1008 Passive H-Masers) and DFM Denmark (DE, 1 × T45 pHMaser 1008 Passive H-Maser). KZ is the only one with an ensemble of three passive H-masers under automated UTCr-based steering. (Source: BIPM clock database (clocklab.csv, 2026); 91 laboratories contributing to TAI).

A Quantifiable Impact

With the modernized Kazakhstan standard and BIPM Circular T data through 29 May 2026, several metrological milestones have been achieved (Figures 3 and 4): UTC(KZ) deviates from UTC with RMS = 2.44 ns and a maximum absolute time difference of 8.9 ns; this corresponds to an approximately 341-fold RMS reduction compared with the legacy cesium configuration. The realization and dissemination of the national time scale UTC(KZ) have continued without interruption since the restoration of BIPM Circular T reporting in June 2021.

All three masers receive weight in the TAI computation, the combined KZ weight reaching 0.13 % in November 2025 (more than double its 2022 level) – a level sustained by only three of the thirteen passive-maser realizations worldwide. Even without external reference data, UTC(KZ) holds within 10 ns of UTC for up to three weeks, providing resilience against GNSS or UTCr outages – a critical property for national infrastructure.

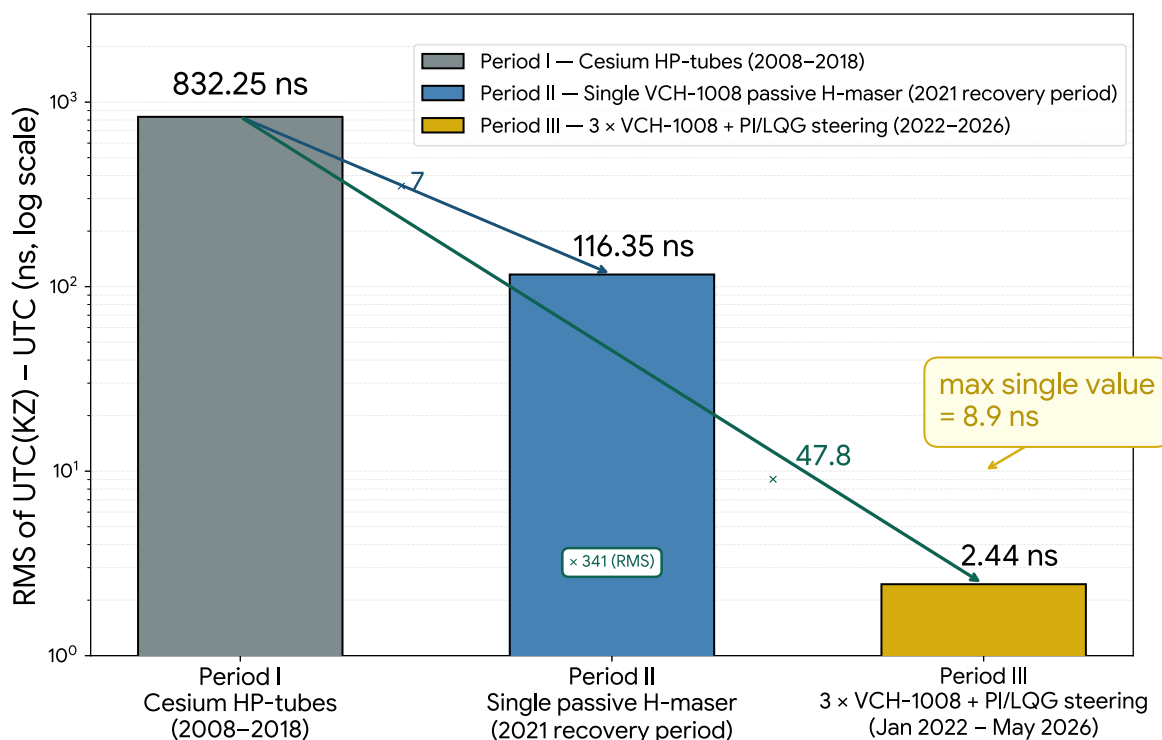


Figure 3. RMS reduction of UTC(KZ) across three operational periods of the Kazakhstan standard. Period I corresponds to the legacy cesium-clock configuration (2008–2018); Period II corresponds to the 2021 recovery period with a single VCH-1008 passive hydrogen maser; Period III corresponds to three VCH-1008 passive hydrogen masers with automated PI/LQG steering, with Circular T data through 29 May 2026. (Source: KazStandard/BIPM Circular T).

Furthermore, UTC(KZ) has appeared in 100 % of monthly Circular T bulletins since June 2021, with no missed months, eliminating the periodic data-submission interruptions that affected the previous standard. In January 2022, KazStandard became the first Central Asian laboratory to participate in weekly UTCr activities, and UTC(KZ) ranks 25th out of 97 laboratories worldwide (top 26 %) in the CCTF-K001.UTC key comparison, having advanced from 42nd just three years earlier.

According to the latest BIPM Circular T (213 reporting dates from 4 June 2023 to 29 April 2026), UTC(KZ) achieves a standard deviation of $\sigma = 2.53$ ns. The Top-10 of CCTF-K001.UTC operate in the 0.5–1.3 ns range – including PTB (Germany, $\sigma = 0.77$ ns, rank #3), NIST (USA, $\sigma = 0.99$ ns, rank #7), SU/VNIIFTRI (Russia, $\sigma = 1.04$ ns, rank #5) and OP (France, $\sigma = 1.22$ ns, rank #6); UTC(KZ) is therefore within a factor of 2–3 of the entire Top-10 cohort.

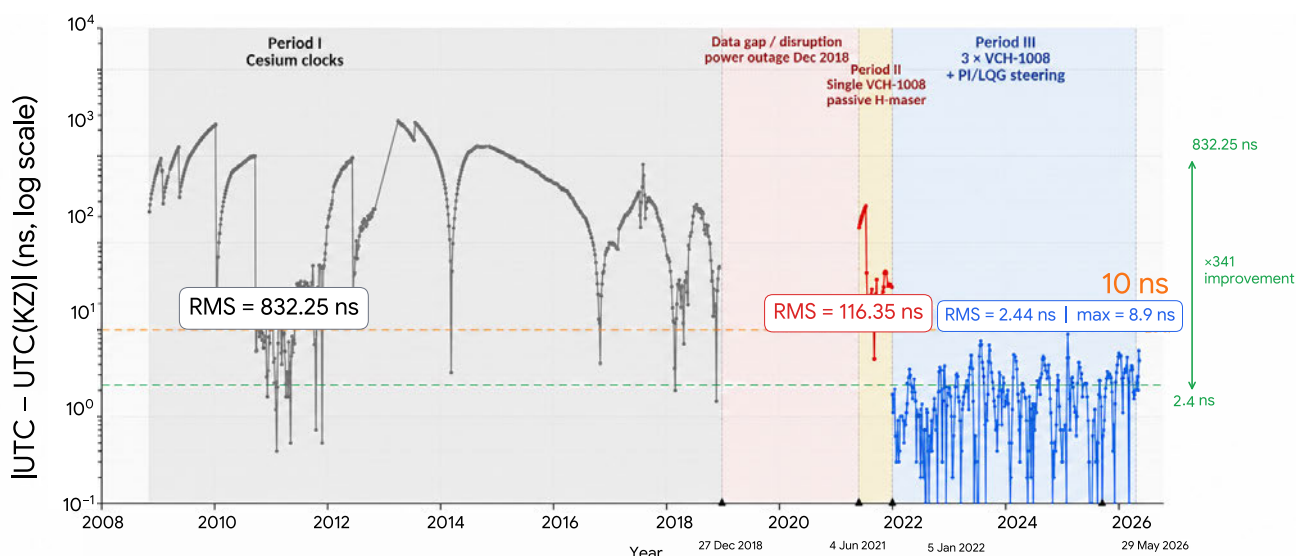


Figure 4. Absolute time difference $|\text{UTC} - \text{UTC(KZ)}|$ across KazStandard's operational periods on a logarithmic scale, from 2008 to 29 May 2026. Data are based on BIPM Circular T values. Data are presented as Period I: Cesium clocks (---), Period II: Single VCH-1008 passive H-maser (---), and Period III: 3 x VCH-1008+PI/LQS steering (---). The pink shaded 2018–2021 interval without data between Period I and Period II illustrate the disruption and recovery following the December 2018 power cable fire. The updated data show an improvement from RMS = 832.25 ns with cesium clocks (Period I, 2008–2018) to RMS = 2.44 ns with three passive hydrogen masers and automated PI/LQG steering (Period III, 2022–2026), corresponding to an approximately 341-fold RMS reduction.

The KZ contribution to TAI grew steadily from 0.055 % in 2022 to a peak of 0.13 % in November 2025 – over a 2-fold increase over three years – and was restored to that level after a manual de-weighting and four-month re-evaluation by the BIPM in early 2025. The frequency stability of the KZ masers reaches $1\text{--}2 \times 10^{-15}$ at averaging times of 1 day or longer, precisely the regime that matters for weekly UTCr-based steering. These results also illustrate the wider significance of this achievement: among the five COOMET member time scales participating in the BIPM Circular T comparison (June 2025–April 2026), UTC(KZ) is the only one that satisfies the ITU-T 5G synchronization threshold of ± 10 ns. This result underscores the strategic and regional value of Kazakhstan’s investment in precision time-keeping infrastructure.

Among laboratories with an equipment class comparable to the modernized Kazakhstan standard (passive H-masers), UTC(KZ) is on par with Justervesenet (JV, Norway), as confirmed by the 2026 BIPM report.¹ A significant cost reduction has also been achieved: passive H-masers are more compact and 5–8 times less expensive than active masers ($\approx 60\,000$ USD versus up to 480 000 USD each), making world-class timekeeping accessible to other developing NMIs.

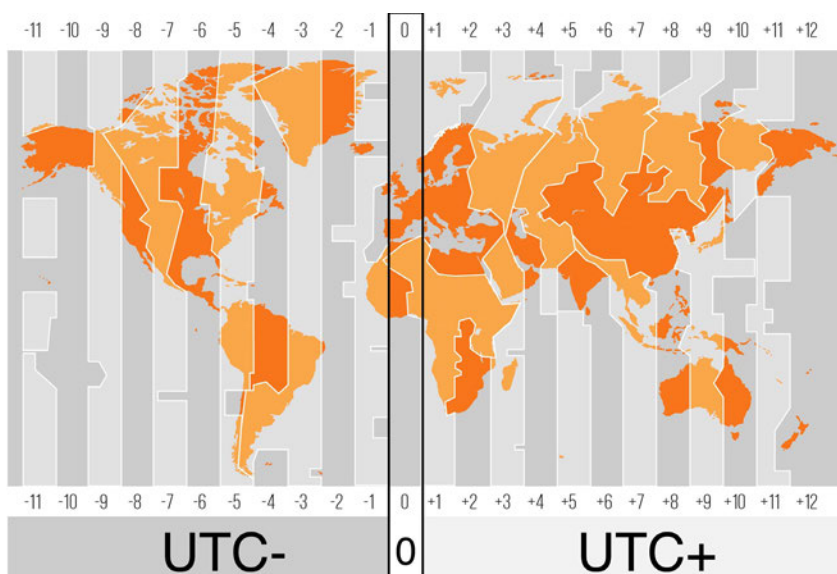
An illustration of both the challenges and progress of Kazakhstan’s now metrologically rigorous and precise timekeeping infrastructure is provided in **Figure 4**. The results of this successful metrological intervention have also been recently published.²

For Kazakhstan, the upgrade delivers a sovereign, traceable national time scale UTC(KZ) for its critical infrastructure – telecommunications, power grids, financial systems, and GNSS-dependent services – reducing reliance on external time sources and positioning the country as a regional time-metrology hub for Central Asia.

As a result of this metrological intervention, Kazakhstan now maintains a sovereign, resilient, and internationally traceable national time scale, UTC(KZ), that supports the timing layer of the country’s critical infrastructure. Its impact extends beyond laboratory metrology: UTC(KZ) provides the national reference for telecommunications, digital services, financial timestamping, power-grid monitoring, transport systems, GNSS-dependent applications, and emerging IoT-based services in healthcare, agriculture, and smart-city systems. By reducing dependence on external timing sources and maintaining nanosecond-level alignment with UTC, the Kazakhstan standard strengthens national digital sovereignty and improves resilience against GNSS disruption, jamming, or spoofing.

Beyond Kazakhstan, this work demonstrates a cost-effective model for other developing or resource-constrained NMIs. A national time scale based on passive hydrogen masers and weekly UTCr-based steering can achieve high UTC tracking accuracy without the capital cost of active hydrogen masers or cesium fountains, thereby enabling more countries to participate effectively in TAI/UTC and build resilient timing infrastructure for modern digital economies.

POC: Smagulov Sultanbek, s.smagulov@ksm.kz



¹Tavella P. Report to KazStandard on the Performance of UTC(KZ). Bureau International des Poids et Mesures (BIPM), 11 March 2026.

²Smagulov S.B., Mishagin K.G. Steering of the National Time Scale UTC(KZ) Based on Passive Hydrogen Masers According to the Rapid UTC Data. Measurement Techniques, 67, 684–692 (2024). <https://doi.org/10.1007/s11018-025-02389-3>



UNITED NATIONS
INDUSTRIAL DEVELOPMENT ORGANIZATION

Bureau
International des
Poids et
Mesures



Trustworthy Data to Enable Evidence-based Climate Action

NPL has helped embed metrological best practice into the activities of the global satellite-based Earth Observation community by providing training, SI-traceable ground and satellite-based measurement capability, and high-quality data and derived information

*National Physical Laboratory (NPL)
United Kingdom (UK)*

The Challenge

Timely, robust, and proportionate action to mitigate the impacts of climate change relies on confidence in the predictive reliability of models underpinned by trustworthy data. These models are highly complex, combining many 'process-level' models that integrate both empirical and physical understanding of how the planet works. They require vast amounts of supercomputing resources and time to simulate how the state of the planet may evolve in response to changes, such as increased greenhouse gas (GHG) emissions.

Most current models indicate a warming of the planet due to GHG emissions; however, there remains significant variance and uncertainty in their predictions (see **Figure 1**). Attempts to predict societal consequences are dependent on the outputs of these models.

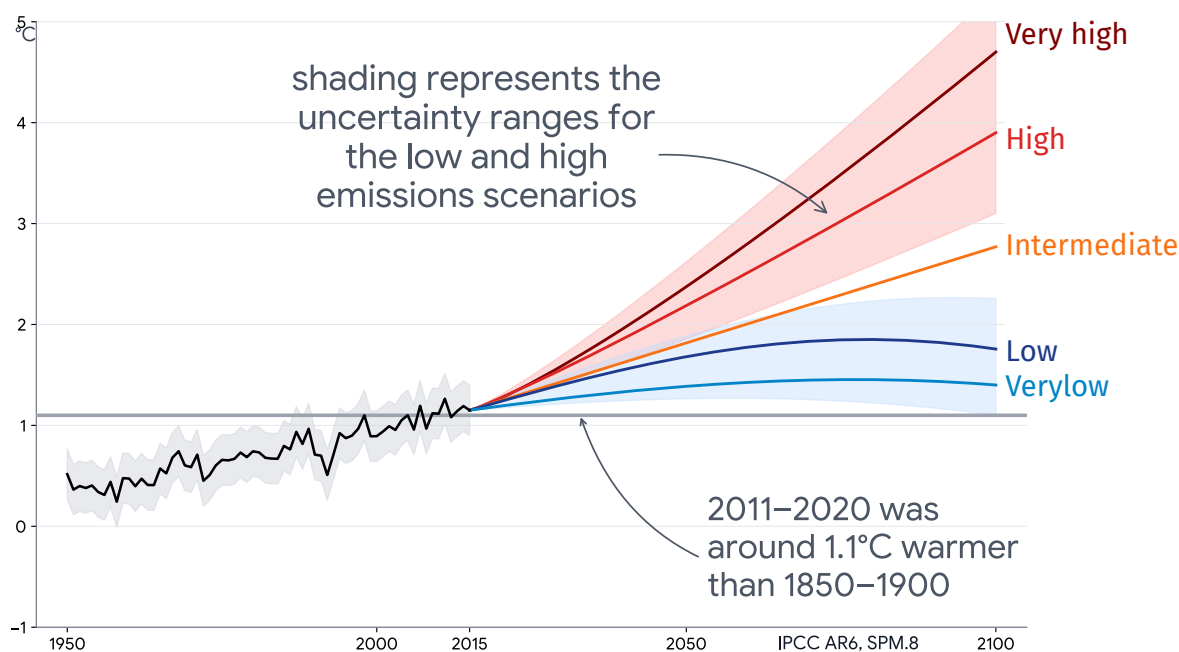


Figure 1. Plot showing the variance of climate models in predicting the future state of the planet (shading) in response to specific GHG forcing levels. From the Fifth Assessment Report of the United Nations Intergovernmental Panel on Climate Change (IPCC AR6) (2022).

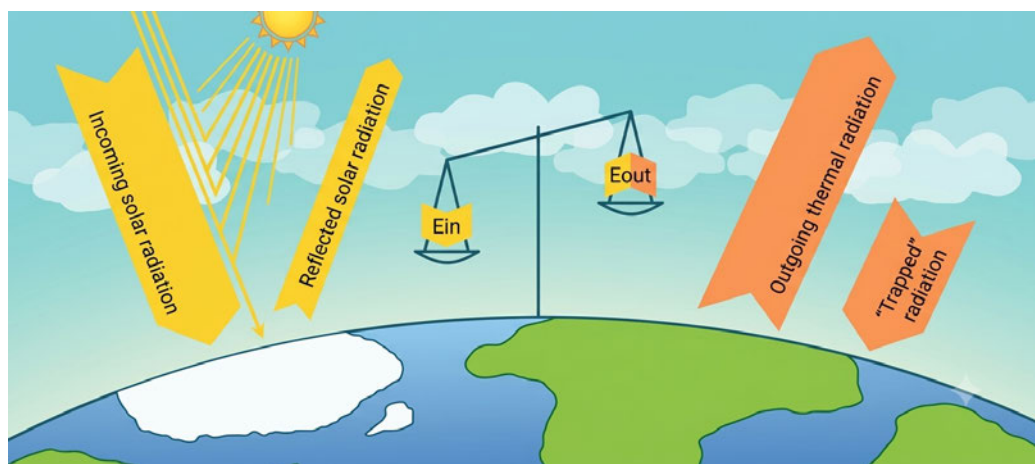


Figure 2. If energy into the Earth (E_{in}) - reflected, compared to that emitted by the Earth (E_{out}) - that absorbed by the atmosphere, remains equal, then the temperature remains stable. If not, then the Earth's temperature changes.

Earth system cycles – water, carbon, and radiation – are complex and interdependent. Hence, changes in atmospheric composition can trap energy, leading to an imbalance in the planet’s radiation budget; the wider consequences are far-reaching (see **Figure 2**). These include rising sea levels, melting snow and ice, extreme weather events, and impacts on the biosphere, to name just a few. These secondary consequences can also create non-linear feedback that further alters the climate response. For example, reduced snow cover means less sunlight is reflected and more is absorbed by the planet, further raising temperatures.

The Global Climate Observing System (GCOS) of the World Meteorological Organization (WMO) has identified 56 Essential Climate Variables (ECVs) (**Figure 3**) that need to be monitored, with varying degrees of accuracy and precision, to improve our understanding of how the planet works and the consequences of our actions.¹ Many of the uncertainty requirements for these often biogeophysical variables are comparable with the best capabilities of National Metrology Institute (NMI) laboratories under ideal laboratory conditions.

