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EURAMET

Driving Impact through Innovation: Highlights from EMPIR

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EMPIR EURAMET
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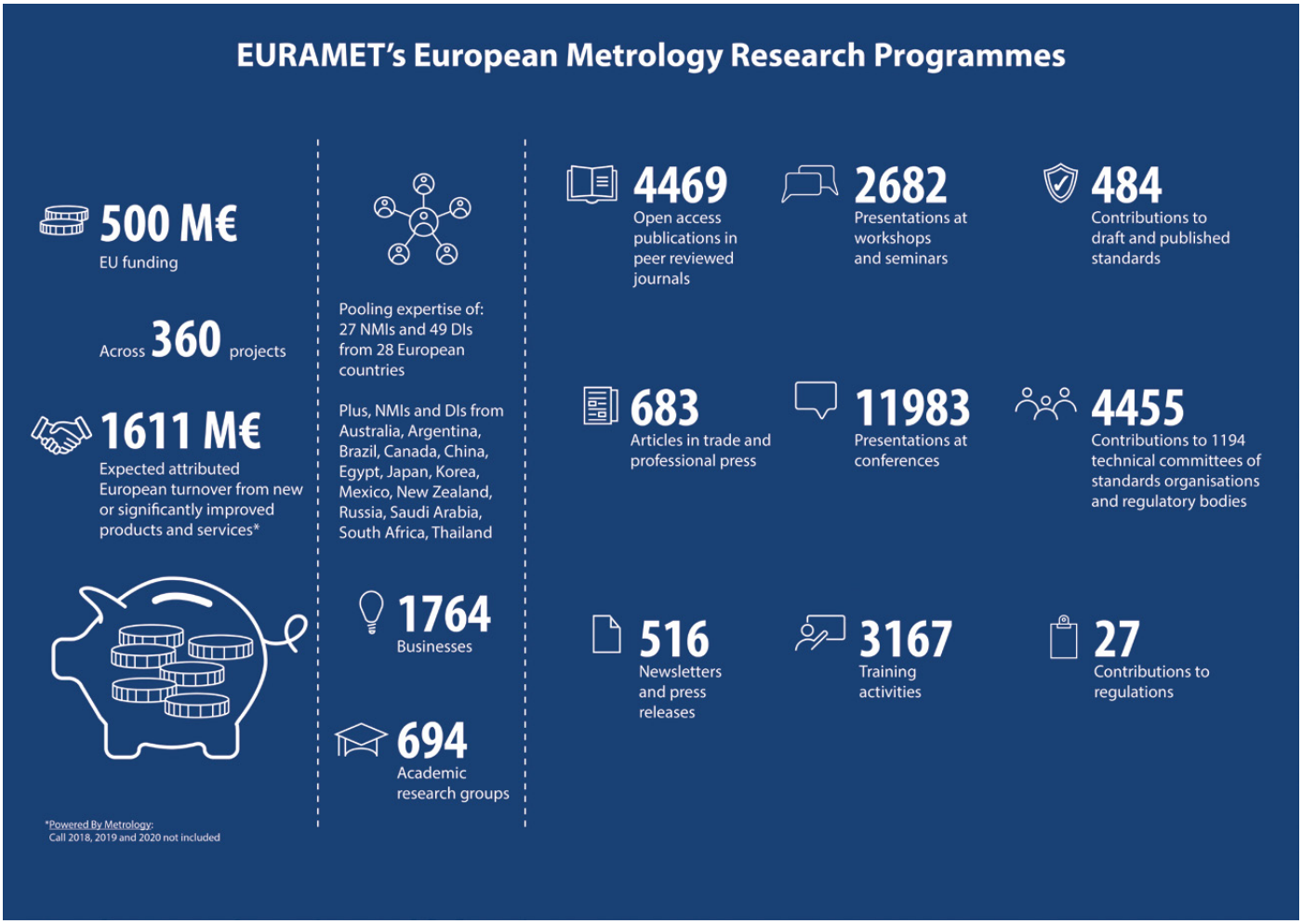
Main Contents

Highlights from EMPIR

The European Metrology Programme for Innovation and Research (EMPIR) coordinated research projects to address grand challenges such as climate change, sustainability and health - while supporting and developing the SI system of measurement units. EMPIR placed emphasis on innovation activities to target the needs of industry and accelerate the uptake of research outputs, supported by standardisation projects crucial for fostering innovation and consumer trust. The programme also advanced fundamental metrology research to drive scientific progress and delivered capacity-building projects to reduce disparities between EU member states with varying levels of measurement capability. EMPIR followed on from the European Metrology Research Programme (EMRP) and its research calls between 2014 and 2020 were supported by 600 million euros, part financed from the EU's Horizon 2020 programme and part financed by EURAMET member countries participating in the programme.



Some of the key outcomes and highlights resulting from the 241 EMPIR projects are detailed within the subsequent pages of this document.

Energy

Europe needs secure, sustainable, and affordable energy, which requires a fundamental transformation of the energy system to a low carbon economy whilst maintaining competitiveness. The EU's Energy Union strategy and 20/20/20 policy were put in place to enable this transition.

The EMPIR Energy projects supported and accelerated the transition through metrological research and development in various areas such as clean and renewable energy, energy gases, energy storage, smart electricity grids and alternative fuels. Through reliable and comparable measurements, the projects also to contributed to normative standards across a wide range of areas relating to energy production or its supply chain. These included ISO 14687 (hydrogen fuel quality), EN 50463 (energy usage rail transportation), IEC 61853 (photovoltaic performance assessment) and the international recommendation for compressed gaseous fuel OIML R139.

Highlights

Clean and renewable energy

Solar power is a vital technology to cut fossil fuel reliance, but photovoltaic (PV) cells need reliable measurements to ensure confidence in their use. The Metro-PV project developed reference devices and measurement procedures to improve power output measurements for PV cells, supporting operators and EU competition in the industry.

Energy gases

Liquid natural gas (LNG) as a fuel is an essential step towards making Europe carbon neutral. The LNG III project developed a new sensor to monitor the liquid natural gas grid, able to measure the composition of LNG in gas engine fuel lines, pipes and other network components to ensure fair trade and improved efficiency.

Energy storage

The MefHySto project developed solutions to support advanced hydrogen measurements and storage technologies. Hydrogen can be generated using excess energy from renewable sources and stored for later use, improving efficiency and stability in the power supply and transport systems without reliance on fossil fuels.