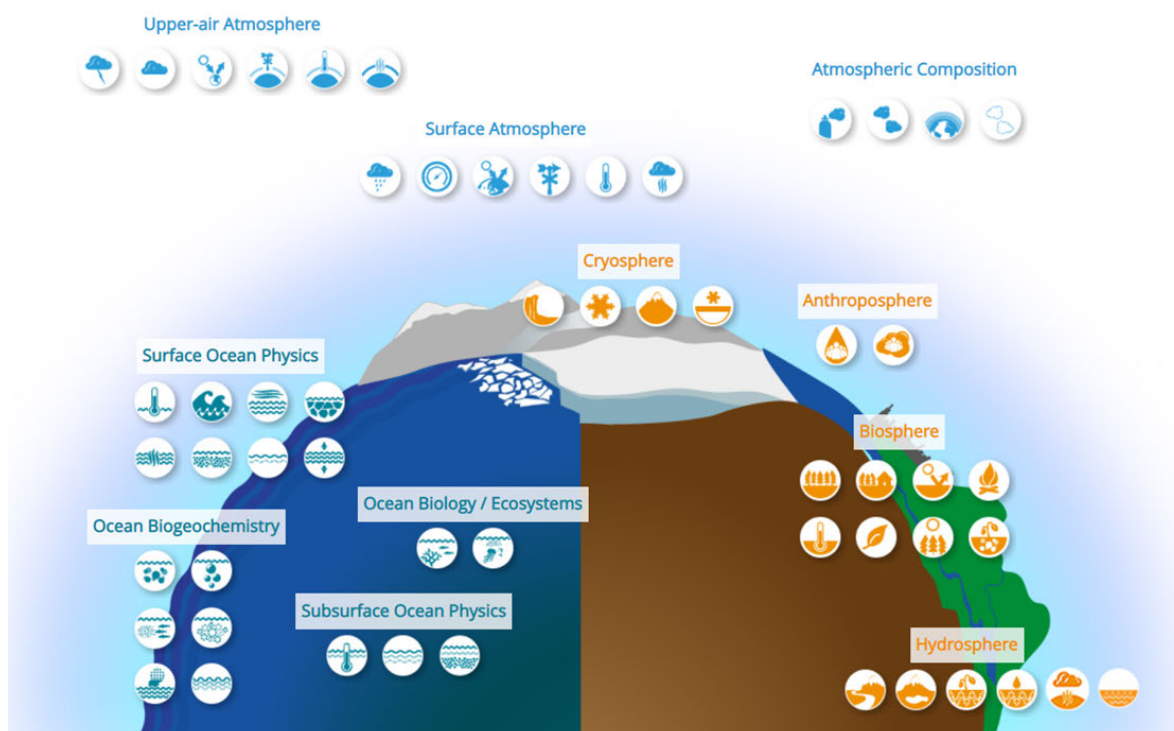


Figure 3. Schematic illustrating the Essential Climate Variables (ECVs) of the Global Climate Observing System (GCOS)

Two-thirds of these ECVs require observations from space-borne instruments to achieve adequate representativeness, and half require optical measurements. Although significant effort is devoted to pre-flight instrument calibration and characterization, the violence of launch and the harsh space environment result in degraded performance upon reaching orbit, with continual degradation thereafter. The unpredictable nature of this change complicates the assignment of reliable estimates of uncertainty to the measurements. This is particularly true for optical instruments, which are highly susceptible to contamination and misalignment due to movement during launch into space.

This not only makes data from individual satellite instruments harder to interpret but also makes it

difficult to reliably combine signals from different satellites into the long time series needed to detect climate trends.

Because the signals of measurements used to detect climate change are often so small, it can take decades for changes to become large enough to be detectable from background environmental and residual instrumental noise. Robust, low uncertainty traceability to SI units, has long been recognized as essential to ensure that information derived from satellites is ‘fit for purpose’. However, achieving that goal is highly challenging and requires changes in the typical working practices of NMIs, i.e., to expand capabilities outside of the laboratory, such as for measurement of biogeophysical quantities that are often transformed by a model, as well as a more direct partnership between space agencies and the climate research community.

¹World Meteorological Organization (WMO), Global Climate Observing System (GCOS), Essential Climate Variables. <https://gcos.wmo.int/site/global-climate-observing-system-gcos/essential-climate-variables>

The Solution

Efforts to recover knowledge of the post-launch performance of satellite instruments have been pursued through on-board calibration infrastructure and observations of dedicated ‘ground truth’ targets and test sites, since the early days of Earth observation (EO) more than 40 years ago. These are characterized independently using other measurement approaches, such as airborne instruments and ground-based optical instrumentation. These post-launch methods also need to be SI-traceable, which brings further challenges and has become more of a focus in the last two decades. Satellite, on-board calibration systems degrade, as do ground-level field instruments. It is also difficult to assess how representative an in situ point measurement of, say, surface reflectance or temperature, is of a satellite pixel spanning hundreds of meters.

The National Physical Laboratory (NPL) in the UK has risen to this challenge by undertaking climate change research supported by national funding, the European Union, and world and national space agencies to embed metrological best practice in the space sector. This included developing measurement capabilities (e.g., a tuneable laser-based calibration facility for satellite instruments, a radiometer to measure Infrared radiance from black bodies for surface temperature calibrations, large aperture black bodies for satellite infrared calibration, etc.) that are traceable to SI, have rigorous uncertainty assessments, and have been demonstrated to be reliable via comparison-based evidence. NPL has also worked within existing international structures such as the Committee on Earth Observation Satellites (CEOS)² for nearly 30 years, promoting common terminology and a shared understanding of how uncertainties should be estimated and combined. This led, in 2010, to the creation of the Quality Assurance Framework for Earth Observation (QA4EO),³ which has been endorsed and imple-

mented worldwide and is underpinned by a set of open-source software tools (Community Metrology; COMET Toolkit) for uncertainty assessment and propagation.⁴ In addition, dedicated in-person and online training courses have been created to support consistent understanding and interpretation.⁵

To reduce uncertainty in satellite data, NPL has coordinated comparisons between satellite instruments and, within the EO community, in situ calibration and validation (Cal/Val) methods for land and ocean reflectance and surface temperature measurements. This also includes additional indirect ECVs, such as leaf area index, sea level height, and ice thickness. Analysis of these comparisons has helped establish community best practices. The importance of adopting this metrological best practice has been recognized by CEOS through the creation of the Fiducial Reference Measurement (FRM) label and the associated certification process.^{6,7} Space agencies are now requesting that post-launch Cal/Val activities become FRM-certified so that their uncertainty can be evidenced against SI units using metrological best practice. In addition to uncertainty assessment, NPL has designed and built instrumentation and methods to reduce measurement uncertainty for a variety of Essential Climate Variables (ECVs), both in space and on the ground. These include networks of field instruments for measuring surface reflectance (RadCalNet,⁸ **Figure 4a**; Hypernets⁹) and vegetation parameters (**Figure 4b**), as well as transportable facilities for pre-flight calibration and characterization of satellite sensors using tuneable lasers in a new facility, the Spectroscopically Tuneable Absolute Radiance calibration and characterisation Optical Ground Support Equipment (STAR-cc-OGSE, or “STAR”).¹⁰ The STAR facility was used to calibrate the recently launched MicroCARB satellite (Carbon Dioxide Monitoring Mission) for GHG monitoring¹¹ (**Figure 5**).

²Committee on Earth Observation Satellites (CEOS). <https://ceos.org/>

³A Quality Assurance Framework for Earth Observation (QA4EO). <https://qa4eo.org/>

⁴A Quality Assurance Framework for Earth Observation (QA4EO). <https://qa4eo.org/>

⁵National Physical Lab. Uncertainty Analysis and Quality Assurance for Earth Observation Datasets. <https://training.npl.co.uk/product/uncertainty-analysis-and-quality-assurance-for-earth-observation-datasets/>

⁶Goryl, P.; Fox, N.; Donlon, C.; Castracane, P. Fiducial Reference Measurements (FRMs): What Are They? *Remote Sens.* 2023, 15, 5017. <https://doi.org/10.3390/rs15205017>

⁷CEOS Cal/Val Portal. FRMs Assessment Framework. <https://calvalportal.ceos.org/web/guest/frms-assessment-framework>

⁸CEOS Radiometric Calibration Network portal. <https://www.radcalnet.org/#/>

⁹LANDHYPERNET data portal. HYPERNETS. <https://landhypernet.org.uk/>

¹⁰EURAMET Case Study. Reducing cost and improving the accuracy of radiometric sensor calibrations: Terrestrial and space. <https://www.euramet.org/casestudies/casestudiesdetails/news/reducing-cost-and-improving-the-accuracy-of-radiometric-sensor-calibrations-terrestrial-and-space>

¹¹EURAMET Case Study. Reducing cost and improving the accuracy of radiometric sensor calibrations: Terrestrial and space. <https://www.euramet.org/casestudies/casestudiesdetails/news/reducing-cost-and-improving-the-accuracy-of-radiometric-sensor-calibrations-terrestrial-and-space>



Figure 4. (Left, a) NPL managed RadCalNet tower hosting a radiometer measuring the reflectance of the Earth in the Namib desert as a reference for satellites. Right b) tower hosting NPL instruments monitoring vegetation at Wytham woods in Oxfordshire, UK.



Figure 5. The NPL STAR facility shown here deployed at the Airbus cleanroom in Toulouse, France. The facility was used to calibrate the French/UK MicroCARB mission for GHG monitoring.

The greatest impact is likely to be realized with the launch of a new class of satellite sensors, originally called SITSats (SI-Traceable Satellites) and now referred to as FRMsats. These FRMsats would provide uncertainties from orbit-based measurements at an unprecedented level and are anticipated to meet the most demanding climate requirements. These would serve as gold-standard reference measurements in space and be used to recalibrate other satellite instruments.¹²

In effect, these satellite sensors would serve as in-flight metrology laboratories, such as that of the European Space Agency (ESA) TRUTHS mission.¹³ Although development of TRUTHS has stalled, it remains a highly desirable mission and is expected to be reinstated in some form in the future.¹⁴

¹²Boesch, H; Brindley, H; Carminati, F; Fox, N; Helder, D; Hewison, T; Houtz, D; Hunt, S; Kopp, G; Mlynchak, M; Pagano, T S; Revercomb, H; Richard, E; Rosenkranz, P; Shea, Y; Simis, S; Smith, D; Stone, T C; Sun, W; Xiong, J; Wielicki, B; Yang, H; Ye, X (2022) SI-traceable space-based climate observation system: a CEOS and GSICS workshop, National Physical Laboratory, London, UK, 9-11 Sept 2019. <https://doi.org/10.47120/npl.9319>

¹³Fox, Nigel. The European Space Agency. Truths: the gold standard reference for climate measurements. https://www.esa.int/Applications/Observing_the_Earth/TRUTHS

¹⁴World Meteorological Organization (WMO). GCOS Report-244. The 2022 GCOS Implementation Plan (GCOS-244). <https://library.wmo.int/records/item/58104-the-2022-gcos-implementation-plan-gcos-244>

A Quantifiable Impact

The principles of the QA4EO framework have been adopted by the world's space agencies, with organizations such as the European Space Agency (ESA) and the EU Copernicus program explicitly requiring compliance in their work programs. Over the last 3 years, the in-person training courses on uncertainty evaluation have been attended by more than 250 researchers, and online participation has increased several-fold. The RadCalNet network, for which NPL ensures consistency and metrological traceability across member sites while also maintaining the Gobabeb site for ESA, has more than 7 000 registered users, of whom around half are active.

At the request of the commercial sector, NPL has also developed online tools¹⁵ to help organizations demonstrate their performance capabilities to a broad set of stakeholders (e.g. buyers and users of their data) in a transparent and fair manner. This includes a demonstration of their measurement capability, including uncertainty, and how they establish metrological traceability to the SI. This helps maximize the utility of their data and commercial return on investment by enabling more science-quality applications through robust quality assurance.

The international metrology community, led by the Bureau International des Poids et Mesures (BIPM), has organized several workshops in conjunction with the WMO to identify research priorities and promote joint work. In Europe, a network of NMIs to coordinate climate-focused research has operated for nearly a decade under the auspices of EURAMET,¹⁶ and a variety of similar initiatives have been established within the working groups of the CIPM consultative committees.

Although much of the climate metrology work of most NMIs currently centers on the calibration of instrumentation, there are increasing examples—particularly at NPL—of activities extending into fieldwork, modeling, and uncertainty propagation through to the derived information ultimately needed by policymakers. This work has recently prompted, and will continue to prompt, new questions for the climate research and measurement community, such as how our measured emissions compare with those estimated using ground-up methods, or how much carbon is stored in our forests.

It is clear from the actions of space agencies, climate researchers, and other users that the role of metrology in climate science is now better understood, and metrology institutes are sought out as partners to help provide the confident results policymakers need to act robustly and in a timely manner. Further, the importance of metrology to the EO and climate community is now widely recognized by both users (space agencies and climate researchers) and the NMI community at large. It is now commonplace for the specifications of climate measurement projects to require the involvement of an NMI, or at least for the organization to follow prescribed metrological best practices, as part of the delivery.

Acknowledgments

This work has been carried out by members of the Climate and Earth Observation and Optical Radiation Measurement teams of NPL. Funding has come from a variety of sources, including the UK National Measurement System of the Department for Science, Innovation and Technology (DSIT), the European Space Agency, UK Space Agency, and from the MetEOC series of projects funded by the European Metrology Research Programme (EMRP) and European Metrology Programme for Innovation and Research (EMPIR), co-financed from the European Union's Horizon 2020 and Horizon Europe Research and Innovation Programmes and by the Participating States.

POC: Nigel Fox, nigel.fox@npl.co.uk

¹⁵RadVAL, Radiometric Validation Analytics Tool, <https://ceos-pvp.org/>

¹⁶EURAMET, European Metrology Network (EMN) for Climate and Ocean Observation, <https://www.euramet.org/climate-and-ocean-observation/>



UNITED NATIONS
INDUSTRIAL DEVELOPMENT ORGANIZATION

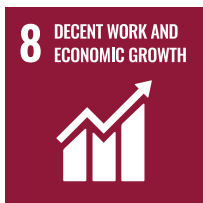
Bureau
International des
Poids et
Mesures



Digital Transformation of Legal Metrology in Saudi Arabia

A new digital legal metrology platform (Taqyees) ensures that the citizens of Saudi Arabia can have confidence in goods and services in a fair and equitable marketplace

*Saudi Standards, Metrology, and Quality Organization (SASO)
Kingdom of Saudi Arabia (SA)*



The Challenge

Prior to 2018, legal metrology activities in Saudi Arabia were distributed across multiple sectors, each operating under sector-specific technical requirements and verification procedures, and with non-standardized measurement procedures. This distribution limited cross-sector coordination and regulatory visibility for effective compliance monitoring and timely responses to market risks, and created inefficiencies in ensuring measurement accuracy across trade and industrial applications. This also created challenges in maintaining a consistently level playing field, increased the potential for commercial disputes, affected confidence in measurement consistency, and led to more complex verification and inspection processes.

These challenges also affected confidence in the essential quantities used in trade and industry, including critical measurement quantities (e.g. mass, volume, and energy consumption) measured by weighing instruments, fuel dispensers, and electricity meters, each of which plays a critical role in economic transactions and national resource management. The core issue extended beyond isolated technical inaccuracies to a limited system-wide integration characterized by fragmentation, and limited tracking of, and access to, measurement data across regulatory bodies.

Between 2018 and 2020, a unified metrology system became available; however, service requests were handled via email, and reports were issued only in paper form. Further, centralized digital records were not yet available for verification status and compliance monitoring. It was evident that market participation was still limited during the initial implementation phase, as few entities were licensed to perform verification activities during the early stages (2018–2020) of the Legal Metrology Program (Taqyees) in Saudi Arabia. These limitations highlighted the need for a comprehensive, scalable, technology-enabled national solution to transform legal metrology into a cohesive, data-driven system.

The consequences of these limitations were significant. From a policy perspective, the limited availability of consolidated measurement data constrained evidence-based decision-making. At the same time, this gap presented a clear opportunity to use digital transformation to enhance measurement reliability, improve transparency, and strengthen governance within the legal metrology system.

The Metrology Solution

In response to these challenges, starting in 2021, the Saudi Standards, Metrology, and Quality Organization (SASO) implemented a comprehensive digital transformation of the Legal Metrology Program (Taqyees), establishing a centralized national platform that integrates all stakeholders within a unified operational ecosystem.

The intervention consisted of developing a fully digital, paperless platform that enables end-to-end management of legal metrology activities. This includes registration, licensing, verification processes, verification scheduling, reporting, and compliance monitoring. In addition, the platform enables the activation and management of core legal metrology activities, including type approval, initial verification for both local and international manufacturers, periodic verification, and market surveillance. The platform seamlessly connects manufacturers, importers, service providers, verification bodies, and regulatory inspectors within a single ecosystem.

Key functionalities of the digital legal metrology platform (**Figure 1**) include:

- Fully online licensing and verification services
- Automatic bulk insertion of large-scale data
- Frictionless user experience
- Robotic Process Automation (RPA) for repetitive business service

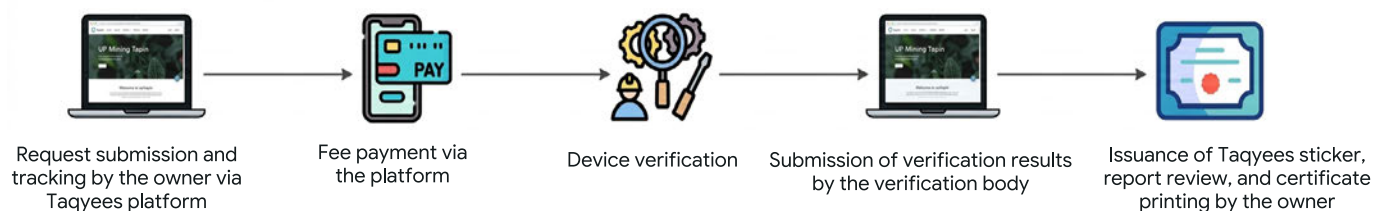


Figure 1. End-to-end digital workflow of the Taqyees legal metrology platform, from service request submission to issuance of verification certificates and stickers.

From a metrological perspective, the intervention represents a large-scale implementation of legal metrology digitization, strengthening the overarching national quality infrastructure and enabling more effective control of measuring instruments used in trade and industry.

The system operates within the national legal metrology framework, ensuring verification activities are conducted by authorized and regulated entities, thereby supporting traceability and consistency. Metrological traceability to the SI is ensured through verified equipment calibrated by the National Metrology Institute (NMI), or through equipment with metrological traceability chains linked to the NMI, which are used to verify measuring instruments on the market.

The intervention involves multiple institutional stakeholders, including the Saudi Standards, Metrology and Quality Organization (SASO) as the national regulatory authority, and aligns with international and regional metrology frameworks and organizations such as the OIML and GULFMET. These collaborations support harmonization with international best practices and enhance the system's credibility. The implementation is also aligned with international conformity frameworks, particularly the OIML Certification System (OIML-CS), which supports mutual recognition and facilitates international trade through standardized and trusted measurement systems. In this context, SASO utilizes OIML-CS certificates in its regulatory and operational processes and contributes as a member of the OIML-CS committee, thereby reinforcing SASO's role in adopting and shaping international best practices in legal metrology.

While the intervention is primarily operational and regulatory, it aligns with international best practices in legal metrology and quality infrastructure development. The digital platform serves as an operational backbone, transforming previously fragmented, manual processes into a coordinated, efficient, and scalable system that supports nationwide implementation.

A Quantifiable Impact

The digital transformation of the Legal Metrology Program has generated substantial, measurable impacts across operational, economic, regulatory, and environmental dimensions. A clear demonstration of performance and impact can be illustrated by comparing data collected before and after the implementation of the digital platform. This included sources from historical records maintained by SASO under the Legal Metrology Program to the real-time data and analytics generated by the current digital platform, as well as reports submitted through the platform by Taqyees operational staff and licensed entities, regulatory records and verification databases, and Customer Relationship Management (CRM) systems, including technical support and ticketing systems.

The Taqyees platform is considered a “one-stop shop” that includes the necessary services and materials to support and enable both individuals and entities in the market through an automated process, increasing efficiency and effectiveness, while reinforcing measurement and calibration laws and regulations, covering legal metrology activities in cooperation with relevant stakeholders in the ecosystem. The digital legal metrology platform achieved full digitalization of services over the 4-year timeframe, with 100 % of transactions now conducted electronically. A more than 3-fold increase in fuel dispenser verifications (from 32 529 to 102 043) and a near 3-fold increase in weighing instrument verifications (from 9 806 to 28 595) have been observed. The total volume of electricity meters increased nearly 2-fold (from 580 390 to 1 133 595) across 75 distinct factories and electricity service providers. Water meters have been recently included, with 354 091 verifications completed through to the end of 2025. The platform has supported a total of over 6.3 million verification processes and over 65 thousand field inspections to ensure alignment with best practices in sectors that contribute to the protection of consumers, businesses, and the environment.