Smart electricity grids/digitisation

Electrical networks are facing new challenges from distributed renewable sources and increased demand, driving transmission levels to ever higher voltages. The FutureEnergy project supported operators to minimise energy losses and improve monitoring through new calibration services and guidance for ultra-high voltages.

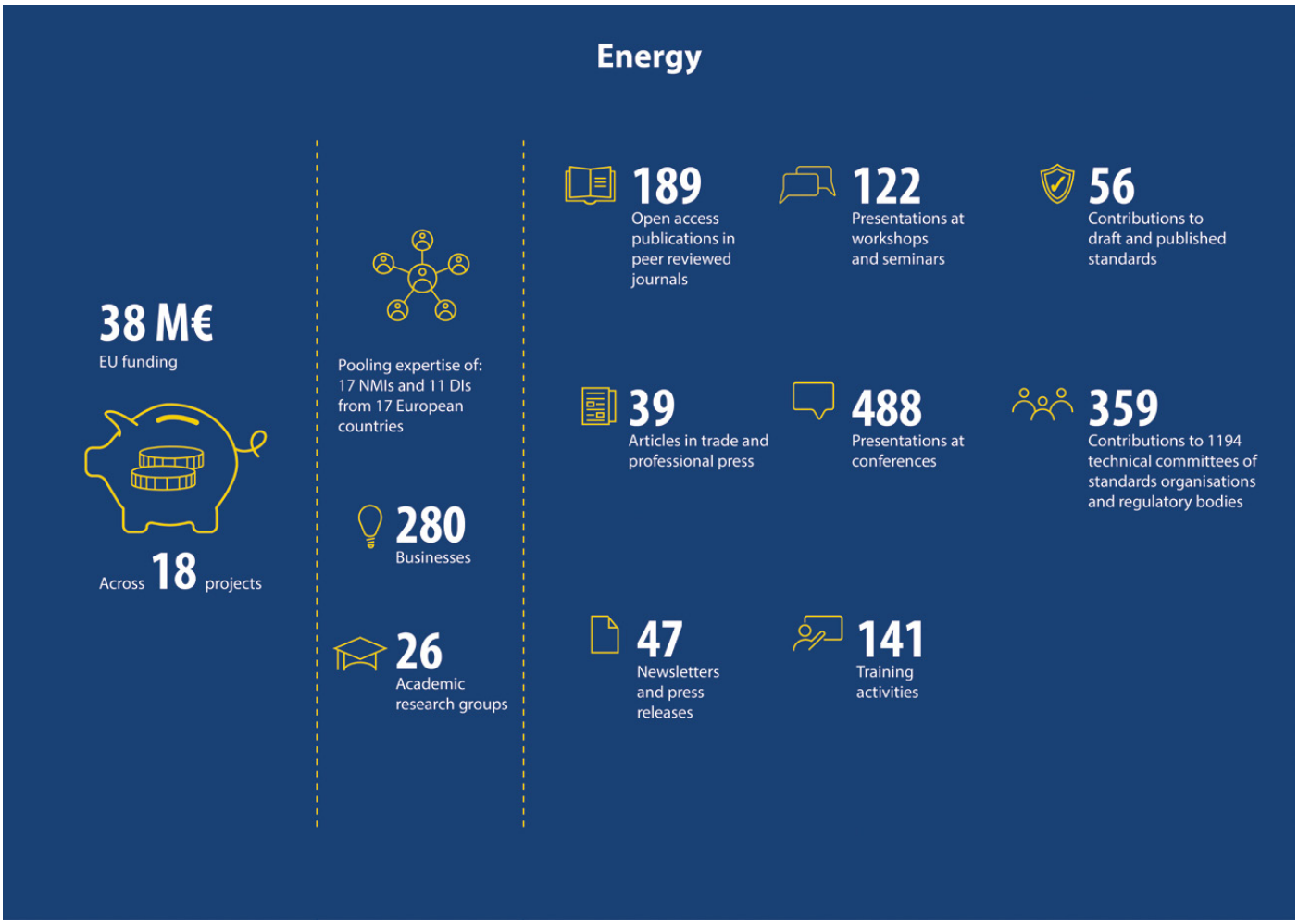
Alternative fuels

Biofuels can be made through renewable methods but, as consumption grows, uncertainty in energy content measurements could result in increasing market distortions. The BIOFMET project developed traceable methods for both solid and liquid biofuels, improving analysis water content, impurities and calorific content.

Annex: Full list of projects

- Metrology for hydrogen vehicles (16ENG01, MetroHyVe)
- Advanced PV energy rating (16ENG02, PV-Enerate)
- Hybrid metrology for thin films in energy applications (16ENG03, HyMet)
- Metrology for smart energy management in electric railway systems (16ENG04, MyRailS)
- Metrology for biomethane (16ENG05, Biomethane)
- Metrology for advanced energy-saving technology in next-generation electronics applications (16ENG06, ADVENT)
- Multiphase flow reference metrology (16ENG07, MultiFlowMet II)
- Metrology for inductive charging of electric vehicles (16ENG08, MICEV)
- Metrological support for LNG and LBG as transport fuel (16ENG09, LNG III)
- Metrology for emerging PV applications (19ENG01, Metro-PV)
- Metrology for future energy transmission (19ENG02, FutureEnergy)
- Metrology for Advanced Hydrogen Storage Solutions (19ENG03, MefHySto)
- Metrology for hydrogen vehicles 2 (19ENG04, MetroHyVe 2)
- High throughput metrology for nanowire energy harvesting devices (19ENG05, NanoWires)
- Metrology of magnetic losses in electrical steel sheets for high-efficiency energy conversion (19ENG06, HEFMAG)
- Metrology for enhanced reliability and efficiency of wind energy systems (19ENG07, Met4Wind)
- Traceable mechanical and electrical power measurement for efficiency determination of wind turbines (19ENG08, WindEFCY)
- New metrological methods for biofuel materials analysis (19ENG09, BIOFMET)

Full details of all projects in the 2016 and Call 2019 Call Energy Theme can be found here:



Summary of outputs from EMPIR Energy theme.

Environment

Environmental metrology is needed to support regulation, protect public health and enable climate action across Europe. The Europe 2020 strategy and the Paris Agreement on Climate laid out the key climate challenges facing Europe, and highlighted the broad benefits of tackling them, from new technological innovation to improved energy security. To address these challenges, the EMPIR Environment projects contributed to a sustainable European metrological infrastructure fit for the future requirements for monitoring climate variables, and pollution sources that effect the citizens quality of life.