The introduction of automation significantly reduced manual intervention, with four key services fully automated, including initial, periodic, and post-maintenance verification requests, as well as type approval. This resulted in faster processing times, improved service delivery, and enhanced user experience. Following the digital legal metrology platform's launch, transaction volumes grew at a compound annual rate of 44 %, reflecting strong stakeholder engagement and improved service accessibility. The average verification time for completed requests decreased from 15 to 10 business days, representing a 33 % reduction, while geographical coverage expanded from 3 to all 13 regions of Saudi Arabia. This improvement was achieved despite the operational demands associated with serving remote locations across the Kingdom's vast geographical area. Furthermore, the technical infrastructure was bolstered by a 3-fold increase in the number of licensed verification entities (from 16 to 48). The regulatory impact is equally significant. The availability of real-time data enabled the execution of over 16 000 field inspections in 2025, ensuring stronger market oversight. Integrated workflows have improved compliance monitoring, enabled more targeted inspections, and strengthened overall market oversight. Data quality is ensured through several mechanisms. The transition to a fully digital system enables high levels of data consistency, traceability, and standardization. Automation reduces the likelihood of human error, while system integrations with external entities enhance data validation and cross-verification. Data accuracy is further supported through sampling verification and field inspection campaigns. The centralized nature of the platform also improves comparability of data across sectors and over time.

The environmental impact further highlights the broader benefits of intervention. By digitizing the verification processes, the platform eliminated the need for paper-based documentation. With over 5.8 million devices verified digitally, approximately 11.7 million sheets of paper were saved, equivalent to preserving around 1 406 trees. This contributes directly to national sustainability objectives and environmental conservation efforts. Compared to prior baseline operations that relied on a fragmented, manual, and resource-intensive system, the transformation is clear: a fully integrated, automated, and data-driven ecosystem that has demonstrated the strategic role of digital metrology in advancing policy development, regulatory effectiveness, and institutional strengthening by delivering actionable, data-driven insights to decision-makers.

It enabled the redesign of the national operational model for metrological supervision, the structured classification of metrological activities, and the enhancement of the regulatory (inspection) model. Furthermore, it directly supported the modernization of the national Law of Measurement and Calibration and its implementing regulations, resulting in stronger governance, improved regulatory coherence, and more effective, evidence-based policymaking.

The availability of reliable, real-time data has enabled more informed and evidence-based decision-making. Regulators are now better equipped to monitor compliance, identify high-risk sectors, and allocate resources more effectively. This has enhanced the overall effectiveness of regulatory enforcement and improved transparency and accountability. This national-level initiative also aligns with the Saudi Vision 2030, the Digital Government Authority strategy, and national transformation programmes. It has strengthened the national quality infrastructure, advanced digital transformation in public services, and supported sustainability by reducing resource consumption and promoting environmentally responsible practices.

Several institutional lessons emerge from this case. First, stakeholder integration is essential to achieving regulatory efficiency and coherence. Second, digital transformation serves as a key enabler of governance, improving coordination, data sharing, and service delivery. Third, user-centric design plays a critical role in driving adoption and improving compliance outcomes.

Finally, the case clearly demonstrates the value of sustained investment in metrology. By modernizing legal metrology systems and embedding them within a digital framework, governments can achieve significant gains in efficiency, cost reduction, and regulatory performance. More importantly, it reinforces metrology's foundational role in achieving sustainable development goals, enabling fair trade, supporting industrial growth, and fostering innovation.

Acknowledgements

Legal Metrology Program "Taqaees" website: WWW.TAQYEES.SA.

POC: Fahad M. AlDawsari,
fmm.dawsari@saso.gov.sa

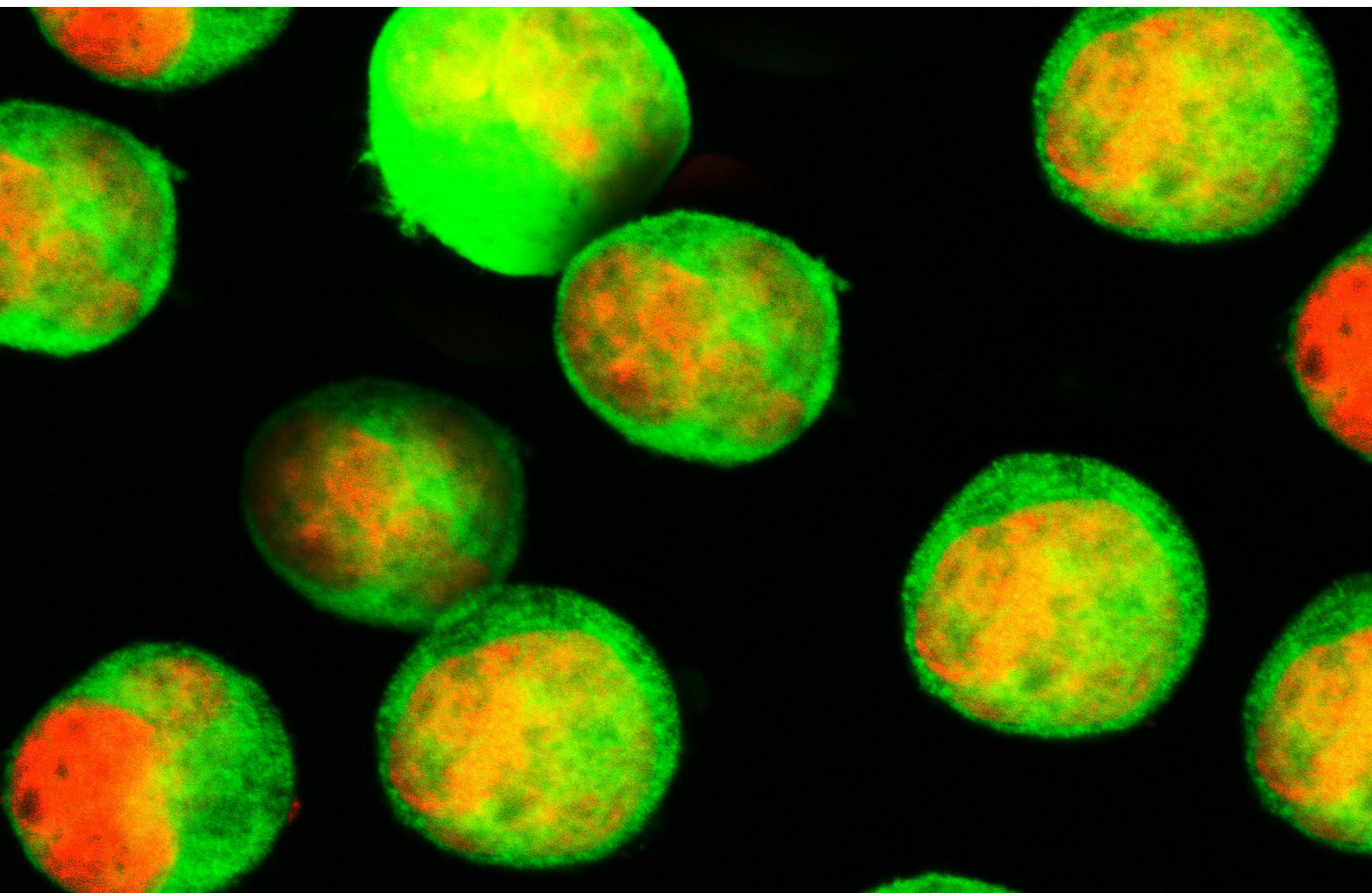


UNITED NATIONS
INDUSTRIAL DEVELOPMENT ORGANIZATION

Bureau
International des
Poids et
Mesures



SUSTAINABLE
DEVELOPMENT
GOALS



Metrology to Harmonize Cell and Particle Measurements and Advance Modern Medicine and Biotechnology

A NIST-led consortium of industry and academic partners has developed calibration beads with SI-traceable fluorescence intensities for accurate, quantitative flow cytometry, to underpin clinical diagnostics, the manufacturing of advanced therapies, and environmental and food safety monitoring

*National Institute of Standards and Technology (NIST)
United States (US)*



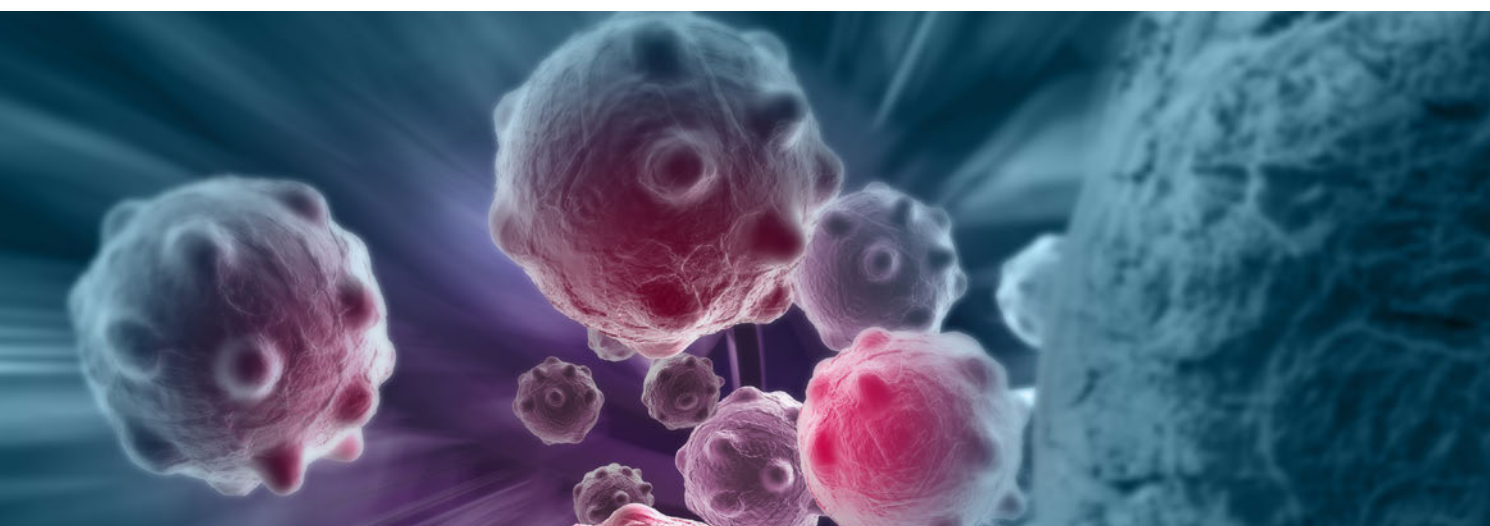
The Challenge

Advances in cell and gene-based therapeutics, as well as other regenerative medicine products, have increased the need for high-quality, robust, and validated measurements for cell characterization. Flow cytometry is a sophisticated laser-based technology used to detect and measure the chemical, physical, and biological characteristics of highly heterogeneous cells and other biological entities, serving as a cornerstone of modern medicine and biotechnology. Its importance lies in its ability to analyze thousands of particles per second in high-speed fluid streams, in a highly multiplexed manner, providing unprecedented insights into complex biological systems.

Despite its enormous potential, broader adoption of flow cytometry as a definitive or reference method has been hindered by a lack of comparability across instrument vendors and models, due to differences in instrument design, including the lasers and detectors used in the detection. In the absence of physical artefact standards, cell and particle measurements have been highly dependent on the specific instrument model and operating conditions, greatly impeding metrological progress toward cell measurement comparability. When results are highly dependent on instrument models and operating conditions, the ability to collate results from different sources to identify trends is substantially weakened.

The Solution

The National Institute of Standards and Technology (NIST), as the US NMI, has collaborated with global flow cytometer manufacturers, reagent providers, and users to standardize flow cytometers in the NIST Flow Cytometry Standards Consortium.¹ NIST formed the consortium in December 2020, and the Consortium launched a large-scale study to collect the data needed to demonstrate, for the first time, a measurement approach² that enables the use of commercially available calibration microspheres (beads) based on assigned fluorescence intensity values. These calibration beads are SI-traceable through NIST-certified reference material SRM 1934 Fluorescent Dyes for Quantitative Flow Cytometry (Visible Spectral Range) with bead fluorescence intensity values, expressed in Equivalent Reference Fluorophore (ERF) units (see **Figure 1**). NIST assigns ERF values to commercial calibration beads via this new measurement service. This ultimately enables the calibration of the fluorescence scale for any flow cytometer channel detector in an instrument-independent manner. In addition, NIST demonstrated the use of an instrument-dependent calibration value, Absolute Reference Intensity (ARI), on the same calibration beads. Together, these new derived units (ERF and ARI) and corresponding reference methods for measuring cells provide a comprehensive metrological framework for characterizing and standardizing global flow cytometer performance.³



¹NIST Flow Cytometry Standards Consortium. <https://www.nist.gov/programs-projects/nist-flow-cytometry-standards-consortium>

²De Rose et al. Assignment of Fluorescence Intensity Values to Calibration Microspheres and Nanospheres for Flow Cytometry. NIST Special Publication 260-264, 2026. <https://doi.org/10.6028/NIST.SP.260-264>

³NIST Flow Cytometry Standards Consortium. <https://www.nist.gov/programs-projects/nist-flow-cytometry-standards-consortium>

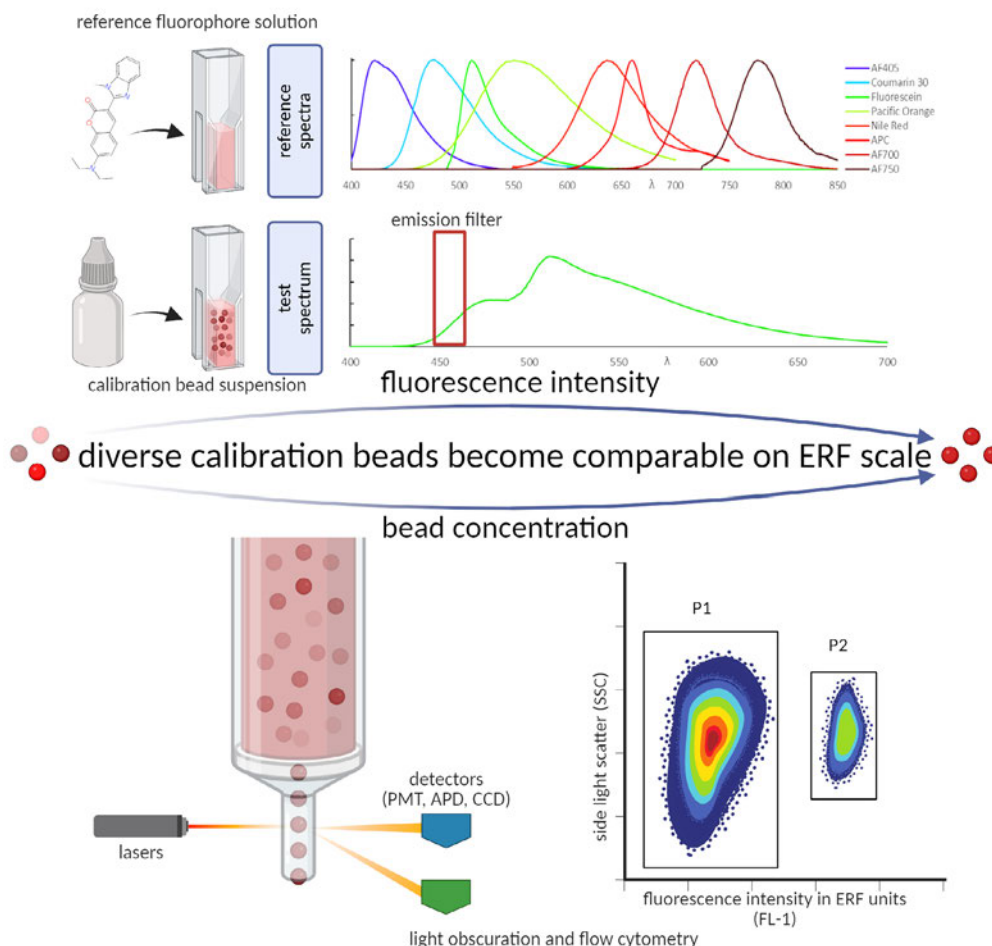


Figure 1. Schematic representation of the Equivalent Reference Fluorophore (ERF) value assignment through comparing fluorescence emissions of reference fluorophore solutions and bead suspensions and quantifying bead concentrations.

The NIST Flow Cytometry Standards Consortium operates through a series of working groups (five in total) that work in collaboration towards the common goal of improving flow cytometry measurement capabilities:

1. ERF-Based Instrument Calibration and Standardization. This working group (WG1) develops standards, including reference materials, reference data, and reference methods, for the calibration of flow cytometers and the standardization of flow cytometry data.

2. Flow Cytometry Assay Standardization. This working group (WG2) designs and conducts interlaboratory studies to develop standards, assay control materials, and best-practice protocols that achieve flow cytometry assay standardization and generate high-quality reference datasets.

3. Data Repository and Centralized Data Analysis. This working group (WG3) organizes, analyzes, and disseminates data generated

by Consortium interlaboratory studies (ILS), including developing and applying standardized metadata schemas that capture relevant aspects of ILS design, and the collaborative development of a robust data repository to catalogue input data, post-processed data, accessory files, and analysis reports.

4. Gene Delivery Systems. This working group (WG4) identifies and minimizes sources of variability in assays of gene delivery systems, including adenoviral, adeno-associated viral, and lentiviral vectors, lipid nanoparticles, and extracellular vesicles. Consensus-based methods, reference materials, and reference data are expected to be made available to the community as a result of these efforts.

5. Artificial Intelligence and Machine Learning (AI/ML) Approaches. This is the newest of the working groups (WG5) and will use high-quality reference datasets generated by Consortium interlaboratory studies to support the development and validation of emerging AI/ML models for flow cytometry.

The Consortium meets regularly with members to continue advancing the goals of the private-public partnership.

Since 2017, the Consortium has held several workshops (see **Figure 2**) to bring stakeholders together and collaborate to identify new measurement challenges.

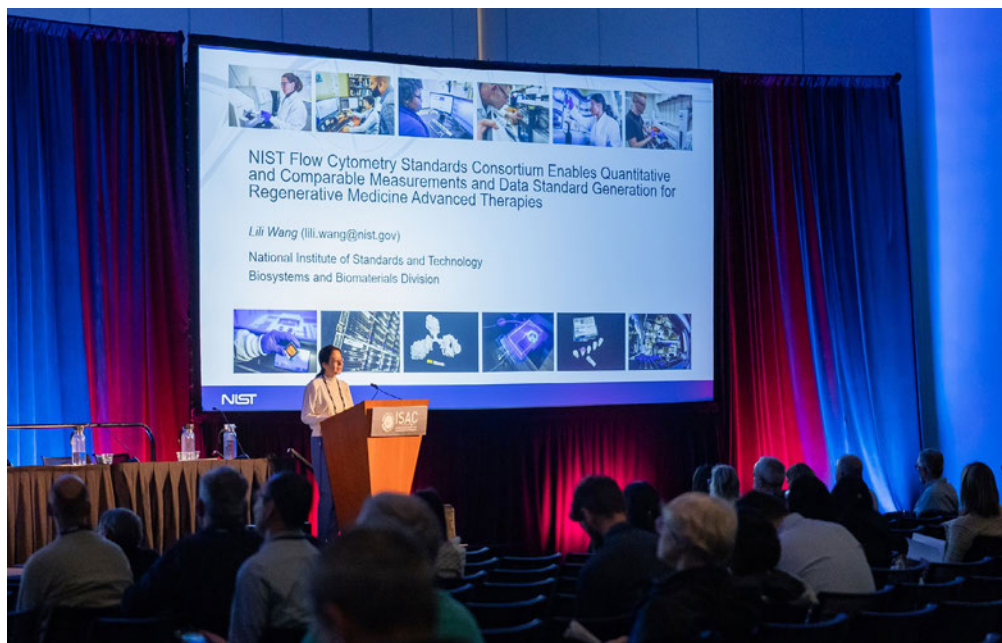


Figure 2. Dr Lili Wang, NIST Flow Cytometry Standards Consortium Principal Investigator, discussing the Consortium's work at the 2025 International Society for the Advancement of Cytometry's CYTO25 Meeting.

A Quantifiable Impact

As a result of this work, metrological traceability for fluorescence measurement procedures is being adopted across the global cytometry industry. Through the Consortium's working groups and activities, NIST provides ERF assignment of commercially-available cytometer calibration beads as a measurement service to many global diagnostics and healthcare companies, as well as to the cytometry professional societies, thereby enabling instrument standardization. More importantly, this work provides the foundational metrology needed to transform flow cytometers from relative to absolute quantification of cells and particles. The potential impact of this work on global health and commerce is profound. In clinical settings, the ability to assign equivalent reference fluorophore values to cells enables standardized analysis of biomarkers, which is essential for diagnosing diseases, selecting therapies, monitoring immune responses in patients after treatment, and ensuring the safety of advanced therapies, such as life-saving cell and gene therapies.