This has been enabled through improved climate and environmental monitoring data quality with increased measurement traceability, data standardisation, greater comparability, and the necessary infrastructure for demonstrating compliance with EU regulations. Projects addressed both local European as well as global challenges and participants were successful in fostering increased NMI links to global networks and major institutes influential within the environmental monitoring community, enhancing the EUs standing and capabilities, and enabling ongoing collaborations. In addition, projects worked with monitoring instrument manufacturers to create innovative solutions within the field of environmental measurements.

Highlights

Climate observation and earth monitoring

Remote sensing is a major source of climate data, but sensors face unique conditions and challenges to measurement accuracy. Following successful EMRP projects MetEOC and MetEOC2, MetEOC-3 and MetEOC-4 improved calibration and validation for remote sensors in space and on Earth, helping to deliver vital data needed to tackle climate change.

Essential climate variables (ECVs)

The Global Climate Observing System defines 55 ECVs across the land, atmosphere and ocean which let us understand Earth's climate. EMPIR projects have provided the metrology needed to assess ECVs, such as MetClimVOC which developed new reference materials to measure volatile organic compounds which are known to damage the ozone layer.

Air quality and pollution monitoring

Air quality has profound effects on human health and the environment – 239,000 deaths in the EU were attributable to fine particulate matter (PM) pollution in 2022 alone. The AEROMET II project developed new calibration methods to improve PM detectors, leading to the creation of a new device which can help identify sources of toxic pollutants.

Radiation protection and public health

Complex nuclear events like the 2011 Fukushima nuclear disaster have highlighted the need for rapid, flexible radiation detection methods to protect the public and the environment. The Preparedness project validated handheld radiation detectors which can be deployed from vehicles or mounted on drones and discriminate between natural and man-made radiation.

Green Deal

Cutting emissions by at least 50 % by 2030 is a key priority of the EU Green Deal. The STELLAR project produced reference materials to help monitoring networks identify different kinds of methane – a greenhouse gas with a warming potential 28 times higher than CO_2 –enabling the tracking of natural and anthropogenic sources to verify emissions reporting.

Carbon measurement and auditing

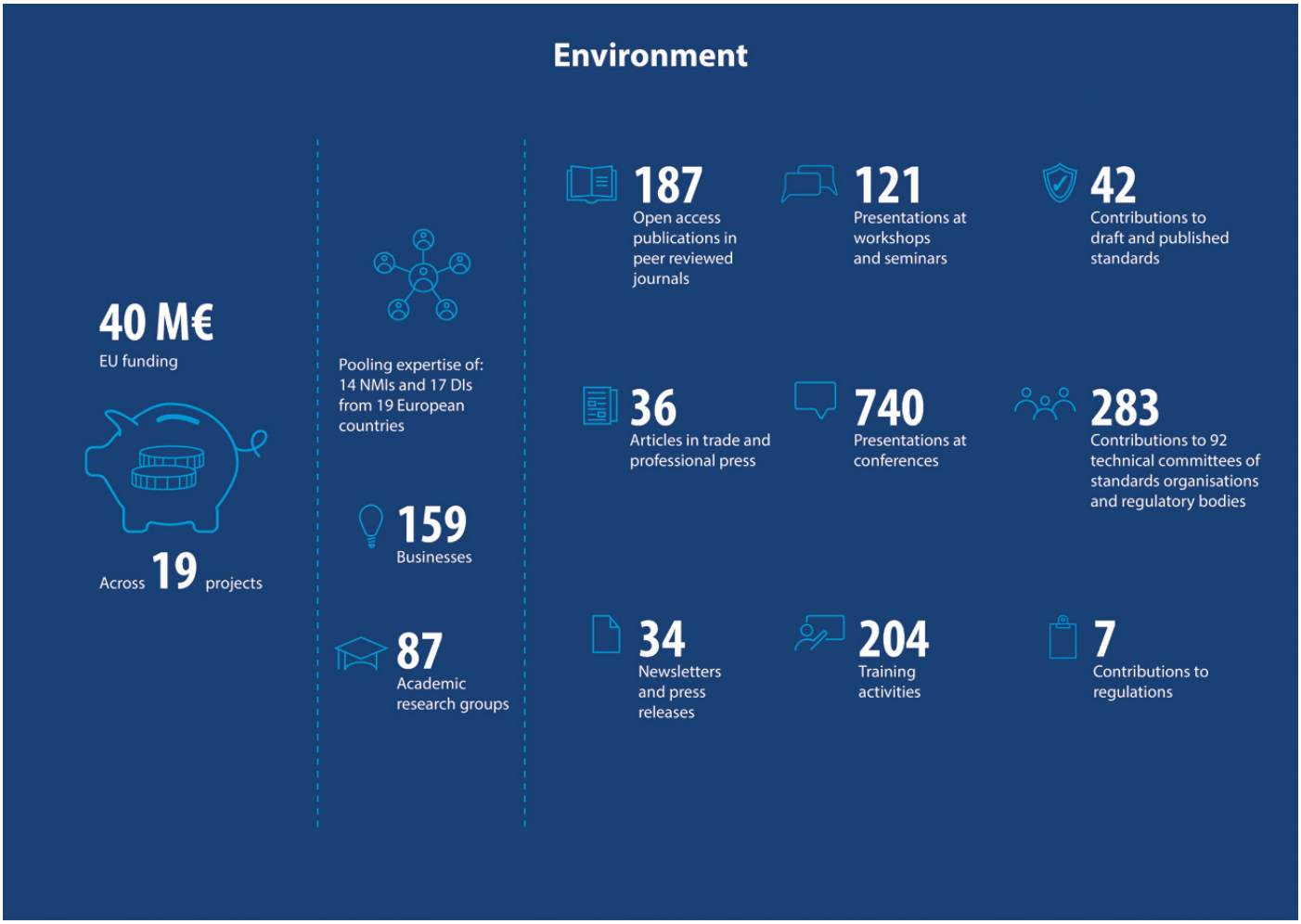
Understanding how greenhouse gases move through the atmosphere is critical for assessing their sources and their impact on climate change. The traceRadon project developed metrology to support the use of radon – a radioactive gas emitted by rocks and soil – as a tracer for CO_2 and created a new atmospheric monitor which is less effected by background noise.

Annex: Full list of projects

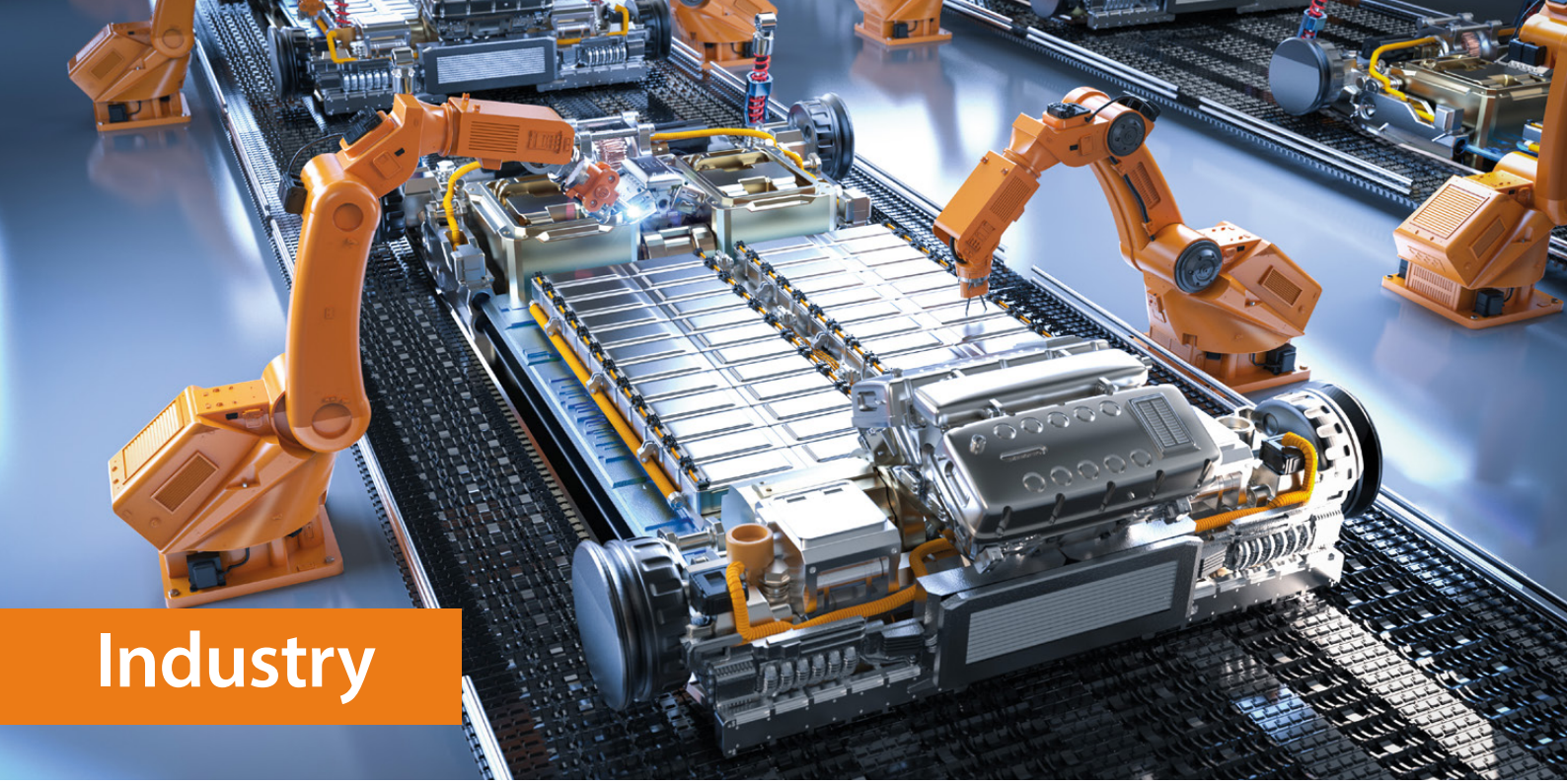
- Metrology for oxidised mercury (16ENV01, MercOx)
- Metrology for light absorption by atmospheric aerosols (16ENV02, Black Carbon)
- Further metrology for earth observation and climate (16ENV03, MetEOC-3)
- Metrology for mobile detection of ionising radiation following a nuclear or radiological incident (16ENV04, Preparedness)
- Metrology for nitrogen dioxide (16ENV05, MetNO2)
- Metrology for stable isotope reference standards (16ENV06, SIRS)
- Aerosol metrology for atmospheric science and air quality (16ENV07, AEROMET)
- Metrology for air pollutant emissions (16ENV08, IMPRESS 2)
- In situ metrology for decommissioning nuclear facilities (16ENV09, MetroDECOM II)
- Metrology for radon monitoring (16ENV10, MetroRADON)
- Radon metrology for use in climate change observation and radiation protection at the environmental level (19ENV01, traceRadon)

- Remote and real-time optical detection of alpha-emitting radionuclides in the environment (19ENV02, RemoteALPHA)
- Metrology for low-frequency sound and vibration (19ENV03, Infra-AUV)
- Metrology for aerosol optical properties (19ENV04, MAPP)
- Stable isotope metrology to enable climate action and regulation (19ENV05, STELLAR)
- Metrology for climate relevant volatile organic compounds (19ENV06, MetClimVOC)
- Metrology to establish an SI traceable climate observing system (19ENV07, MetEOC-4)
- Advanced aerosol metrology for atmospheric science and air quality (19ENV08, AEROMET II)
- Improved vehicle exhaust quantification by portable emission measurement systems metrology (19ENV09, MetroPEMS)

Full details of all projects in the 2016 and 2019 Call Environment Theme can be found here:



Summary of outputs from EMPIR Environment theme.



Industry

Europe 2020 highlighted the need for smart, sustainable and inclusive growth to transform the EU economy, tackle climate change and respond to social challenges. Within this, European industry was given a key role to play. Priority sectors such as telecommunications, semiconductors and electronics, photonics and advanced manufacturing all required support to increase certainty in investment and drive innovation identified. With the introduction of the EU Green Deal in 2019, focus was also given to the need for clean energy, a circular economy and digital transformation – including the EC's aim to become autonomous in the semiconductor and quantum technology sectors.

The EMPIR Industry projects, addressed the need for a robust metrology infrastructure to support the success of industrial innovation and technological developments. Exploitation was a key activity and EMPIR projects used many types of commercialisation pathways to enable their outputs to be up taken. This includes new or improved measurement devices, new measurement services, licensing and new spin-off SMEs (e.g. Alcyon Photonics, FOCUS). Investment in these projects has enabled economic and competitive advantage and innovations for key European industrial sectors as well as supported compliance, normative standards and access to the market.