Over 90 % of globally-available flow cytometry instrument platforms (47 instrument models from 7 instrument manufacturers) participated in the 2024-2025 NIST Flow Cytometry Consortium-led interlaboratory study.⁴ Seven major global cytometry instrument manufacturers are members of the NIST Consortium and underpin the health industry across clinical diagnostics, drug development, immunological research, and cell and gene therapy biomanufacturing. Preliminary results from this study across sites and cytometer platforms indicate successful calibration of fluorescence intensities, which varied by seven orders of magnitude (10^7) prior to the metrological intervention.⁵ This has clearly advanced the capabilities of the global health industry through more quantitative and comparable measurements.

NIST has provided this measurement service to the majority of global cytometry instrument manufacturers that utilize reference materials. Furthermore, these manufacturers are collaborating within the NIST Flow Cytometry Consortium to further advance measurement accuracy and comparability across different cytometer platforms. These measurement services are also necessary for the broader adoption of newer flow cytometry instrumentation that offers higher multiplexing and increased resolution or sensitivity.

⁴Wang et al. 2026, Standardizing A Human TBMNK Cell Assay Across Instrument Platforms: A New Framework for Producing High-Quality, AI-Ready Reference Dataset, *Frontiers in Immunology*. <https://doi.org/10.3389/fimmu.2026.1946801>

⁵Wang et al. 2026, Standardizing A Human TBMNK Cell Assay Across Instrument Platforms: A New Framework for Producing High-Quality, AI-Ready Reference Dataset, *Frontiers in Immunology*. <https://doi.org/10.3389/fimmu.2026.1946801>

The study also suggests an unexpected preliminary finding that relatively inexpensive, shelf-stable calibration beads are often sufficient to achieve SI-traceable calibration of flow cytometry measurements. In cytometry, there has been a long-held expectation that beads functionalized with the actual fluorophores used in the assay will function best for fluorescence intensity calibration. Since fluorophores can include exotic dyes and recombinant fluorescent proteins, fluorophore-functionalized beads can be expensive and typically must be used within days of preparing a working suspension. However, for six of the ten fluorescence emission channels included in the study, the results show near-equivalent calibration performance whether a simple “hard-dyed” bead or a fluorophore-functionalized bead is used as the ERF-assigned calibrant. Some hard-dyed beads are 100x less expensive compared to fluorophore-functionalized beads, and many are shelf-stable for years. The Consortium will continue to investigate this result as it has the potential to make cell cytometry standardization more accessible and cost-effective, in addition to making the results more comparable and SI-traceable.

Industry stakeholders also view this non-destructive particle analysis technology as not only accelerating results for measuring cells or cell-based components, but also contributing to new measurement capability for larger-scale anthropogenic components, such as microplastics:

“Flow cytometry is a critical technology across a variety of industries, and we see it expanding to new spaces where particle analysis is also needed, such as aquatic presence of microplastics. The applications are extensive and give users access to answers rapidly versus genomic or proteomic methods.”

Matthew Goff, Head of Hardware for Flow Cytometry, Beckman Coulter Life Sciences

With a value exceeding 5 billion USD in 2025, the global flow cytometry market is projected to double by 2033. This growth is anticipated from classical applications in clinical diagnostics, advanced therapy development and manufacturing, and patient immune health monitoring; emerging uses in environmental water monitoring, food and beverage fermentation, and agricultural biotechnology; and increased adoption of flow cytometric methods in healthcare and manufacturing across Asia.⁶

Furthermore, as a method that records tens of measurands from each of thousands of individual cells or particles in a matter of minutes, flow cytometry is poised to be transformed by, and to transform, artificial intelligence and machine learning (AI/ML) tools for researchers, manufacturers, and clinicians.

Qualitative flow cytometry has underpinned cutting-edge clinical and biotechnological advances as an investigative tool for decades. Now, quantitative flow cytometry, grounded in the solid metrological foundation of calibrant ERF assignment, is a standardizable measurement tool. Standardizing flow cytometry in the biopharmaceutical and clinical diagnostics research and development industry sectors is essential to support assay development, decision-making, and cross-site collaboration by ensuring that data generated in different laboratories can be compared. It helps to minimize sample processing and analytical variability, making it easier to distinguish true biological signals from noise and background signals from analytical instrumentation or other technical processes. Standardization also supports clinical trials by enabling cost-effective, reproducible transfer of assays to contract research organization (CRO) partners, ensuring that trial data are suitable for downstream interpretation, regulatory submission, and strategic decisions. It is also critical for QC and release testing in cell therapy and immune-oncology manufacturing, where standardized assays help ensure consistent product characterization, quality, and compliance.

NIST, through its partnerships and measurement services, is enabling standardized, quantitative flow cytometry to underpin similar advances for decades to come.

Acknowledgments

NIST would like to thank the invaluable contributions of the NIST Flow Cytometry Standards Consortium and its members, which made this work possible.

POC: Sheng Lin-Gibson,
sheng.lin-gibson@nist.gov

⁶Mahajan and Nanadikar. Flow Cytometry Market – Global Forecast to 2033. MarketsandMarkets, 2025.
<https://www.marketsandmarkets.com/PressReleases/flow-cytometry.asp>



UNITED NATIONS
INDUSTRIAL DEVELOPMENT ORGANIZATION

Bureau
International des
Poids et
Mesures



Kenya-led Regional Quality Infrastructure Cooperation

KEBS has leveraged its technical infrastructure to strengthen metrology capacity across East Africa and beyond

*Kenya Bureau of Standards (KEBS)
Kenya (KE)*



The Challenge

Regional integration is often discussed in terms of markets, tariffs, and policy agreements, but it relies on the silent infrastructure of metrology based on confidence in measurements, standards, and calibration certificates. These measurement foundations support laboratory testing, inspection, certification, and market surveillance decisions used in conformity assessment. Where quality infrastructure is weak, cross-border trade in goods faces delays due to duplicate testing, limited mutual recognition, and uneven regulatory confidence. Across the East African Community (EAC) and the wider African Continental Free Trade Area (AfCFTA) region, many national quality infrastructure institutions still face capacity constraints in metrology, conformity assessment, market surveillance, and standardization. The United Nations Economic Commission for Africa report identifies significant gaps in Africa's quality infrastructure, with 22 of 54 African countries having minimal or no quality infrastructure. Across the EAC member states, the report classifies the quality infrastructure development as follows: Kenya – well developed; Tanzania – well developed; The Democratic Republic of Congo – reasonably well developed; Rwanda and Uganda – partially developed; Burundi and South Sudan – limited; and Somalia – none or very little.¹

The International Committee of Weights and Measures has further noted that countries without internationally recognized metrology systems are more likely to face non-tariff barriers, delayed market access, and slower industrial growth.² The recent OECD (Organisation for Economic Co-operation and Development)/Bureau International des Poids et Mesures (BIPM) analysis³ notes that trusted, comparable measurements help trade work more effectively and support regulation, safety, and environmental protection. The regional cooperation provided by the Kenya Bureau of Standards (KEBS) is more than routine technical support: it helps build confidence in the measurements that underpin regional integration and sustainable development.

Before this metrological intervention via regional cooperation took shape, several limitations

persisted: gaps in specialized laboratory capability, limited access to advanced testing systems, insufficient technical competence, and weak or still-maturing quality management systems. These weaknesses created practical risks, including unreliable measurements and test data, low regulatory confidence, and the need for repeated testing and calibration. Metrology and quality infrastructure interventions can address these weaknesses by opening technical co-operation channels and strengthening competence in quality management systems, metrology, standardization, and conformity assessment. The main challenge was that many East African partner institutions, including those across the wider African region, had limited capacity to generate, verify, compare, and rely on measurements and test results across borders. In practice, the issue was whether the results generated in the individual laboratories were technically sound, metrologically traceable, comparable, and ultimately trusted across the region. Partner institutions also needed stronger systems for metrological traceability, equipment calibration, method validation, uncertainty evaluation, and laboratory quality management. Without these systems, technically sound measurements cannot command the level of trust needed to support trade and mutual recognition.

The Solution

This case study examines how to strengthen quality infrastructure to better support trade, consumer protection, industrial competitiveness, and regulatory confidence. The focus of this case study is metrology-led quality infrastructure co-operation. While the interventions also supported broader quality infrastructure functions, the technical core of the case lies in the role of metrological traceability, calibration, measurement comparability, uncertainty evaluation, and laboratory competence in building regional trust. KEBS has supported this effort through technical training, laboratory visits, memoranda of understanding, and calibration services that provide pathways to metrological traceability. It has also responded by hosting delegations, supporting benchmarking visits, signing cooperation agreements, and sharing expertise in metrology, standardization, and conformity assessment.

Together, these engagements have illustrated how Kenya's national capability is being used to support the region. In the near term, this will strengthen quality infrastructure institutions, improve measurement reliability, and increase confidence in cross-border conformity assessment. These actions may not have begun as one formal regional strategy, but together they show a clear pattern of practical support for regional technical needs, with a particular focus on knowledge sharing, capacity building, institutional partnerships, and regional cooperation.

This challenge also creates a clear role for metrology-led cooperation as a practical development tool. By sharing expertise through benchmarking visits, providing calibration and training services, and entering cooperation agreements, KEBS helped close some of the region's metrology capacity and quality infrastructure gaps to institutions and laboratories across the continent, including in Uganda, Rwanda, the Democratic Republic of the Congo, Somalia, Seychelles, Tanzania/Zanzibar, Nigeria, and Namibia. These services covered a wide range of measurement fields, including force, Alternating Current/Direct Current (AC/DC) electrical quantities, pressure, length, mass, time, dosimetry, density, temperature, volume, photometry, and acoustics.

Regional institutions and firms are actively seeking metrologically traceable calibrations, technical training, and laboratory support from Kenya to sustain confidence in instruments used for conformity assessment and regulatory decision-making. As a result, Kenya's national capability helped build regional trust by strengthening labo-

ratory practice, staff skills, and institutional cooperation. The metrology interventions were based on the Kenya Bureau of Standards' measurement capabilities as a regional platform to build confidence in calibration and conformity assessment. KEBS provided practical support through calibration and technical training services to laboratories, manufacturing companies and other firms, and institutions across East Africa and the wider continent, covering several measurement fields. These services improved metrological traceability, built technical skills, and strengthened quality infrastructure, thereby supporting confidence in measurements and conformity assessment in partner countries. The specific interventions are outlined below.

In 2024, KEBS provided direct calibration services to Congo Petrol in the Democratic Republic of the Congo for force and pressure measurements, and to the primary cement manufacturing company (CIMERWA PLC) in Rwanda for force measurements on material testing equipment. In the same year, KEBS also trained personnel from a helicopter maintenance company (Proheli International Limited) of Uganda across several measurement areas, including force and torque, electrical measurements, dimensional measurements, pressure, and mass. A particularly important intervention in 2024 was the attachment of a team from the Malawi Bureau of Standards to the Time and Frequency and Temperature laboratories in November 2024 (see **Figure 1**). The team received training in the fundamentals of metrology and calibration to build the competencies needed to establish the scientific metrology arm of Malawi's NMI.



Figure 1. A delegation from the Malawi Bureau of Standards at the 1) Time and Frequency Laboratory and 2) Temperature Laboratory during an attachment.

¹United Nations Economic Commission for Africa. (2025). Economic Report on Africa 2025: Advancing the Implementation of the Agreement Establishing the African Continental Free Trade Area—Proposing Transformative Strategic Actions.

²International Committee for Weights and Measures (CIPM). (2003). "Evolving needs for metrology in trade, industry and society and the role of the BIPM: A report prepared for the governments of the Member States of the Metre Convention." Bureau International des Poids et Mesures.

³OECD/BIPM (2020), "International Regulatory Co-operation and International Organisations: The Case of the International Bureau of Weights and Measures (BIPM)", OECD and BIPM.

In 2025, KEBS expanded its support in both calibration services and formal institutional cooperation. This included force calibrations for Tororo Cement Limited, a cement company in Uganda, as well as dosimetry support and calibration services for the Uganda National Bureau of Standards and the Bank of Uganda. KEBS also provided measurement support to the Zanzibar Bureau of Standards in density, AC/DC electrical quantities, and force. Further, KEBS and the Uganda National Bureau of Standards signed a memorandum of understanding to strengthen collaboration in metrology, standardization, conformity assessment, and training (see **Figure 2**). The Memorandum of Understanding (MoU) established a framework for technical and scientific cooperation, joint metrology research, harmonization of standards, exchange of technical documents, sharing of laboratory and testing information, inspection cooperation, reciprocal training, and mutual recognition of reports and certificates.

The policy significance of the KEBS–UNBS (Uganda National Bureau of Standards) MoU was captured by Esther Ngari, EBS, Managing Director of the Kenya Bureau of Standards, who described the agreement as a pledge to harmonize approaches to “standardisation, testing, metrology, inspection, certification, training and the seamless exchange of information” as core tools for unlocking trade between Kenya and Uganda. She further noted that “standards are the quiet enablers of trade, the invisible threads that make trust possible between markets” and described them as the “passports our goods carry as they cross borders.”

This statement reinforces the central policy message of the case study: metrology and quality infrastructure cooperation are not simply technical or administrative activities. They provide the trust infrastructure required for goods, certificates, test reports, and regulatory decisions to move across borders with greater confidence.



Figure 2. Signing of a memorandum of understanding between the Kenya Bureau of Standards and the Uganda National Bureau of Standards.

During the same period, KEBS engaged regional partners through benchmarking visits and study tours. These included the Somalia Bureau of Standards, Malawi Bureau of Standards, Standards Association of Zimbabwe, Standards Organization of Nigeria, Burundi Bureau of Standards, and Quality Control, and the Zanzibar Bureau of Standards.

KEBS also worked with international partners on quality infrastructure cooperation, including TradeMark Africa, Physikalisch-Technische Bundesanstalt (PTB), and the Economic Community of West African States (ECOWAS) Commission. Together, these engagements reinforced Kenya’s role as a platform for technical capacity development and measurement-related institutional cooperation.



Figure 3. Lead determination in paint training at the Kenya Bureau of Standards (KEBS) laboratories.

In 2026, technical regional metrology support continued with KEBS, which provided calibration services to Keane Engineering Technologies Ltd, a calibration service provider in Uganda across force, mass, AC/DC electrical quantities, time, temperature, and dosimetry. It also delivered force measurement calibration for Kongsberg Maritime, a maritime company in Namibia and VS Hydro Rwanda Ltd, a hydropower engineering company in Rwanda, as well as mass and force measurement support to Docol Construction Rehabilitation and Trading Company, a construction and infrastructure company in Somalia. Further support took the form of specialized technical training and laboratory exposure. An example was the regional training on lead determination in paint, which brought together experts from Uganda, Tanzania, Rwanda, Zimbabwe, and Burundi, with support from the Lead Exposure Elimination Project. The program also included a two-week attachment for 11 Mercer University students, providing hands-on experience with advanced lead-analysis technologies (see **Figure 3**). This intervention strengthened laboratory capability in an area directly linked to consumer safety and public health.

Across these interventions, metrological traceability was ensured, where relevant, through KEBS' calibration system, reference standards, documented procedures, uncertainty evaluation, competent personnel, and laboratory quality management practices. The interventions were anchored in both international and regional metrology frameworks, and all the measurement scopes were supported by Kenya's published Calibration and Measurement Capabilities (CMCs).

Where Kenya has not yet published CMCs for specific scopes, KEBS maintains metrological traceability by calibrating its reference standards against internationally equivalent primary standards maintained by national metrology institutes that issue the CMCs.

A Quantifiable Impact

The metrological intervention produced measurable results across four levels: 1) calibration and training services delivered, 2) regional reach, 3) metrology capability strengthening, and 4) institutional and capacity building interventions. The available evidence is strongest on outputs and operational reach, and less conclusive on broader developmental effects.

Evidence collected before, during, and after the intervention showed both regional demand for Kenya's metrology services and the practical support that KEBS provided. Throughout the intervention period, the evidence pointed to sustained demand for calibration and training, laboratory visits, benchmarking tours, and records of institutional cooperation, including memoranda of understanding.

The main operational dataset consisted of metrology services request records. These records from 2024 to 2026 documented calibration and training services delivered to clients in Uganda, Rwanda, the Democratic Republic of the Congo, Somalia, Seychelles, Tanzania/Zanzibar, Nigeria, and Namibia.

The services covered measurement scopes in AC/DC electrical quantities, mass, force, pressure, time, temperature, density, dosimetry, volume, photometry, and acoustics. Force measurement was the most prominent, appearing in 12 of the 18 metrology services request records. Other recurring fields included AC/DC electrical measurements, pressure, length, time, dosimetry, mass, and temperature. The consolidated metrology services request data show that KEBS delivered 18 documented regional metrology interventions across Africa. Of these, 17 were calibration assignments, and 1 was a technical training assignment. The majority of these assignments served East Africa (Uganda and Rwanda were the most frequent).

Evidence of institutional cooperation and capacity building was captured separately through memoranda of understanding (MoUs), study visits, attachments, benchmarking visits, and technical training (see **Table 1**). This evidence also covered engagements with institutions from Malawi, Burundi, Somalia, Zanzibar, Zimbabwe, Nigeria, ECOWAS-related partners, and other regional and international organizations.

KEBS also facilitated visits and signed memoranda of understanding to expand regional cooperation. **Table 2** highlights some of the institutional cooperation engagements.

Table 1. Evidence of institutional cooperation and capacity building.

Source category	Evidence used	Purpose in the case study
Operational metrology records	Consolidated metrology services request records; calibration and training records	To show countries served, dates, clients, measurement areas and services delivered.
Training and attachment evidence	Training records, laboratory attachment examples and regional technical training posts	To show capacity building and transfer of practical measurement knowledge.
Institutional cooperation records	MoUs, cooperation announcements, benchmarking visits and study tours	To show formal and structured cooperation between quality infrastructure institutions.
Public disclosures	KEBS social media posts (LinkedIn/X posts, Facebook) and institutional communication.	To corroborate visits, technical exchanges, MoUs, and training activities.



Table 2. KEBS-facilitated institutional cooperation engagements.

Date	Intervention	Countries/ institutions involved	Focus area	Measurable/observable result
30 Nov 2024	Laboratory attachment/ scientific metrology capacity building	Malawi Bureau of Standards; KEBS Temperature Metrology Laboratory; KEBS Time & Frequency Metrology Laboratory	Fundamentals of measurement and calibration; scientific metrology development	The Malawi Bureau of Standards team attached to KEBS laboratories to support the development of Malawi's scientific metrology capability.
Jun 2025	Work visit/ institutional learning	Somali Bureau of Standards; Somalia livestock-sector delegates; KEBS	Quality infrastructure, regional trade, and laboratory systems	Five-day work visit to KEBS headquarters; strengthened knowledge of KEBS systems and facilities.
30 Jul 2025	MoU/ formal regional cooperation	Uganda National Bureau of Standards; KEBS; Governments of Uganda and Kenya	Standards, conformity assessment, metrology, training, testing, inspection, mutual recognition	MoU signed to enhance trade, market access, and industrial development through cooperation in standards, metrology, conformity assessment, and training.
Aug 2025	Bench-marking visit	Malawi Bureau of Standards; KEBS	Standardized practices; regional integration; AfCFTA alignment	A three-day benchmarking visit was undertaken to strengthen professional links and align standardized practices.
Oct 2025	Regional study/ technical exchange	ECOWAS Commission; TradeMark Africa; KEBS	TBT, SPS, standards harmonization, laboratory systems	ECOWAS delegation toured KEBS laboratories and exchanged best practices on TBT/SPS and standards harmonization.
Nov 2025	QI cooperation/ technical project engagement	PTB; KEBS	Leather proficiency testing, regional exchange programs, and accreditation support	Collaboration discussions held on strengthening quality infrastructure for selected EAC sectors, including leather proficiency testing and accreditation support.
Nov 2025	Study tour	Standards Association of Zimbabwe; KEBS	SME certification model; import inspection systems	Five-day study tour focused on learning from KEBS' SME Certification Model and import inspection systems.
Mar 2026	Courtesy visit/ laboratory exposure	Standards Organization of Nigeria; KEBS	Standards development, certification frameworks, consumer protection, and laboratory services	Delegation toured KEBS laboratories and engaged in institutional collaboration in standards, certification, and consumer protection.
24 Mar 2026	MoU/ technical cooperation	KEBS; Burundi Bureau of Standards and Quality Control	Standardization, metrology, and conformity assessment	A framework for cooperation was established to facilitate the exchange of scientific and technical expertise between the two institutions.
May 2026	MoU/ institutional cooperation	Zanzibar Bureau of Standards; KEBS	Collaboration, alignment, and mutual support	MoU signed to provide a cooperation framework between KEBS and the Zanzibar Bureau of Standards.
May 2026	Regional technical training/ laboratory capacity building	KEBS; Lead Exposure Elimination Project; experts from Uganda, Tanzania, Rwanda, Zimbabwe, Burundi, and Mercer University students	Lead determination in paint; consumer safety; laboratory competence	Regional training delivered on lead-in-paint testing; strengthened technical capacity in lead analysis and included laboratory attachment for 11 Mercer University students.