Highlights

Telecommunications

New technologies, like autonomous cars and 5G networks, require higher frequencies and broader bandwidths, leading to increased energy consumption and complex interference. The FutureCom project developed techniques to characterise high-wavelength electronics under real-world conditions and optimise signal integrity while improving energy efficiency.

Semiconductors and electronics

Next-generation silicon chips pose unique measurement challenges due to their complexity and narrow tolerances, with some techniques taking days or weeks to render precise details. To address this, the ATMOC

project created reference materials and powerful computational methods to better simulate chips, catching defects to improve products and reduce waste.

Quantum and photonics

Quantum sensors (QS) exploit superpositions in fundamental particles, like photons, to make supersensitive measurements for medical diagnosis, navigation or environmental monitoring. During QADeT, partners created single-photon emitters by implanting germanium ions inside diamonds, one of the first instances of practical QS being taken beyond the prototype stage.

Resilience

Almost all areas of modern life rely on precision time and frequency, disseminated via radio signals or satellites, but more resilient ground-based systems are being developed. The WRITE project validated the White Rabbit precision time protocol (WR-PTP) which provided reliable support to orbital-based time and frequency dissemination.

Advanced manufacturing

Many industries rely on parts which can't be measured using conventional means – modern aircraft can have wingspans as long as 50 m, so need to be measured *in situ*. In the LaVA project, a new 3D Large Volume Metrology system was developed which uses infrared LEDs and low-cost cameras to measure parts as large as 10 m to sub-millimetre accuracy.

Circular economy

The amount of e-waste generated annually could fill 1.55 million 40-tonne trucks – enough to encircle the equator. The MetroCycleEU project worked to improve e-waste recycling, developing world-first traceable methods and reference materials to improve the reclaiming of Technology Critical Elements, like lithium or cobalt, to be reused in new electronics.

Energy efficiency

As energy grids incorporate more renewable energy sources, real-time digital metering is needed to account for increased variability in supply and grid conditions. In the FutureGrid II project, new metrology tools were developed including a new calibration facility for stand-alone merging units, critical devices which digitise analogue voltage and current signals.

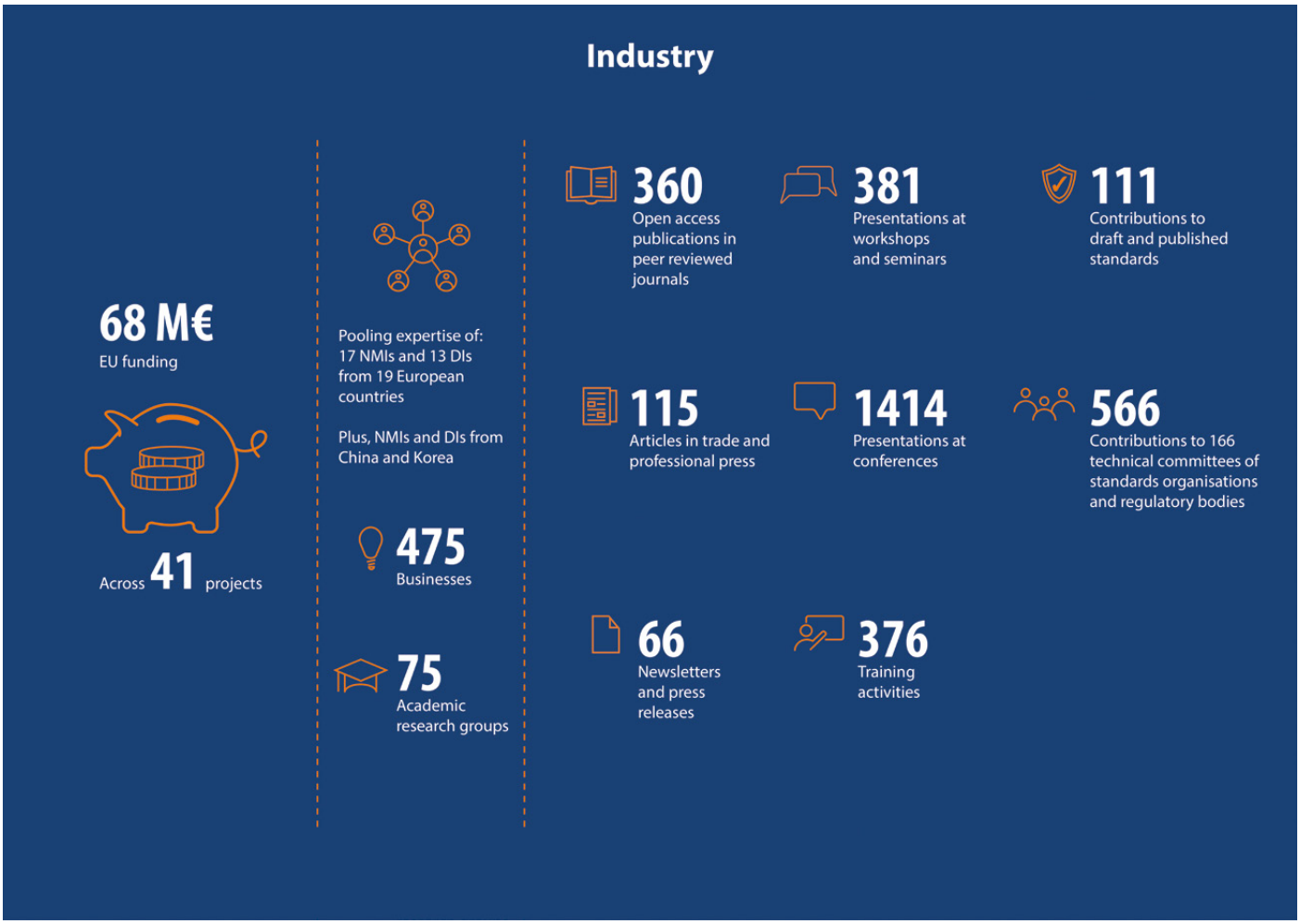
Annex: Full list of projects

- Advanced 3D chemical metrology for innovative technologies (14IND01, 3DMetChemIT)
- Microwave measurements for planar circuits and components (14IND02, PlanarCal)