The interventions produced several important capability outcomes across the region. First, partner institutions gained access to metrologically traceable calibration services in multiple measurement fields. Second, technical personnel received specialized training, while institutions were exposed to KEBS' laboratory systems, procedures, traceability practices, and quality management approach.

A key milestone was the 2024 attachment of a team from the Malawi Bureau of Standards to KEBS' Temperature and Time and Frequency Metrology laboratories. This cooperation supported Malawi's effort to establish the scientific metrology arm of its NMI. Its importance lies in the fact that it went beyond service delivery: it showed Kenya's active support for the development of another country's national measurement capability. Formal agreements and technical exchanges also laid the foundation for continued collaboration. For example, the memorandum of understanding between the Uganda National Bureau of Standards and KEBS established a broad framework covering metrology, conformity assessment, training, testing, inspection, mutual recognition of test reports, and joint metrology research. This, in turn, strengthens the foundation for future measurement comparability and greater confidence in trade.

Prior to the metrological intervention, the regional measurement environment was fragmented. Laboratories and partner institutions often had to seek support outside the region to develop competence, facilitate technical exchange, enhance metrological traceability, and build greater measurement confidence in conformity assessment. Such extra-regional support generally came at a higher cost, making it harder to sustain robust measurement systems over time.

As part of the metrological intervention, KEBS used its technical infrastructure to strengthen metrology capacity across East Africa and beyond. This formed part of a broader effort to use national laboratory capability for regional calibration, training, and cooperation. The evidence is strong on outputs and capability gains, but less clear on wider socioeconomic effects. Follow-up data is still needed to confirm impacts such as shorter turnaround times, lower costs, or better public health compliance. Even so, the broader economic case remains persuasive. Research, including work commissioned by BIPM, suggests that mutual recognition systems are more efficient than fragmented bilateral arrangements.⁴ Kenya's metrology system is therefore helping to build the trust needed for deeper intra-African trade.



The interventions supported policy implementation by improving the technical reliability of measurement methods used for testing, certification, inspection, and market surveillance. Calibration services provided to regional clients helped ensure that measurement instruments generated dependable results. This is important because many regulatory decisions depend on measurement evidence. Products may be accepted, rejected, certified, recalled, or further investigated based on test and inspection results. If the instruments behind those results are not calibrated, metrologically traceable or properly used, enforcement becomes weaker and easier to challenge. KEBS' support helped partner institutions and regional clients build stronger confidence in their measurement systems. Specialized training also had direct policy relevance. For example, regional training in lead determination in paint strengthened laboratory capability in an area linked to consumer safety and public health. Likewise, benchmarking of import inspection systems, SME certification models, and laboratory operations supported more consistent approaches to enforcement, certification, and market access.

Several practical lessons emerge from this case study:

- Measurement capacity is a governance asset. It helps public institutions make decisions based on reliable evidence rather than assumptions, repeated tests or disputed certificates.
 - Regional cooperation must be operational rather than ceremonial. MoUs matter most when calibration services, training, attachments, benchmarking visits, laboratory exposure, and technical follow-up.
 - Trust in trade depends on trust in data. A certificate, inspection report, or test result has significance only when the underlying measurement system is reliable, traceable, and comparable.
 - Capacity building is most effective when it combines people, systems, and infrastructure. Training alone is insufficient if laboratories lack procedures, reference standards, quality systems, and opportunities for comparison. In the same way, equipment alone cannot deliver results without skilled personnel and strong institutional discipline.
- Evidence registers matter. By organizing interventions by date, country, focus area, output, and evidence source, institutions can turn scattered activities into institutional memory and policy-relevant evidence.

This case study has illustrated that metrology infrastructure is more than a laboratory function—it helps policy work in practice. Metrology provides a practical mechanism for addressing the regional problem identified at the outset: the limited capacity to generate, verify, compare, and trust measurement results across borders. Standards, regulations, and trade agreements only deliver results when they rest on reliable measurements, trusted test results, and sound conformity assessment. Better access to metrologically traceable calibrations, technical training, laboratory exposure, and institutional cooperation strengthens the conditions needed for trade, consumer protection, industrial development, and public confidence in regulation. Metrology should be treated as strategic infrastructure. It helps governments apply standards, enforce regulations, protect consumers, support industry, and take part more effectively in regional trade.

Lastly, this case study demonstrates the long-term value of sustained investment in national metrology capability. Kenya's ability to support regional partners grew from earlier investments in laboratories, reference standards, trained personnel, calibration systems, quality management, international recognition, and institutional credibility. When a country invests in metrology, it strengthens not only its own industrial and regulatory systems but also its ability to support regional development. KEBS's work with neighboring and regional institutions shows how a national measurement system can also serve a wider regional purpose by helping other institutions improve traceability, comparability, and confidence in measurement results.

Acknowledgments

This case study draws on evidence from the KEBS and its regional partner institutions. It also recognizes the contribution of partner institutions from Malawi, Uganda, Somalia, Zanzibar, Burundi, Zimbabwe, and Nigeria, as well as regional and international partners such as ECOWAS, TradeMark Africa, PTB, and the Lead Exposure Elimination Project.

POC: Kiplangat Kobur koburk@kebs.go.ke



UNITED NATIONS
INDUSTRIAL DEVELOPMENT ORGANIZATION

Bureau
International des
Poids et
Mesures



Trusted and Accurate Metrology for Electric Vehicle Supply Equipment (EVSE) in China

NIM has developed metrological methods and tools for an integrated EVSE supervision framework that combines SI-traceable EVSE testing, online performance evaluation, and risk-matched follow-up to support reliable charging services, sustainable infrastructure, clean urban transport, and the low-carbon transition

*National Institute of Metrology (NIM)
China (CN)*



The Challenge

China has built the world's largest EV charging infrastructure network. According to the National Energy Administration of China, by the end of March 2026, the total number of electric vehicle charging facilities, counted by charging connectors or charging guns, exceeded 21 million. Among them, public connectors numbered approximately 4.9 million, and private connectors exceeded 16 million. In this case, connector-level statistics describes the scale of the infrastructure, while electric vehicle supply equipment (EVSE) refers to the legal metrology-relevant equipment, metering channel, or transaction measurement function used in commercial or trade-settlement transactions.

For users, the EVSE is both a terminal for delivering an energy service and a legal metrology instrument. The measured electricity directly determines the amount the user pays. Accurate and trustworthy measurement is therefore essential not only for consumer protection and fair trade, but also for building confidence in charging services and sustaining electric mobility through clean, low-carbon urban transportation services.

The scale of deployment creates a measurement management challenge: millions of distributed and networked EVSE units used for trade settlement must continue to measure accurately after installation, software updates, maintenance, and long service periods. The specific risks are not only ordinary measurement drift, but also parameter tampering, hidden software functions or backdoors, data manipulation, and a mismatch between metered energy and billing data. Therefore, metrological control must maintain SI-traceable measurement for electric energy (kWh), voltage, current, power, time, and accumulated energy under dynamic charging conditions, while also ensuring well-documented digital metering records within an appropriate quality infrastructure (QI).

Three main challenges exist for the reliable and efficient operation of EVSE infrastructure, for which metrology plays a significant role.

Firstly, the accurate operation of EVSEs must be verified through trusted, legal metrology procedures and standards.¹ Because EVSE is digital and networked, the risks mentioned above may arise, which would potentially affect fair billing for consumers and weaken end-user confidence.

Secondly, the accuracy of the energy delivered by an EVSE requires calibration with metrologically traceable, accurate measurement standards. Energy and power measurement must be traceable to SI-based national standards and must remain valid under AC, DC, high-power DC fast-charging, and supercharging conditions. High-power DC fast-charging EVSEs may reach 1500 V and hundreds of amperes. Existing and commercially available validation equipment may not cover future charging conditions, posing challenges for both testing instrumentation and the calibration standards required for metrological traceability.

Thirdly, the inspection of EVSE infrastructure requires risk- and cost-matched considerations. Practical field-based EVSE verification experience indicates that routine on-site verifications may cost about RMB 500 and take between 20 and 40 minutes per EVSE connector, making a complete one-by-one field verification difficult to scale. Given that millions of connectors already exist and are expected to expand further, this poses a high prospective cost for maintaining adequate verification of EVSE specifications through a conventional inspection scheme alone.

The objective is not to unconditionally reduce metrological control. Rather, it is to align the level and cost of metrological verification with the measured risk of potential fraud, so that targeted resources can be allocated to locations that deliver the most public value. Conversely, relying only on a fixed periodic verification cycle, for example, a three-year interval, may miss drift or abnormal behaviour between verifications; online evaluation results can help identify where earlier follow-up is needed.

¹State Administration for Market Regulation (China), JJG 1148-2022 AC Charge Spots for Electric Vehicles(for Trial Implementation); JJG 1149-2022 Off-board Chargers for Electric Vehicles(for Trial Implementation); JJG 1192-2023 Calibrator of Off-board Chargers for Electric Vehicles; JJG 1193-2023 Calibrator of AC Charging Piles for Electric Vehicles.

The Solution

The National Institute of Metrology (NIM), together with regulators, local metrology institutes and industrial partners, provided metrological technical support for the EVSE supervision framework led by the competent government authorities.

NIM's work supported traceability, method development, validation, calibration and verification capability, online evaluation, and technical evidence for risk-based decision-making, but did not constitute direct administrative supervision or enforcement.

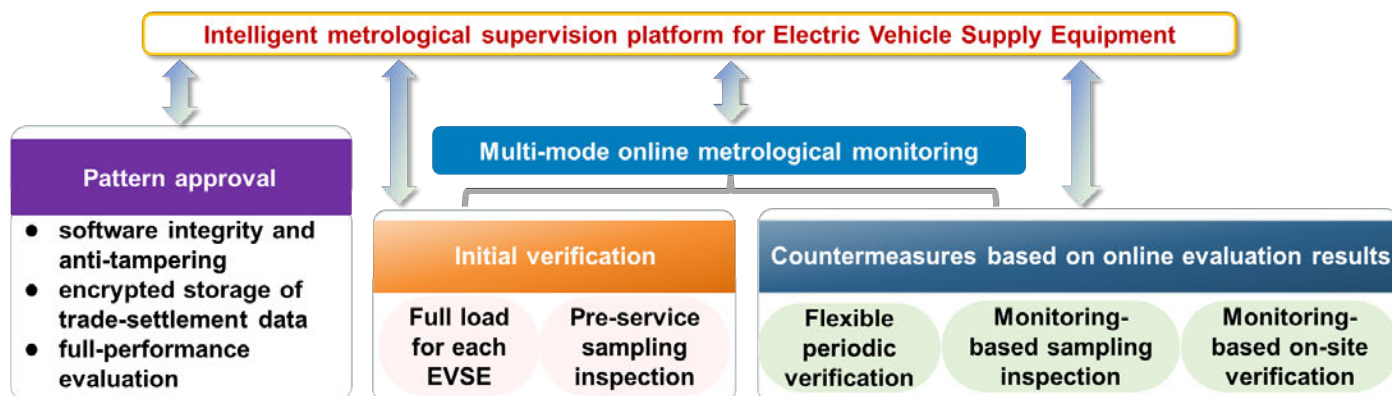


Figure 1. An overview of the integrated metrological supervision framework for EVSE.

This framework combines trusted and accurate metrology with risk- and cost-matched supervision across pattern approval or type evaluation, initial verification, in-service online evaluation, and differentiated countermeasures. It is supported by an intelligent metrological supervision platform and multi-mode online metrological monitoring, as illustrated in **Figure 1**.

NIM-related technical activities supporting this framework include field inspection experience, pilot validation, multi-mode algorithm research, high-power DC fast-charging and supercharging traceability, and data-reference demonstration work. **Table 1** maps these specific activities and timeframes to the main roles within the integrated framework without implying that NIM directly implements administrative supervision.

Table 1. A timeframe and summary of NIM's metrological interventions supporting the EVSE framework.

Timeframe	NIM-led metrology efforts	Main role in EVSE framework
2021	EVSE metrological inspection and technical support (Sanya location)	Field baseline and practical verification experience
2023	EVSE compulsory verification technical service (Beijing location)	Field workload and verification practice evidence
2023-2024	Online evaluation pilot and technical specification support	Energy-conservation online evaluation as part of NIM-supported follow-up confirmation route
2023-2027	NQI project on multi-mode EVSE metering error evaluation	Energy conservation, vehicle-EVSE interaction and method validation
2024	Quality-chain task on devices for supercharging metrological traceability standards	High-power traceability and dynamic energy testing
2025	Quality-chain work on supercharging metrological traceability data reference standards and demonstration	Factory-side verification, data records and mutual-recognition support

As part of the metrological intervention, NIM maintained SI-traceable electric energy standards and, since the 2024 quality-chain task of China's State Administration for Market Regulation on supercharging metrological traceability, developed suitable transfer instruments for high-power EVSE. NIM supported the EVSE traceability framework linking national electricity standards, AC and DC energy standards, verification devices, calibrators, and EVSE used for trade settlement (i.e. commercial transactions).

For supercharging, NIM developed two complementary field calibrators (see **Figure 2**): a liquid-cooled calibrator for high-current on-site

testing up to 1500 V/800 A (**Figure 2a**, energy accuracy class 0.05), and a portable handheld calibrator for more flexible field checks up to 1000 V/800 A (**Figure 2b**, energy accuracy class 0.1). NIM also developed a verification device for these calibrators. The verification device supports up to 1500 V/1 kA (energy accuracy class 0.01) and includes a dynamic waveform testing component (energy accuracy class 0.02) with step, trapezoidal, and triangular signal generation. This capability is important because EV charging is an energy-integration process with time-varying voltage and current, not only a steady-state power measurement.

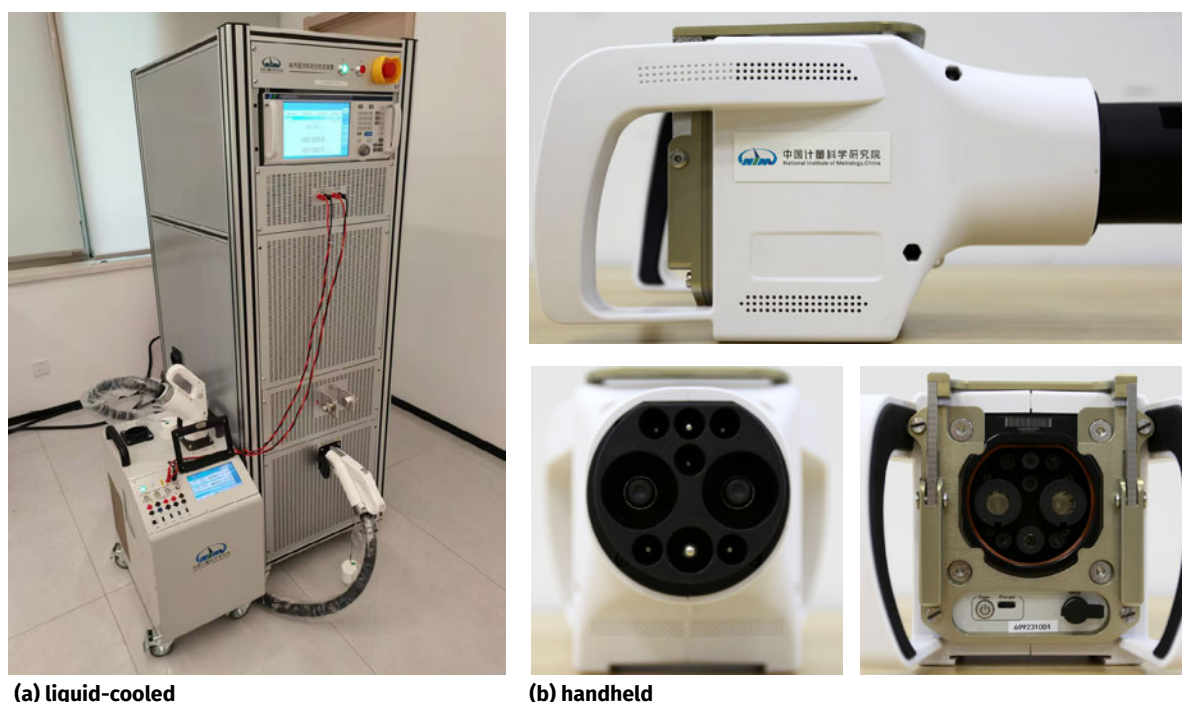


Figure 2. NIM supercharging traceability equipment and key capabilities used for on-site metrological traceability testing: (a) liquid-cooled high-current calibrator with a capability of 1500 V/800 A (energy accuracy class 0.05), (b) portable handheld calibrator with a capability of 1000 V/800 A (energy accuracy class 0.1).

The initial verification of each EVSE unit combines full-load verification with pre-service sampling inspection. Remote intelligent verification cabins are controlled test bays containing load equipment, reference metering, communications, and data-security modules. They can be deployed either at the end of an EVSE production line or in a controlled pre-service testing environment. Newly manufactured EVSE can then be tested under full-load or simulated-load conditions, while data are encrypted, digitally signed and uploaded to a metrological data platform. This is not pattern (or type) approval; it is a factory-side or pre-service measurement assurance step that supports source quality control before equipment enters service.

Conventional on-site EVSE verification remains necessary, especially for high-risk or suspicious EVSE. However, intelligent online metrological monitoring can support the selection of appropriate countermeasures based on online evaluation results. NIM developed an online platform evaluation approach that uses an energy conservation method: the station-level input energy is compared with EVSE-reported output energy after accounting for losses and non-charging loads, and the results are then classified and used to guide any necessary follow-up countermeasures (see **Figure 3**). According to the results and considering the uncertainty level, the countermeasures (via verification or inspection) may include variable periodic verification, monitoring-based sampling inspection, or monitoring-based on-site verification.

NIM has collected data on national infrastructure statistics, practical field experience, NIM project tests, and method-validation results for this metrological intervention. Since 2021, the NIM-related work has included technical services and pilot studies, online energy-conservation evaluation, and NQI research on multi-mode EVSE metering error evaluation.

Further, in 2024, NIM initiated a quality-chain project on EV supercharging metrological traceability, which is ongoing and includes the development of EVSE traceability data reference standards and demonstration applications.



Figure 3. Snapshot of an example NIM-related online metrological monitoring platform and calculation interface.

The online evaluation route depends on both the suitability of the data and the calculation method. Before applying the energy-conservation evaluation, NIM checks the EVSE station topology, reliability of total-meter and charging-order data, time alignment, meter resolution, and, where available, the process data from the vehicle or EVSE. Any missing, low-resolution, or poorly synchronized data increases uncertainty and therefore triggers stricter sampling or field-based confirmation. Field validation of the energy-conservation method covered 8 stations and 98 EV charging connectors. Separately, simulation validation covered 50 stations, 1 000 EVSE units and 180 days of data across multiple simulation scenarios. The reported simulation results included a mean absolute error (MAE) of 0.32 %, and a root mean square error (RMSE) of 0.34 %.

In each scenario, overall accuracy (ACC) was defined as the proportion of all samples whose predicted metering status agreed with the reference status; the false-positive rate (FPR) was the proportion of truly compliant samples incorrectly flagged as out-of-tolerance; and the false-negative rate (FNR) was the proportion of truly out-of-tolerance samples incorrectly classified as compliant. The reported ACC, FPR and FNR of 99.7 %, 0.4 %, and 12.3 % respectively, are averages of the scenario-specific metrics. Because the proportions of compliant and out-of-tolerance samples varied among scenarios and the three metrics were averaged separately, these average values are not equivalent to metrics calculated from a single pooled confusion matrix. The results are summarized in **Table 2**.