- Metrology for length-scale engineering of materials (14IND03, Strength-ABLE)
- Enhancing process efficiency through improved temperature measurement (14IND04, EMPRESS)
- Optical metrology for quantum enhanced secure telecommunication (14IND05, MIQC2)
- Industrial standards in the intermediate pressure-to-vacuum range (14IND06, pres2vac)
- Metrology for manufacturing 3D stacked integrated circuits (14IND07, 3D Stack)
- Metrology for the electrical power industry (14IND08, ElPow)
- Metrology for highly-parallel manufacturing (14IND09, MetHPM)
- Metrology for 5G communications (14IND10, MET5G)
- Metrology for humidity at high temperatures and transient conditions (14IND11, HIT)
- Metrology for innovative nanoparticles (14IND12, Innanopart)
- Metrology for the photonics industry - optical fibres, waveguides and applications (14IND13, PhotInd)
- Torque measurement in the MN•m range (14IND14, MNm Torque)
- Procedures allowing medical implant manufacturers to demonstrate compliance with MRI safety regulations (17IND01, MIMAS)
- Communication and validation of smart data in IoT-networks (17IND02, SmartCom)
- Large Volume Metrology Applications (17IND03, LaVA)
- Enhancing process efficiency through improved temperature measurement 2 (17IND04, EMPRESS 2)
- Multifunctional ultrafast microprobes for on-the-machine measurements (17IND05, MicroProbes)
- Metrology for the next-generation digital substation instrumentation (17IND06, FutureGrid II)
- Development of measurement and calibration techniques for dynamic pressures and temperatures (17IND07, DynPT)
- Advanced Computed Tomography for dimensional and surface measurements in industry (17IND08, AdvanCT)
- Metrology for Airborne Molecular Contaminants II (17IND09, MetAMCII)
- Quality assessment of electric vehicle Li-ion batteries for second use applications (17IND10, LiBforSecUse)
- Industrial process optimisation through improved metrology of thermophysical properties (17IND11, Hi-TRACE)
- Metrology for the Factory of the Future (17IND12, Met4FoF)
- Metrology for real-world domestic water metering (17IND13, Metrowamet)
- Precision Time for Industry (17IND14, WRITE)
- Metrology for the recycling of Technology Critical Elements to support Europe's circular economy agenda (20IND01, MetroCycleEU)
- Dynamic applications of large volume metrology in industry of tomorrow environments (20IND02, DynaMITE)
- RF Measurements for future communications applications (20IND03, FutureCom)
- Traceable metrology of soft X-ray to IR optical constants and nanofilms for advanced manufacturing (20IND04, ATMOC)
- Quantum sensors for metrology based on single-atom-like device technology (20IND05, QADeT)
- Metrology for trace water in ultra-pure process gases (20IND06, PROMETH2O)
- Traceable industrial 3D roughness and dimensional measurement using optical 3D microscopy and optical distance sensors (20IND07, TracOptic)
- Traceability of localised functional properties of nanostructures with high speed scanning probe microscopy (20IND08, MetExSPM)
- Metrology in manufacturing compound semiconductors for power electronics (20IND09, PowerElec)
- Metrology for decarbonising the gas grid (20IND10, Decarb)

- Metrology infrastructure for high-pressure gas and liquified hydrogen flows (20IND11, MetHyInfra)
- Electrical nanoscale metrology in industry (20IND12, Elena)
- Sustainable advanced flow meter calibration for the transport sector (20IND13, SAFEST)

Full details of all projects in the 2014, 2017 and 2020 Call Industry Theme can be found here:



Summary of outputs from EMPIR Industry theme.

Health

Future healthcare will increasingly rely on the integration of patient data from clinical tests, high throughput analyses, multi-modality imaging, personal monitoring devices and electronic health records. This creates significant challenges, as all these measurements for diagnosis and therapy need to be accurate, reproducible, comparable and traceable.

The EMPIR Health projects supported – through metrological research and development – innovation and confidence in the development, testing and application of new patient diagnostics and therapy technologies with alignment to Horizon 2020 goals for healthcare. This was realised by leveraging research efforts across complementary programmes for antimicrobial resistance and infectious diseases, early diagnosis and personalised medicine, patient safety, healthcare efficiency, and regulatory support. To enhance the impact, projects actively engaged the user community (including medical practitioners, industry, regulators) as well as patient interest groups.

Highlights

Predictive and preventative diagnosis

Cardiovascular disease covers a range of blood vessel and heart disorders. The PerfusImaging project developed a new standard for quantitative medical imaging, improved the accuracy of tests for cardiovascular disease and developed an approach to support diagnostics. This will result in more efficient and cost-effective cardiovascular healthcare.

Cancer therapy

Radiotherapy is an effective treatment for cancer, one of the leading causes of death worldwide. Projects have improved the monitoring of ultra-high dose rate electron beams for advanced cancer treatment as well as dosimetry for MR-Linacs. This improved accuracy enables more precise and personalised treatments, shorter treatment times and reduced total costs.

Preparedness

Sepsis is a life-threatening condition where time to diagnosis is critical to patient outcome. The SEPTIMET project developed reference methods for identifying the causes of sepsis as well as a reference measurement procedure for detection of a biomarker of infection used for sepsis diagnosis. This will lead to more rapid and accurate clinical measurements in sepsis management.

Medical devices and advanced therapies

The accuracy of drug delivery devices is critical to patient safety. The project MeDDII has developed methods to accurately calibrate flow rates in medical devices. This has improved patient safety and helped to improve patient outcomes by ensuring that the treatments they need are delivered over the correct timeframe.

Data analysis

The use of electrocardiography data obtained using non-invasive leads to record electrical signals from the heart is essential to the detection of heart problems. The MedalCare project developed tools to allow objective detection of heart disease. Project results will bring a greater clarity to ECG traces, allowing automated detection of pathologies in a clear, unbiased way.