Table 2. Evidence-based and data-quality indicators for this metrology intervention

Evidence Type	Supporting Data and/or Example	Use in this case study
National scale	21 481 million charging connectors by March 2026; 4 863 million public connectors ²	Defines the scale of the measurement challenge
Field baseline	Traditional on-site verification: approximately RMB 500 and 20-40 minutes per EVSE ³	Explains why risk-matched methods are needed
Supercharging metrological traceability	1500 V / 800 A field calibrator and 1500 V / 1 kA verification device ⁴	Shows high-power measurement capability
Field validation	Energy conservation method tested with 8 stations and 98 connectors] ⁵	Provides practical validation evidence for the energy-conservation online evaluation route
Simulation validation	50 stations, 1000 EVSE units and 180 days of data; MAE 0.32 %, RMSE 0.34 %, accuracy 99.7 %, false alarm 0.4 %, missed detection 12.3 % ⁶	Evaluates algorithms as metrological methods

A Quantifiable Impact

Within the broader NIM-related NQI research work, energy conservation, vehicle-EVSE interaction, remote metering modules, and remote verification calibrators were studied and presented in this case study as complementary technical routes. The vehicle-EVSE interaction method, for example, uses repeated charging records between vehicles and a small number of reference EVSE units that have either been verified or equipped with high-accuracy metering modules. These records can be used to characterize the vehicle as a transfer standard, which can then be used to compare EVSE units requiring verification. The integrated metrological EVSE monitoring framework can therefore accommodate different technical routes, while specific applications may select the route that best matches data availability, infrastructure conditions, and metrological risk.

The SI-traceable standards and calibration devices, together with the verification and fieldable testing equipment, ensure accurate EVSE measurements in commercial transactions. One of the key results of this work is the integrated technical framework that supports trusted, accurate EVSE measurement and risk- and cost-matched supervision. The online EVSE infrastructure monitoring tool facilitates real-time evaluation of EVSE performance and accuracy estimation, enabling a holistic, data-driven decision process for how best to verify and inspect EVSE within municipalities across China.⁷

The broader impact of this EVSE framework is the expectation that these measurement devices are being adequately tested and evaluated for correctness; the resulting trust in this metrological process reduces the risk of fraud or manipulation and strengthens consumer confidence. Further, the SI-traceable calibration and verification processes not only underpin industrial quality but also promote fairness in routine EVSE trade settlements. The online evaluation process also identifies where abnormal metering may require differentiated countermeasures and facilitates the risk-matched use of verification resources, making supervision more scalable for large EVSE networks.

This framework is also aligned with the international direction represented by OIML G 22 and ongoing EVSE legal-metrology activities.⁸ For other countries or regions, the route can be adapted according to local scale and resources. In all cases, trustworthy EVSE charging depends on metrology-based traceability, secure and protected data, validated evaluation methods, and cooperation among metrology institutes, regulators, operators, and manufacturers.

²National Energy Administration of China, EV charging infrastructure data, March 2026; source cited in NIM case-file materials. Public agency website: <https://www.nea.gov.cn/>.

³Xiao Zishang, NIM master thesis, 2025 (non-public NIM thesis/material used for method-validation data; available from NIM on request).

⁴National Institute of Metrology (NIM), China, Supercharging metrological traceability project report, 2024 (internal project report; available from NIM on request).

⁵Xiao Zishang, NIM master thesis, 2025 (non-public NIM thesis/material used for method-validation data; available from NIM on request).

⁶Xiao Zishang, NIM master thesis, 2025 (non-public NIM thesis/material used for method-validation data; available from NIM on request).

⁷National Institute of Metrology (NIM), China, Smart metrology and monitoring report, 2025 (internal technical report; available from NIM on request).

⁸OIML Bulletin, Navigating the gap: Australia's experience in regulating electric vehicle supply equipment ahead of an OIML Recommendation, 2026, <https://www.oiml.org/en/publications/oiml-bulletin/2026-02/20260208>.

As a key takeaway from this case study, EVSE metrological supervision at the national or policy level is best designed as a life-cycle system. This includes trusted design and software/data-security assessment at pattern approval or type evaluation, measurement accuracy and confirmation of metrological traceability at the initial verification step, and the flexibility to implement a range of countermeasures based on real-time evaluation results during in-service supervision. Further, digitalization does not replace metrology. A digital platform without metrologically traceable standards, data integrity, and uncertainty evaluation would lack the underlying trust and credibility. Conversely, conventional periodic verification alone cannot efficiently cover tens of millions of connectors.

Acknowledgements

This case study is based on work carried out by the National Institute of Metrology (NIM), China, in cooperation with national and local authorities, local metrology institutes, EVSE operators, EVSE manufacturers, power-grid companies, universities, software companies, and other technical partners. NIM also cooperates internationally through the CIPM MRA, APMP, OIML technical work, international comparisons, training, and technical exchanges.

POC: Jiafu Wang, jiafu.wang@nim.ac.cn





UNITED NATIONS
INDUSTRIAL DEVELOPMENT ORGANIZATION

Bureau
International des
Poids et
Mesures



Digital Transformation of Azerbaijan's Metrology Services

AzMI has developed a fully digital metrology module that manages all calibration and equipment certification services, invoicing, and contracts, including customer service tracking through a custom mobile application

*Azerbaijan Metrology Institute (AzMI)
Azerbaijan (AZ)*

The Challenge

Before the digitalization of metrological services by the Azerbaijan Metrology Institute (AzMI), the submission, processing, and execution of service requests were largely carried out through traditional methods. Applications were received through various channels; data was stored in separate documents and information sources; and most processes were managed manually. This approach made it difficult to process information efficiently and manage services in a unified manner. Since the prior system did not enable real-time tracking of application status, monitoring and management capabilities were limited. Information generated during service delivery was stored on different media, creating additional risks related to data completeness, accuracy, and reliability. The absence of a centralized platform for orders, completed services, issued certificates, calibration reports, and other related documents made data retrieval, monitoring, and analysis challenging.

Transparency was also limited with the traditional method of handling service requests. Applicants were unable to track the status of their requests in real time and often had to submit additional inquiries to obtain information about their progress. The lack of full digitalization restricted accountability, oversight, and performance measurement across service delivery processes. Furthermore, document circulation was primarily paper-based, requiring repeated data entry and manual information exchange between departments. This increased the likelihood of human error and extended service delivery times. As a result, there was a growing need to improve efficiency, accessibility, traceability, and overall management of metrological services.

The Solution

AzMI initiated a phased digital transformation of its calibration and certification processes, which included improvements to both technical and organizational functions. The development of the Metrology Submodule began in October 2023, following a comprehensive analysis of existing business processes and user requirements. The system was subsequently deployed and entered into operational service in June 2024, becoming fully available for the electronic management of metrological services.

To digitalize metrological services and improve service delivery processes, AzMI first conducted a comprehensive analysis of existing business processes, identified user needs, and developed functional requirements for electronic service delivery. In line with these requirements, a Metrology Submodule was developed and deployed as an integrated component of the Quality Portal. The module provided a unified digital platform for managing all processes related to metrological services. Through the module, legal entities and individuals can electronically create, submit, and monitor service requests. The entire workflow, including request registration, assignment, distribution among executors, execution, and completion, is managed electronically within the system. To support digital customer relationship management, electronic contract and electronic invoicing functionalities were introduced. Based on information from service requests, contracts and invoices are automatically generated by the system, which are then electronically delivered to customers, and legally validated via electronic signatures. This ensures that contractual and financial documents are circulated entirely in a digital environment. The module also includes dedicated mechanisms for issuing and managing metrological service results. Verification certificates and marks, notices of non-compliance, calibration certificates, and certificates of metrological attestation for testing equipment are generated, registered, approved, and delivered electronically.

A centralized database was also established to store and manage service requests, completed services, verification and calibration results, issued certificates, and other related information. In addition, monitoring, statistical reporting, and management dashboard functionalities were implemented to support performance tracking and informed decision-making.

To further improve accessibility, a mobile application was developed for both AzMI customers and employees (see **Figure 1**).

Through the mobile application, users can create and monitor requests, submit service results, upload information from on-site activities, access electronic documents, and perform various operational tasks. This approach enables uninterrupted service delivery through both web and mobile platforms. Any evolving user needs, implemented innovations, and emerging technical or regulatory requirements are regularly assessed. Ongoing development activities are planned to expand the module's functionality, enhance user experience, and introduce new digital solutions.

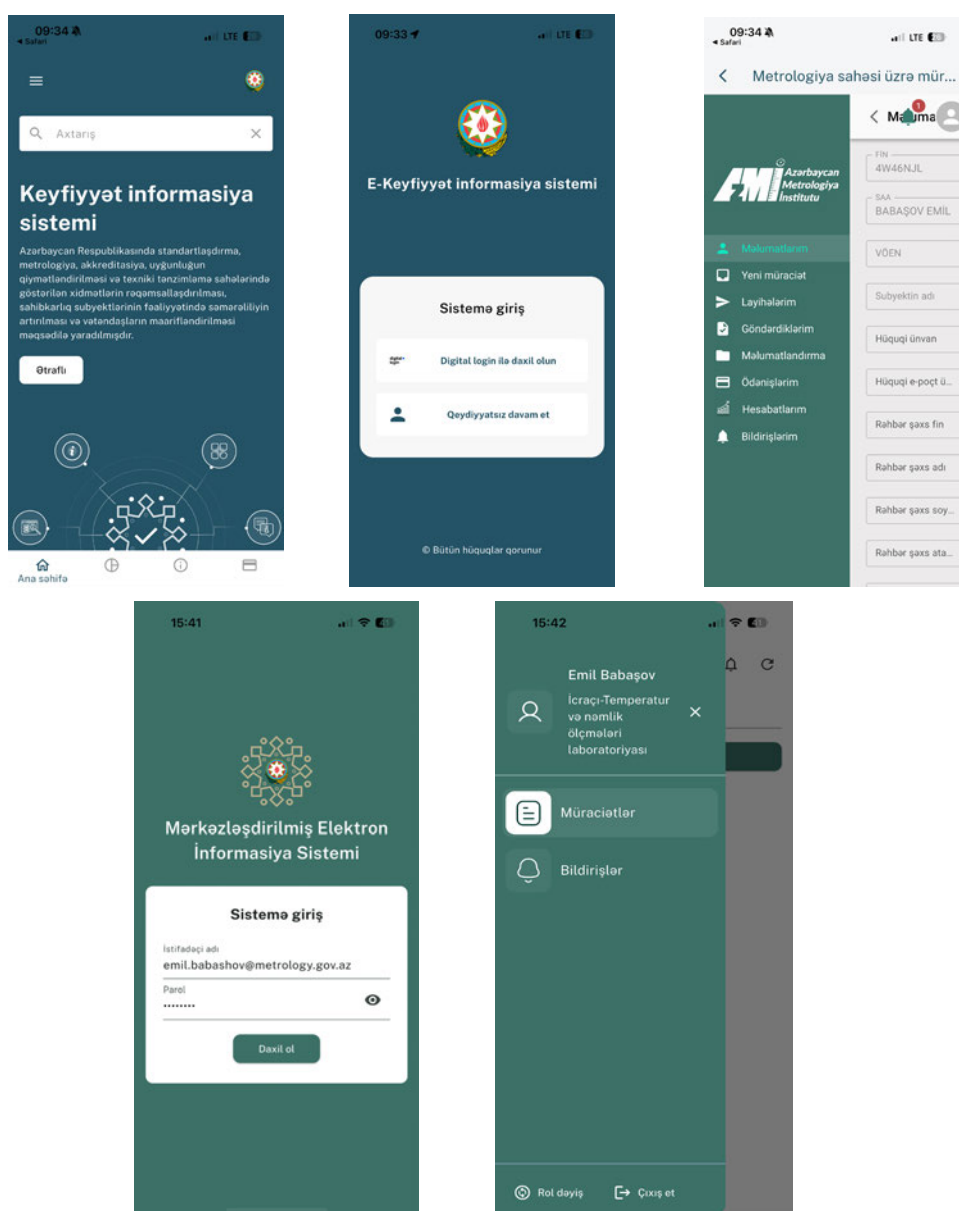


Figure 1. Screenshots of the AzMI Metrology mobile application for digital access to metrology services and requests for customers, and operational tasks for employees. (a) For customers – the home page, login screen, and the service request submission form for metrology services; (b) For executors – a separate centralized electronic information system with a login screen and a “Requests” section.

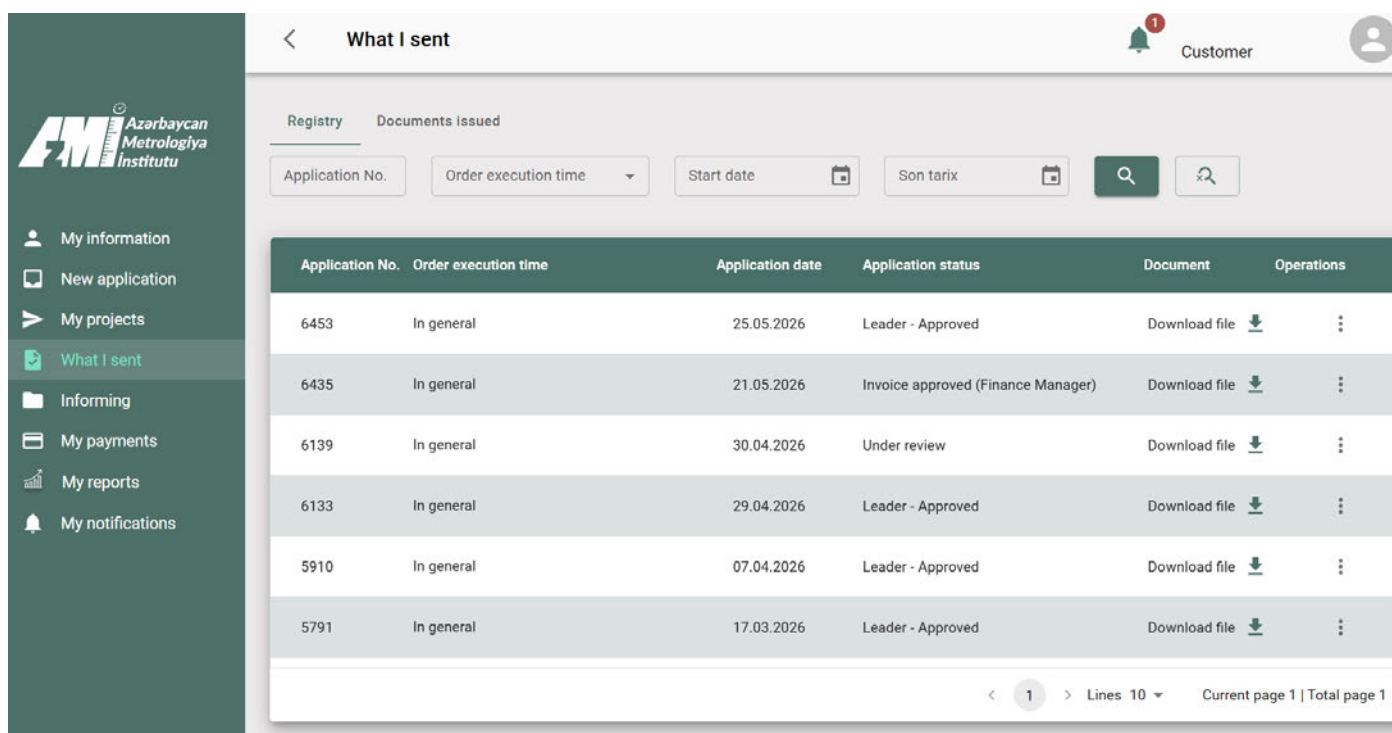


Figure 2. A screenshot of the status page for the AzMI Metrology Submodule where customers can monitor the status of their requests in real time.

A Quantifiable Impact

The implementation of the Metrology Submodule has significantly improved the organization and management of metrological services provided by AzMI. The digitalization of all stages, from service request submission to result delivery, has enabled faster, more accessible, and more efficient service provision. Electronic submission and processing of requests have streamlined application management, reducing administrative workload and service delivery times. Overall, the intervention has led to an estimated 50 % reduction in average turn-around time for service requests, while administrative workload has decreased by approximately 80 % due to the automation of document generation and digital workflow management. Customers can now monitor the status of their requests in real time, increasing transparency and improving access to information throughout the service process (see **Figure 2**).

The introduction of electronic contracts and invoices has fully digitized document circulation and reduced reliance on paper-based documentation. Automatic generation, electronic delivery, and digital signing of contracts and invoices have accelerated workflows, reduced operational costs, and improved resource efficiency.

It is estimated that the introduction of electronic contracts, invoices, and digital certification documents has reduced paper-based document processing by approximately 70–80 %, significantly reducing administrative effort and operational costs. Document preparation and circulation times have improved by around 50–60 % due to automation and electronic workflows, ensuring faster generation, delivery, and storage of official metrological documents. The electronic generation and delivery of verification certificates and marks, notices of non-compliance, calibration certificates, and metrological attestation certificates have optimized the processes for document preparation, storage, and retrieval.

At the same time, the reliability, security, and metrological traceability of issued documents have been significantly strengthened. The risk of manual data-entry errors has been significantly reduced by automatically generating documents from service request data. The use of electronic signatures, centralized storage, and complete audit trails has further strengthened document integrity, authenticity, security, and metrological traceability.

The establishment of a centralized database has enabled comprehensive management of all metrological service information. Service requests, electronic contracts, invoices, verification and calibration results, certificates, and related documents are now maintained within a single platform, significantly enhancing data accessibility, monitoring, and analytical capabilities. The launch of the mobile application has further improved the accessibility of metrological services. Customers and institute employees can perform service-related operations remotely, access information instantly, and continuously monitor processes. This has increased service flexibility and improved user satisfaction. To measure customer satisfaction, AzMI has implemented an electronic service quality assessment form. After each service request is completed, customers automatically receive an SMS with a link to the survey, inviting them to evaluate the quality of the service. The feedback collected through this mechanism is used to monitor customer satisfaction, identify areas for improvement, and support the continuous enhancement of service delivery. Furthermore, this has facilitated evidence-based decision-making and strengthened institutional oversight and reporting.

The implemented digital solutions have reduced risks associated with human error, improved data accuracy and integrity, and ensured full process traceability. Access to metrological services has expanded for citizens, businesses, and public institutions, while transparency, accountability, and operational efficiency have significantly improved. As a result of the project, the delivery and management of metrological services have been successfully transformed through digitalization, leading to greater transparency, traceability, accessibility, and efficiency across the entire service lifecycle.

POC: Ali Muradov, ali.muradov@metrology.gov.az





Improved Dosimetry Enables Online MRI-guided Radiotherapy

VSL, together with other NMI, DI and academic partners, has established trusted absolute dosimetry to enable online MRI-guided radiotherapy and enhance cancer patient treatment

The National Metrology Institute in The Netherlands (VSL), Coordinator Netherlands (NL)



The Challenge

Magnetic resonance imaging (MRI) guided radiotherapy (MRgRT), which combines high-resolution imaging with radiation therapy, has shown promise as an innovative non-invasive cancer treatment. However, existing methods for delivering accurate radiation doses were incompatible with a prototype MRgRT device, so-called MR-linacs. Without a measurement method compatible with the new technology to ensure delivery of accurate radiation doses, patient trials could not proceed.

In 2022, the number of new cancer diagnoses was estimated at 20 million, of which half of the patient's received radiotherapy in the course of their treatment.¹ Here radiotherapy, which is a non-invasive treatment, is used either as stand-alone treatment or in combination with more invasive treatments such as chemotherapy and surgery. In radiotherapy a harmful dose of invisible ionizing radiation is delivered to the tumour. Effective radiotherapy relies on delivering a radiation dose that is sufficient to destroy tumour cells while minimizing side effects, due to the unavoidable dose that is delivered to healthy tissue.

To optimize this balance, it is important to see what you treat. Magnetic resonance imaging-guided radiotherapy, which integrates high-resolution Magnetic Resonance Imaging (MRI) with a radiotherapy device via a linear accelerator (Linac), or MR-linacs, developed in collaboration with the medical device industry and hospitals, fulfils this demand.

Critical to successful radiotherapy is the delivery of accurate radiation doses, with clinical evidence that the dose delivered to the patient must be within 2.5 %.² Prior to the clinical introduction of radiotherapy equipment, hospitals must calibrate the monitoring device of this equipment by measuring the radiation dose under reference conditions, using secondary standard ionization chambers. However, the existing methods for reference dosimetry, which safeguard the calibration chain from primary dosimetry standards at NMIs to secondary standards and field standards used in clinical devices, could not work with MR-linacs as the presence of the MRI scanner magnetic fields would interact with treatment beams and ionization chambers. Without recognized methods to ensure accurate measurements of radiation doses, advancement to patient trials and, eventually, clinical treatments could not be given the go-ahead.