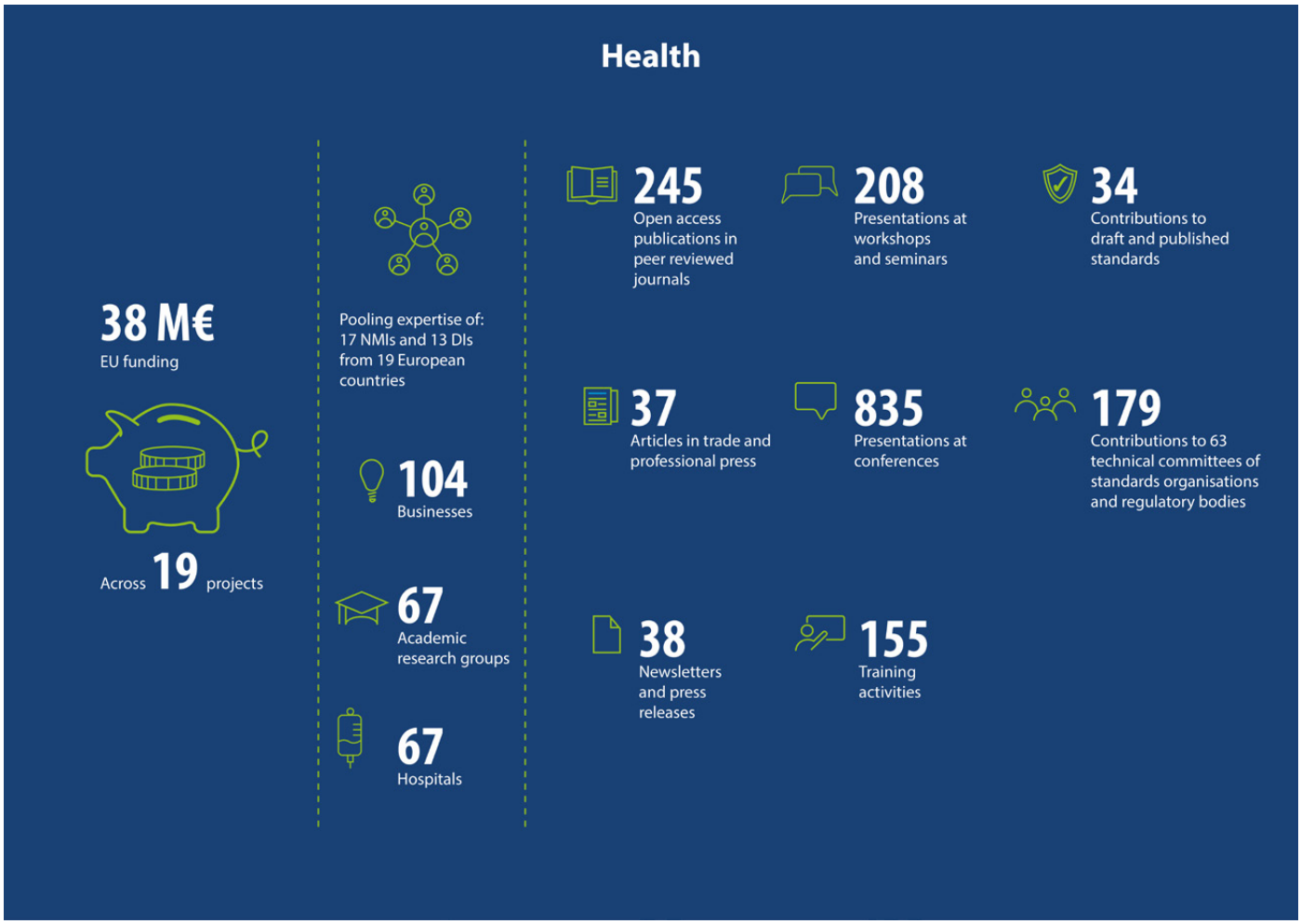
Annex: Full list of projects

- Quantitative measurement and imaging of drug-uptake by bacteria with antimicrobial resistance (15HLT01, MetVBadBugs)
- Role of metals and metal containing biomolecules in neurodegenerative diseases such as Alzheimer's disease (15HLT02, ReMiND)
- Metrology for modern hearing assessment and protecting public health from emerging noise sources (15HLT03, Ears II)
- Innovative measurements for improved diagnosis and management of neurodegenerative diseases (15HLT04, NeuroMet)
- Metrology for multi-modality imaging of impaired tissue perfusion (15HLT05, PerfusImaging)
- Metrology for clinical implementation of dosimetry in molecular radiotherapy (15HLT06, MRTDosimetry)
- Novel materials and methods for the detection, traceable monitoring and evaluation of antimicrobial resistance (15HLT07, AntiMicroResist)
- Metrology for MR guided radiotherapy (15HLT08, MRgRT)
- Metrology for additively manufactured medical implants (15HLT09, MetAMMI)
- Standards and e-learning course to maximise the uptake of infusion and calibration best practices (15SIP03, InfusionUptake)

- Standardisation of concentration measurements of extracellular vesicles for medical diagnoses (18HLT01, METVES II)
- Measurements for mitigating adverse health effects from atmospheric particulate pollutants (18HLT02, AeroTox)

- Metrology to enable rapid and accurate clinical measurements in acute management of sepsis (18HLT03, SEPTIMET)
- Metrology for advanced radiotherapy using particle beams with ultra-high pulse dose rates (18HLT04, UHDpulse)
- Quantitative MR-based imaging of physical biomarkers (18HLT05, QUIERO)
- Radiotherapy coupled with hyperthermia - adapting the biological equivalent dose concept (18HLT06, RaCHy)
- Metrology of automated data analysis for cardiac arrhythmia management (18HLT07, MedalCare)
- Metrology for drug delivery (18HLT08, MeDDII)
- Metrology and innovation for early diagnosis and accurate stratification of patients with neurodegenerative diseases (18HLT09, NeuroMET2)
- Providing the measurement infrastructure to allow quantitative diagnostic methods for biomarkers of coronary heart diseases (18HLT10, CardioMet)

Full details of all projects in the 2015 and 2018 Call Health Theme can be found here:



Summary of outputs from EMPIR Health theme.

SI Broader Scope

Measurement standards ensure that quality control, consumer safety and fair trade are possible around the world. However, to ensure trust and enable impact, they must be underpinned by robust measurements traceable to the International System of Units (SI). In 2019, a revision of the SI came into force, following the 26th meeting of the General Conference on Weights and Measures (CGPM) under the Metre Convention. This revision means that the seven units of the SI are each based on unchanging universal constants, ensuring longevity and universality for the foundation of metrology.

Under the European Metrology Research Programme (EMRP), the "SI Fundamental" topic prepared for the implementation of the SI redefinition and supported development of practical realisations ("*mise-en-pratique*") of the redefined base units and derived units. Building on this work, the EMPIR SI Broader Scope projects implemented a longer-term and larger-scale approach to develop a joint, coherent and efficient European landscape and brought European measurement capabilities to an internationally competitive level.