¹Zhu H, et al. Global radiotherapy demands and corresponding radiotherapy-professional workforce requirements in 2022 and predicted to 2050: a population-based study. The Lancet Global Health, 2024; 12, e1945-e1953

²International Commission on Radiation Units and Measurements (ICRU) 1976, Determination of Absorbed Dose in a Patient Irradiated by Beams of X or Gamma Rays in Radiotherapy Procedures. ICRU Report 24, Bethesda, Maryland and Washington DC.

The Solution

In the EMRP project *MRI Safety*,³ VSL showed the potential of a newly designed portable water calorimeter as a primary standard for absorbed dose measurements in the presence of magnetic fields. In the context of the EMPIR project *Metrology for MR guided radiotherapy*,⁴ VSL optimized the water calorimeter to serve as a primary standard for the prototype MR-linac. The calorimeter was characterized, tested, and used for the first time worldwide for the measurement of radiation dose in an Elekta Unity MR-linac at UMCU, with and without a magnetic field present. By comparison with the optimized calorimeter, calibration coefficients for several secondary standard ionization chambers were determined. Based on this dataset, device-specific correction factors to account for the presence of magnetic fields were determined for secondary standard ionization chambers commonly used by clinicians for reference dosimetry.

A method to deliver reference dosimetry in MRI-linacs was devised by applying these correction factors to existing methods, enabling clinicians to calibrate their MRI-linac's beams based on secondary standard ionization chambers, as is more commonly used in practice.

Two other methods to determine device-specific correction factors were devised, accounting for magnetic field orientation and the beam axis. The first method, developed by PTB, uses Monte Carlo simulations coupled with finite element modelling. The second method developed by NPL uses measurements with solid-state dosimeters. Both methods showed good consistency with the water calorimeter-measured correction factors. The resulting methods and datasets for the correction factor have been evaluated in a review paper.⁵ This has served as the basis for two protocols for reference dosimetry in MRI-linacs.^{6,7}

A Quantifiable Impact

Ionization chambers calibrated to the optimized primary standard were used to deliver the first clinical treatments with an MR-linac, an Elekta Unity at UMCU, in the First in Man study,⁸ supported by the Dutch Cancer Society. Four spine cancer patients were treated from May to July 2017. Absolute doses post-treatment were established as highly accurate, no adverse events were reported by November 2017, and palliative effects were achieved in all treated patients, demonstrating the clinical feasibility of MRgRT. The results of the research enabled clinical trials using the prototype MR-linac device to proceed, while enabling metrology institutes to use the results to type-test ionization chambers and deliver proficiency testing (PT) services.

The Elekta Unity gained its CE mark in June 2018, providing clearance for commercial sales and clinical use across Europe. With approval from the U.S. Food and Drug Administration (FDA) and China's National Medical Products Administration (NMPA), regulatory clearance was subsequently extended to over 75 countries. To date, more than 240 MRI linacs have been installed worldwide, representing an annual treatment capacity of 48 000 patients.

Since the CE mark was granted, several clinical trials have demonstrated the benefit of MRgRT. For prostate cancer, positive effects from MRgRT on treatment outcome have been reported.^{9,10} For selected patient groups with renal cancer, the effectiveness of MRgRT was demonstrated to be on the same level as invasive treatments, thereby offering a non-invasive alternative to invasive treatments such as surgery.¹¹ In addition, MRgRT has been used to reduce treatment time from 30 fractions of 10 minutes to 2 fractions of 45 minutes,^{12,13} representing a significant economic improvement.

³EMRP Project HLT06 MRI safety, "Metrology for next-generation safety standards and equipment in MRI"

<https://www.euramet.org/research-innovation/search-research-projects/details/project/metrology-for-next-generation-safety-standards-and-equipment-in-mri>

⁴EMPIR Project 15HLT08 MRgRT, "Metrology for MR guided radiotherapy" <https://www.euramet.org/casestudies/casestudiesdetails/news/absolute-dosimetry-for-mr-linacs>

⁵de Poorter, J et al. 2021 Phys. Med. Biol. 66 05TR02 DOI 10.1088/1361-6560/ab9efe

⁶AAPM task group report 351: Protocol for clinical reference dosimetry in external beam MR-guided radiotherapy. <https://doi.org/10.1002/mp.17884>

⁷Billas, I et al. 2025. Reference dosimetry for MRI-Linacs: an addendum to the 2020 IPEM code of practice for high-energy photon therapy dosimetry. Phys. Med. Biol. 70 085007. DOI 10.1088/1361-6560/adc0e0

⁸Raaymakers, BW et al. 2017 Phys. Med. Biol. 62 L41 DOI 10.1088/1361-6560/aa9517

⁹Kishan AU, et al. Magnetic Resonance Imaging Versus Computed Tomography Guidance for Stereotactic Body Radiotherapy in Prostate Cancer: 2-year Outcomes from the MIRAGE Randomized Clinical Trial. Eur Urol. 2025 Jun; 87(6):622-625. DOI: 10.1016/j.eururo.2024.10.026

¹⁰Hall, WA et al. Daily Online Adaptive Recontouring for Prostate Cancer Using 1.5 Tesla Magnetic Resonance Image Guidance (MRgRT) Improves Patient Reported Urinary Symptoms, A Prospective, International, Observational Cohort Study (NCT04075305), International Journal of Radiation Oncology Biology Physics, Volume 123, Issue 1, Supplement, 2025, Pages S81-S82. <https://doi.org/10.1016/j.ijrobp.2025.06.1104>

¹¹Siva S, et al. Ultra-hypofractionated stereotactic ablative body radiotherapy for primary renal cell carcinoma: 5-year outcomes from a pooled analysis of the FASTRACK trials. Lancet Oncol. 2026 Jun; 27(6):721-728. DOI: 10.1016/S1470-2045(26)00170-1

¹²Lalmahomed TA, et al. Two-fraction Ultrahypofractionated Radiotherapy with focal B0ost for intermediate-risk, localized prostate cancer (TURBO): study protocol of a phase II, randomized controlled clinical trial. Trials. 2025 Dec 29;26(1):586. DOI: 10.1186/s13063-025-09297-5.

¹³Cooper S, et al. HERMES: Randomized Trial of 2-Fraction or 5-Fraction Magnetic Resonance Imaging-Guided Adaptive Prostate Radiation Therapy. Int J Radiat Oncol Biol Phys. 2025 Nov 1;123(3):773-782. DOI: 10.1016/j.ijrobp.2025.05.008

International Basic Safety Standards serve as the basis for national legislation regarding medical exposures to ionizing radiation. These standards require that all sources giving rise to medical exposure be calibrated to appropriate quantities using internationally or nationally accepted protocols, and that calibration of all dosimeters used for patient dosimetry and for source calibration be metrologically traceable to a standards dosimetry laboratory. The developed primary standards, characterized secondary standards, data sets of correction factors, and methods for clinical dosimetry are the basis for demonstrating compliance with these regulations.

The establishment of reliable absolute dose measurements advanced the development of MRgRT and clinical acceptance of MR linacs, enabling hospitals to deploy this advanced form of radiotherapy. This trusted absolute dosimetry and superior imaging technique has resulted in more precise, personalized cancer treatment and potentially improved quality of life.

Acknowledgments

Funding for the research detailed in this case study was provided by the European Metrology Programme for Innovation and Research (EMPIR), co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

A complete list of participants is provided on the EMPIR Project 15HLT08 MRgRT page.¹⁵

POC: Jacco de Pooter, JdPooter@vsl.nl



¹⁵Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards. 2014. <https://doi.org/10.61092/iaea.u2pu-60vm>.
¹⁶EMPIR Project 15HLT08 MRgRT, "Metrology for MR guided radiotherapy" <https://www.euramet.org/casestudies/casestudiesdetails/news/absolute-dosimetry-for-mr-linacs>.



UNITED NATIONS
INDUSTRIAL DEVELOPMENT ORGANIZATION

Bureau
International des
Poids et
Mesures



Enhancing Air Quality Measurement Accuracy to Support Public Health and Climate Action

MolAT has developed metrologically traceable measurement services to monitor indoor and outdoor air quality, thereby underpinning the health of the UAE population

*Ministry of Industry and Advanced Technology (MolAT)
United Arab Emirates (AE)*



The Challenge

Air quality is a critical environmental and public health issue, directly impacting human well-being and environmental sustainability. In the United Arab Emirates (UAE), rapid urbanization and industrial growth have heightened the need for reliable, accurate air quality data to support effective environmental and health policies. Prior to the intervention, there were significant challenges, including inconsistent measurement practices, a lack of metrological traceability, and variability in measurement accuracy across laboratories and environmental monitoring stations. A unified national framework was needed to ensure that air quality data were metrologically traceable, accurate, and comparable.

Accurate air quality measurements are essential for protecting public health and supporting environmental policy. The key issue was the lack of reliable and consistent measurements of air quality indicators, including particulate matter (PM_{2.5}, PM₁₀), and air pollutants such as ozone (O₃), carbon dioxide (CO₂), and nitrogen dioxide (NO₂). Inconsistent measurement practices and gaps in laboratory calibrations and monitoring stations posed risks to data reliability and policy effectiveness in the UAE. These issues directly affected data reliability and limited the effectiveness of evidence-based decision-making.

The main challenges observed included significant variability in measurement results between laboratories, pervasive use of uncalibrated measurement instruments, the absence of structured proficiency testing programmes for testing laboratories, and limited compliance with international accreditation standards. These gaps in the metrological system directly reduced confidence in environmental monitoring data from testing laboratories. Subsequently, this led to significant challenges in evaluating environmental policies and disseminating international alignment and reporting standards. Ultimately, these significant gaps were identified as potential risks to public health, prompting the UAE government to take action to address them.

The Solution

A technical programme for air quality measurements was developed by the Ministry of Industry and Advanced Technology (MoIAT) to ensure proper control and oversight of air quality monitoring stations and laboratories that conduct these measurements, thereby ensuring the accuracy, reliability, and harmonization of measurement results in accordance with approved technical requirements. Coordination and integration among federal and local government entities, along with collaboration with private sector partners, led to the development of a national technical regulation for air quality monitoring that aligned with the National Measurement System. This further led to the development and implementation of UAE Cabinet Decision No. 86 of 2023 on the Technical Regulation for Air Quality Measurement Control, which establishes a national regulatory framework for air quality measurement control. The regulation directly improves the efficiency and accuracy of measurements of air-quality parameters, such as ozone, carbon dioxide, nitrogen oxide, sulphur dioxide, and other environmental pollutants.

MoIAT's accreditation department is responsible for ensuring the metrological traceability of calibration activities by accrediting laboratories in accordance with the requirements of the international standard ISO/IEC 17025, which includes specific provisions for achieving metrological traceability in measurements and calibrations. In addition, the technical regulation for air quality measurements and testing mandates that all laboratories operating in this field obtain national accreditation. This requirement ensures laboratory competence and the reliability of measurement and testing results in accordance with approved international standards and requirements. A national-level technical working group implemented the regulation, which included mandatory calibration of all air quality instruments, compliance with ISO/IEC 17025 accreditation requirements for testing laboratories to ensure traceability to the International System of Units (SI), coordination with environmental monitoring stations, and the requirement for proficiency testing (PT) programmes for laboratories and monitoring stations utilizing international standards (i.e., ISO/IEC 17043).

All air quality measurements were required to be metrologically traceable to national and international standards.

The rollout of the nationwide proficiency testing infrastructure was deemed essential for appropriate oversight of laboratories and monitoring stations across the UAE. An air quality measurement PT programme consisting of 50 participants, including 47 air quality monitoring stations and three testing laboratories, who participated in the PT rounds, was conducted between June 2025 and January 2026.

Performance evaluation was carried out using the En-score methodology, in which results with $|En| < 1.0$ were considered satisfactory, while those with $|En| \geq 1.0$ were considered unsatisfactory and required corrective action. Ten measurands were evaluated, including sulphur dioxide (SO_2), carbon dioxide (CO_2), methane (CH_4), nitrogen oxides (NO_x), BTEX compounds, and hydrogen sulphide (H_2S). A snapshot of the real-time collection of several measurands at an air monitoring station is provided in **Figure 1**.

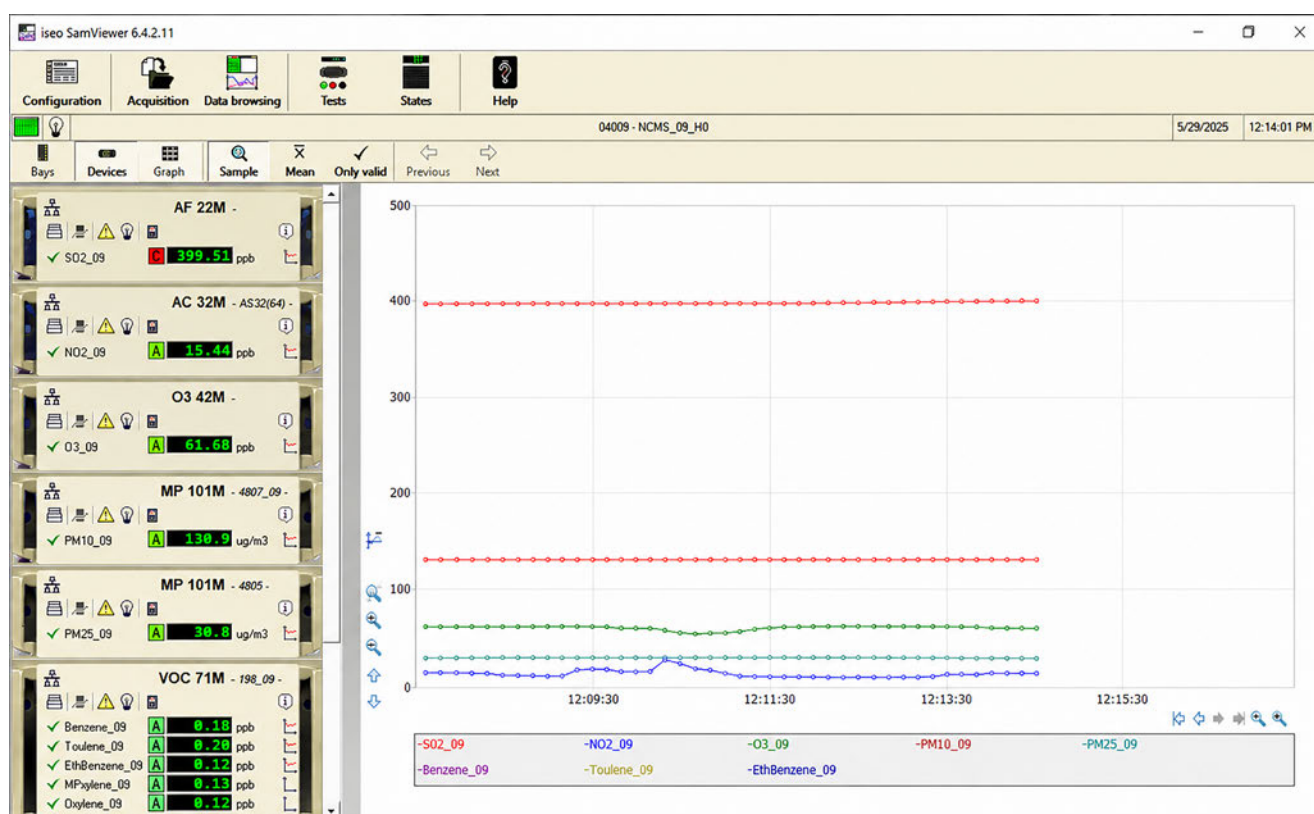


Figure 1. A screen capture of the data management system for tracking the real-time measurements of ambient air quality parameters, including sulphur dioxide (SO_2), nitrogen dioxide (NO_2), ozone (O_3), particulate matter (PM10 and PM2.5), volatile organic compounds (VOCs), and BTEX compounds (benzene, toluene, ethylbenzene, and xylenes).

This multi-stakeholder effort involved a wide range of authorities and ministries, including the Ministry of Industry and Advanced Technology (MoIAT), the Ministry of Climate Change and Environment (MOCCA), the National Center of Meteorology, local environmental authorities, and national accreditation bodies.

A Quantifiable Impact

From the outset of the UAE's Air Monitoring programme, metrology-based data were collected from 73 environmental monitoring stations across the UAE. A campaign to apply metrologically traceable calibrations to all monitoring instruments was implemented across all UAE monitoring stations, utilizing ISO/IEC 17025-accredited laboratories. An example of a monitoring station is provided in **Figure 2**.



Figure 2. Air monitoring stations are used for proficiency testing (PT) of outdoor ambient air quality monitoring, conducted in industrial areas.

At the start of the programme in 2023, it was determined that only approximately 75 % of the measurement instruments used in laboratories measuring indoor and outdoor air quality were properly calibrated. Following the implementation of this programme based on regulatory audits and compliance assessments performed by MoIAT, over a short period, it has been verified that 100 % of instruments are calibrated using metrologically traceable national standards and procedures under a national quality system. Not only has traceability to the SI been established for air quality measurements, but this intervention has also contributed to improved measurement consistency and comparability across monitoring facilities.

The capabilities of the testing laboratories and environmental monitoring stations were further validated through interlaboratory comparisons via the PT programme and through implementation of international documentary standards for uncertainty and measurement comparability (ISO/IEC 17025 General requirements for the competence of testing and calibration laboratories and ISO/IEC 17043 Conformity assessment – General requirements for the competence of proficiency testing providers). A total of 50 participants, including 47 air quality monitoring stations and three testing laboratories, participated in the PT round conducted between June 2025 and January 2026. Performance evaluation was carried out using the En-score methodology, in which results with $|En| < 1.0$ were considered satisfactory, while those with $|En| \geq 1.0$ were considered unsatisfactory and required corrective action.

In contrast, some parameters demonstrated excellent analytical performance and full compliance among all participants. For instance, nitrogen oxides (NO_x) achieved 100 % satisfactory performance, reflecting excellent comparability and consistency between laboratories and monitoring stations. Similarly, BTEX compounds and hydrogen sulphide (H_2S) also showed very strong analytical reliability and compliance. For the sulphur dioxide (SO_2) assessment, most participants achieved satisfactory En-scores, while only a limited number of participants showed deviations requiring corrective action. Similar trends were observed for carbon dioxide (CO_2) and methane (CH_4), with a small number of participants ($n=2$ and $n=4$, respectively) producing En-scores exceeding the acceptance criteria, suggesting possible calibration or analytical bias. Methane (CH_4) recorded the highest number of unsatisfactory results among the assessed parameters.

Overall, the participation of testing laboratories in the PT programme for determining indoor and outdoor air quality has resulted in 95 % satisfactory outcomes. The high satisfaction rate reflects robust calibration practices, reliable analytical methodologies, and strong comparability among participating laboratories and monitoring stations. At the same time, the limited number of unsatisfactory results helped identify areas requiring targeted improvement, particularly in calibration procedures, uncertainty estimation, instrument maintenance, and method validation.

The national metrology system of the UAE also achieved a significant milestone in 2023, with the recognition of its metrology and calibration capabilities for over 41 CMCs by the Emirates Metrology Institute (EMI), as published in the BIPM KCDB. This covered physical measurement areas such as frequency, electrical, temperature, ionizing radiation, and mass, enabling the metrology laboratories to conduct metrological traceability measurements. This fundamental capability enabled the Ministry of Industry and Advanced Technology (MoIAT) to develop a national-level testing programme for air quality monitoring and to review and enhance the performance of environmental metrology laboratories and monitoring stations across the UAE. These internationally-recognized programmes were enhanced through specialized technical committees operating under the auspices of GULFMET and were launched in collaboration with accreditation bodies and local environmental departments to drive sustainable industrial development nationwide.

Furthermore, the legal and scientific metrology achievements of the National Measurement System in the UAE have underpinned technical regulations that support public health and safety requirements and ultimately ensure fairness and accuracy in measurements, including those used in commercial transactions.

The collaborative effort between federal and local authorities clearly demonstrated the critical role of metrology in environmental governance and sustainable industrial development. This was illustrated by the importance and value of metrologically traceable calibration and accreditation processes in routine laboratory and monitoring facilities. Overall, the metrological intervention through the PT programme has improved measurement accuracy and consistency of national air quality data, increased confidence in monitoring systems, reduced errors, and aligned practices with international standards.



Figure 3. The collaborative team with members from MoIAT and the UAE's Ministry of Climate Change and Environment and representatives from local environmental authorities and national accreditation bodies at an air monitoring station managed by the UAE's National Center of Meteorology.

Data from reliable, metrologically traceable air quality measurements generated by monitoring stations and testing laboratories also support climate action policies by providing precise information on pollutant concentrations to assess emission trends and mitigation measures, and to evaluate the effectiveness of overall emission-reduction policies. These high-quality datasets also contribute to atmospheric and climate assessments by improving the accuracy of emission inventories and providing reliable inputs for environmental models and climate-related analyses. This metrological intervention has strengthened national air quality policies and regulatory enforcement, while also supporting public health policy and improving public health protection. This effort has also increased trust in environmental data, thereby informing and strengthening the UAE's evidence-based environmental policymaking and promoting the reduction of pollutants to support climate action and improve air quality and public health.

Acknowledgements

This initiative was developed and implemented through collaboration between the UAE's Ministry of Industry and Advanced Technology (MOIAT), the UAE's Ministry of Climate Change and Environment, and the local environmental authorities and national accreditation bodies.

POC: Amina Hassan Mohammad AlBastaki,
aalbastaki@moiat.gov.ae





UNITED NATIONS
INDUSTRIAL DEVELOPMENT ORGANIZATION

Bureau
International des
Poids et
Mesures



Accurate and Traceable Measurements for Photovoltaic (PV) Systems: Ensuring Electrical and Power Performance and Quality

INMETRO maintains a comprehensive metrology programme to support the reliability of solar energy systems, including the calibration of reference solar cells and power quality instruments, as well as technical support for accredited photovoltaic (PV) testing laboratories

*National Institute of Metrology, Quality and Technological (INMETRO)
Brazil (BR)*



The Challenge

Brazil has experienced rapid growth in solar photovoltaic (PV) adoption over the past decade, driven by national policies such as energy auctions and distributed generation incentives. Solar energy is now one of the fastest-expanding sources in the country's electricity mix, contributing to national goals of diversifying energy supply and meeting climate commitments. Solar energy now accounts for approximately 25 % of the national electricity matrix, with installed capacity exceeding 44 GW. However, this expansion has also revealed three critical challenges for Brazilian metrological infrastructure: 1) prevention of fake power ratings, 2) assurance of PV inverter power quality, and 3) metrological traceability through new calibration services for Brazilian testing laboratories.

First, the circulation of solar PV panels that claim exaggerated or false power ratings has become a significant concern for Brazil's energy infrastructure. Many imported modules claim higher efficiency than they deliver, leading to underperformance in households, businesses, and utility-scale projects. This undermines consumer trust, creates financial risks for investors, and threatens Brazil's ability to meet its renewable energy targets. Further, the widespread integration of PV inverters poses technical challenges for proper grid integration, including harmonic distortion and voltage fluctuations (i.e., flicker). Beyond grid stability, these phenomena can affect human health, as excessive flicker can cause eye strain, fatigue, visual discomfort, and even convulsions in people, especially those who are photosensitive.

Metrology can address this challenge by establishing standardized, metrologically traceable testing of PV modules' performance (i.e., solar panels). Brazil's National Metrology Institute (INMETRO) and accredited laboratories are primed to ensure that panels meet declared specifications. This strengthens compliance in energy auctions, protects consumers in distributed generation, and builds confidence in the renewable energy market.

Such testing infrastructure is specified by the regulation of PV modules and their components, established by Inmetro Ordinance No. 140/2022,¹ later complemented by Inmetro Ordinance No. 515/2023,² which mandates safety and performance certification for modules above 5 Wp, inverters, and batteries, setting a minimum quality and reliability level for equipment placed on the national market.

This regulatory framework also relies on a consolidated laboratory infrastructure that currently comprises only ten accredited calibration laboratories and eight accredited testing laboratories within the PV supply chain. These testing laboratories currently base their measurements on robust, metrologically traceable standards. A calibration service for reference solar cells will require full metrological traceability to national radiometric standards and alignment with international PV standards. Further, the PV inverters will need to be tested in accredited laboratories to comply with specific power quality emission limits (IEC 61000 series), including harmonic measurements as per IEC 61000-4-30³ and flicker interference with flickermeters as per IEC 61000-4-15.⁴ To support such measurements, there is a need to broaden the scope of power harmonics measurements and to calibrate flickermeters, a new service not yet available in Brazil.

The opportunity is clear: accurate measurement and certification of PV panels and inverters will not only prevent fraud but also accelerate Brazil's transition to clean energy, making this a nationally relevant case study with sectoral impact across energy, industry, and sustainability.

¹Inmetro Ordinance No. 140/2022: Requisitos de Avaliação da Conformidade para Equipamentos de Geração, Condicionamento e Armazenamento de Energia Elétrica em Sistemas Fotovoltaicos: <http://sistema-sil.inmetro.gov.br/rtac/RTAC002957.pdf>

²Inmetro Ordinance No. 515/2023: alters Ordinance 140/2022: <http://sistema-sil.inmetro.gov.br/rtac/RTAC003010.pdf>

³IEC 61000-4-30: Testing and measurement techniques - Power quality measurement methods

⁴IEC 61000-4-15: Electromagnetic Compatibility (EMC) - Flickermeter - Functional and Design Specifications.

The Solution

To address these challenges, INMETRO worked with the General Coordination for Laboratory Accreditation (CGCRE) to establish ISO/IEC 17025-accredited testing laboratories and to introduce metrologically traceable calibration services for solarimeters, pyranometers, reference PV modules, and power quality meters for PV inverters. This was followed by the implementation of certification programmes requiring manufacturers and importers to submit panels and inverters for testing before commercialization. In addition to these accredited laboratories, INMETRO's Inspection Division established its own testing laboratory, as the responsible unit for market surveillance in Brazil, to evaluate the power output of PV systems. Items that failed to meet declared performance (i.e., possessing 'fake power') are barred from auctions and consumer markets. All calibration measurements complied with consolidated standards, such as the Brazilian Association of Technical Standards (ABNT) NBR IEC 61.215-2,⁵ to ensure accuracy and comparability. See **Figure 1** for an overview of INMETRO's metrology programme to provide reliable solar energy for Brazil.

In 2026, INMETRO designed and implemented an experimental differential spectral responsivity (DSR) system to calibrate reference solar cells, linking their spectral irradiance responsivity directly to the electric substitution cryogenic radiometer as the national primary optical power scale through standard photodetectors. The system comprises a custom Czerny–Turner monochromator with automated wavelength and slit control, a stabilized auxiliary LED illumination system, active temperature control of the reference cell at 25 °C, and characterization of beam spatial uniformity over the active cell area.

⁵Brazilian Association of Technical Standards (ABNT) NBR IEC 61.215-2 Módulos fotovoltaicos (FV) para uso terrestre – Qualificação de projeto e aprovação de tipo – Parte 2
⁶IEC 60904-4:2019, Photovoltaic devices - Part 4: Photovoltaic reference devices - Procedures for establishing calibration traceability.

The calibration is performed in two main steps: 1) measurement of the relative spectral responsivity of the reference cell by comparison with a nationally calibrated photodetector using modulated monochromatic radiation (DSR mode), followed by 2) an absolute spectral irradiance measurement at 546.1 nm with a homogenized integrating-sphere setup to convert the relative curve into absolute spectral responsivity in irradiance mode. Measurement protocols, linearity checks, and uncertainty evaluation were established in accordance with IEC 60904-4:2019,⁶ ensuring full metrological traceability to SI units.

The DSR system measured the relative spectral responsivity of a silicon reference solar cell over 320 nm to 1100 nm, with good repeatability and reproducibility. Spatial non-uniformity of the irradiance field over a 20 mm × 20 mm test area was measured at approximately 0.75 %, comparable to class A+ solar simulators (non-uniformity < 1 %), thereby supporting high-quality irradiance-based calibration. The measured responsivity spectra of reference solar cells agreed with available calibration certificates within expanded uncertainties (normalized error < 1), thus validating the INMETRO DSR system and its metrological traceability chain, illustrated in **Figure 2**.

In addition, in 2025, INMETRO expanded its PV panel testing capabilities to address the metrological traceability of power quality measurements conducted by PV system testing laboratories. This included increasing the operational ranges for single-phase harmonic current measurements ($I < 80$ A) and officially implementing a new calibration service for voltage flickermeters. This intervention now provides high-accuracy traceability to the International System of Units (SI) for these parameters. By establishing this metrological foundation, INMETRO has enabled national laboratories to perform standardized compliance testing of PV inverters in accordance with international IEC standards.



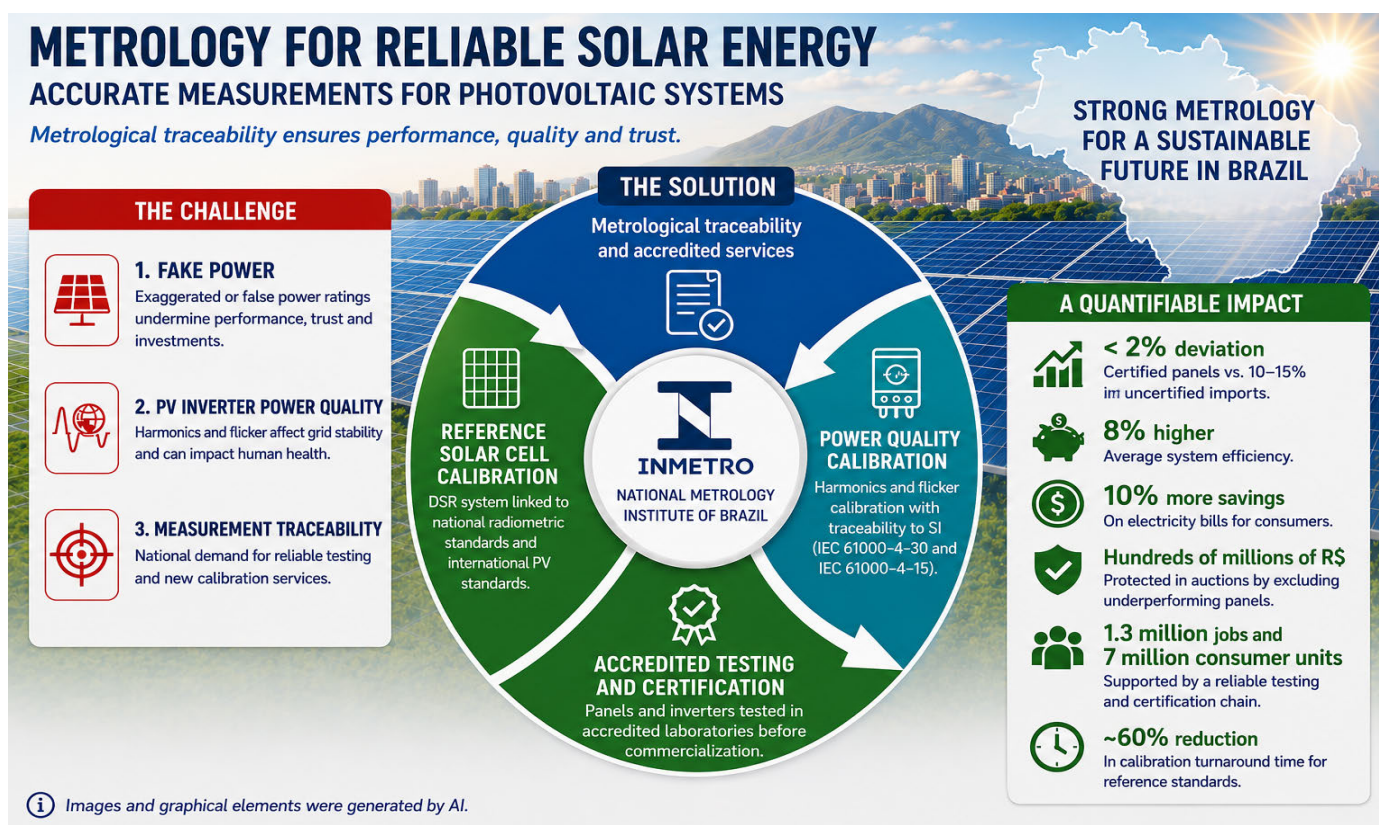


Figure 1. An overview of Inmetro’s metrology programmes to provide reliable solar energy for Brazil, summarizing the challenges, the solutions and the quantifiable impacts.

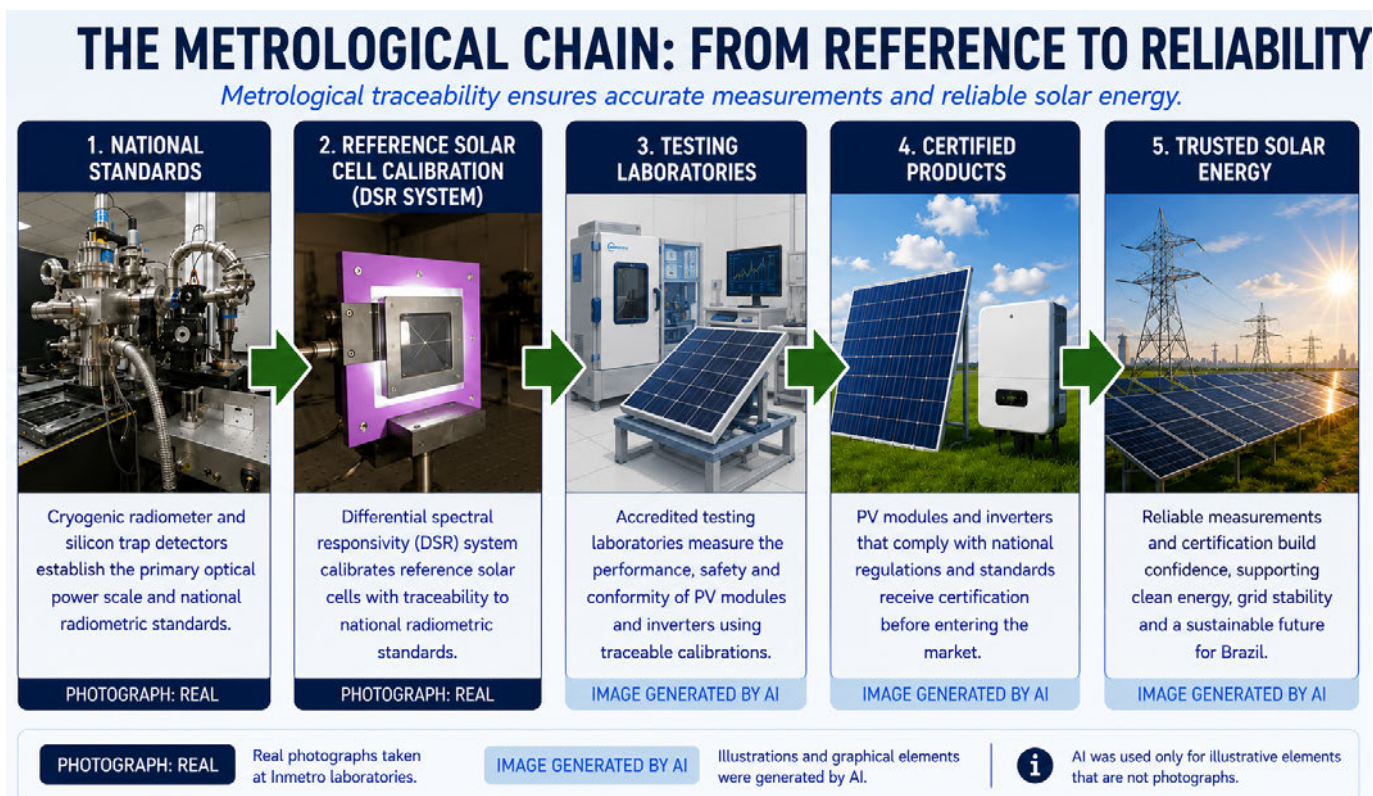


Figure 2. Metrological chain supporting PV measurements in Brazil, from national radiometric standards to trusted solar energy.

A Quantifiable Impact

As a result, consumers who used distributed generation as their energy source saved up to 10 % more on their electricity bills when certified panels delivered the expected output.

Solar panel testing also identified specific products with inflated power ratings, thereby protecting consumers and investors. Energy auctions have also avoided losses estimated at hundreds of millions of reais by excluding underperforming panels, since after the non-conformities of the photovoltaic modules are confirmed, INMETRO cancels the product registrations, preventing their commercialization. The solar panel certification process increased trust in PV technology, encouraging adoption across distributed generation and utility-scale projects and providing market confidence. The integration of this metrology-based programme with policy enforcement energy auctions ensured systemic compliance and alignment with Brazil's renewable energy expansion.

The recently established INMETRO calibration service of reference solar cells also addresses a critical metrological gap for PV testing laboratories by providing accurate, metrologically traceable measurements of solar irradiance and PV device performance, thereby strengthening the reliability of test results and enhancing the effectiveness of Brazil's PV technical regulations. The project's achievements represent a breakthrough for the PV sector in Brazil through capacity building in metrology at INMETRO. This impacts not only the direct calibration cost but also the indirect costs associated with the time required to temporarily export the reference cells. Offering a local calibration service makes metrological traceability accessible to all ten accredited and designated laboratories responsible for efficiency tests on PV modules and panels, as well as for conformity testing and market regulator agents. This project also consolidated the national testing and certification chain for PV inverters. The overall solar industry in Brazil, with 1.3 million jobs and 7 million consumer units, is directly supported by such laboratory infrastructure. By providing a primary reference for flickermeters, INMETRO now meets 100 % of the national demand for metrological traceability for flicker, supporting a network of eight accredited laboratories for flickermeters (including three specifically focused on PV inverters).

Key outcomes include removing technical barriers to trade for hundreds of PV technology providers and ensuring that approximately 1 000 grid-tied inverter models meet the mandatory requirements of national regulations (Ordinance 140/2022).⁷ Furthermore, the intervention reduced the calibration turnaround time for reference flickermeters by an estimated 60 %, eliminating international logistics and customs burdens for the domestic industry. As stated by Cepel, an electrical energy research institution, one of INMETRO's clients:

"We are interested in continuing to perform these calibrations, primarily because, within the Brazilian network, INMETRO is the only laboratory that carries out flicker calibration. This is a parameter of utmost importance in photovoltaic inverter testing."

In conclusion, the implemented calibration services for reference solar cells and power quality meters will enable a complete metrological traceability chain for PV panel and inverter testing in Brazil, with a direct impact on the PV sector, thereby strengthening conformity assessment, improving the reliability of efficiency ratings, and supporting the sustainable growth of the solar energy sector, preserving grid stability and population well-being, and preventing eye-related health problems. Addressing the increasing demand for a smooth transition towards an even greener energy matrix, INMETRO's metrological capabilities and services for testing photovoltaic panels and inverters will underpin a reliable solar energy sector, facilitate the nation's financial investments in this sector, and contribute to sustainable energy production.

This case study has demonstrated a significant economic impact by reducing risk for investors and consumers by ensuring PV systems deliver the promised output. This metrological intervention has also increased social awareness and confidence in renewable energy, accelerating household and institutional adoption. Furthermore, this supports Brazil's clean energy transition, reduces reliance on fossil fuels, and contributes to environmental protection and climate goals. In addition, this ensures that the transition to clean energy remains grid-compatible and protects the health of citizens nationwide, avoiding eye-related health problems like fatigue, headaches and convulsions caused by flicker grid interference from non-compliant equipment.

POC: Silvio Francisco dos Santos,
sfsantos@inmetro.gov.br

⁷Inmetro Ordinance No. 140/2022: Requisitos de Avaliação da Conformidade para Equipamentos de Geração, Condicionamento e Armazenamento de Energia Elétrica em Sistemas Fotovoltaicos: <http://sistema-sil.inmetro.gov.br/rtac/RTAC002957.pdf>

Copyright © 2025 United Nations Industrial Development Organization.

This document has been produced without formal United Nations editing. The designations and the presentation of the material in this document do not imply the expression of any opinion whatsoever on the part of the Secretariat of the United Nations Industrial Development Organization (UNIDO) concerning the legal status of any country, territory, city or area of its authorities, or concerning the delimitation of its frontiers or boundaries, or its economic system or degree of development. Designations such as “developed”, “industrialized” and “developing” are intended for statistical convenience and do not necessarily express a judgment about the stage reached by a particular country or area in the development process. Mention of company names or commercial products does not constitute an endorsement by UNIDO. Although great care has been taken to maintain the accuracy of the information presented, neither UNIDO nor its member states assume any responsibility for consequences which may arise from the use of the material.

Vienna International Centre
Wagramer Str. 5, P.O. Box 300,
A-1400 Vienna, Austria
+43 1 26026-0
www.unido.org
unido@unido.org



UNITED NATIONS
INDUSTRIAL DEVELOPMENT ORGANIZATION