Highlights

Quantum and SI redefinition

The unit for temperature, the kelvin, was redefined in terms of the Boltzmann constant, opening the door for temperature calibrations outside of the lab, at point-of-use. The Real-K project supported this by developing new approaches to thermometry, including alternative realisations of the ITS-90 temperature scale to help end reliance on toxic mercury.

Optical clocks/time and frequency

Time and frequency (T&F) reference signals underpin electricity grids, global navigation and the internet, but for applications like quantum research, satellite connections are insufficient. In the TiFOON project, major improvements were made to hardware needed to send T&F signals via fibre optic links, which are now provided to over 30 laboratories across France.

Dimensional and surface metrology

Tools and methods developed during the GeoMetre project helped establish EURO5000, a new geodetic reference baseline. EURO5000 now enables distance measurements of up to 5 km with uncertainties of less than 1 mm which are needed to track plate tectonics, assess the effects of climate change on glacial melt and monitor large-scale structures like dams.

Electrical metrology and waveform analysis

All accurate electrical measurements, from nanoelectronics to domestic billing, rely on traceability to the ampere, the SI unit for electric current. The e-SI-AMP project developed single-electron sources and measurement instruments to improve traceability for nano-currents, including a new travelling standard to deliver fast, room temperature calibrations.

Photometry

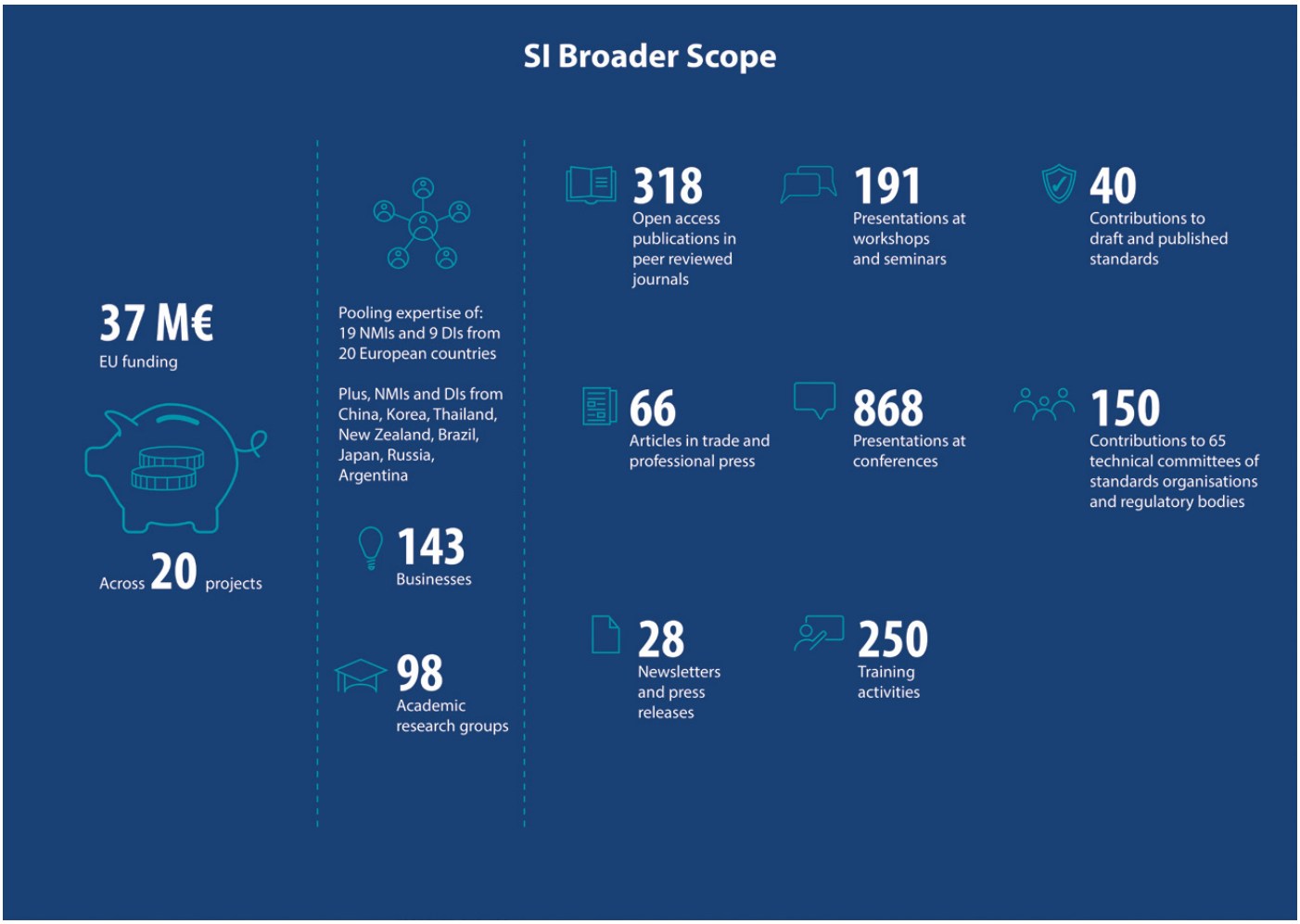
In 2012, new regulation saw the phasing out of incandescent bulbs in favour of energy-efficient solid-state lighting (SSL) like LEDs. But lighting standards lagged behind. The PhotoLED project created a new LED reference spectrum and standard lamps to calibrate SSL-based photometers, supporting the technology and improving consumer confidence.

Annex: Full list of projects

- Reference algorithms and metrology on aspherical and freeform lenses (15SIB01, FreeFORM)
- Implementing the new kelvin 2 (15SIB02, InK 2)
- Optical clocks with 1E-18 uncertainty (15SIB03, OC18)
- Waveform metrology based on spectrally pure Josephson voltages (15SIB04, QuADC)
- Optical frequency transfer - a European network (15SIB05, OFTEN)
- Nano-scale traceable magnetic field measurements (15SIB06, NanoMag)
- Future photometry based on solid-state lighting products (15SIB07, PhotoLED)
- Quantum realisation of the SI ampere (15SIB08, e-SI-Amp)
- Traceable three-dimensional nanometrology (15SIB09, 3DNano)
- Radionuclide beta spectra metrology (15SIB10, MetroBeta)
- Large-scale dimensional measurements for geodesy (18SIB01, GeoMetre)
- Realising the redefined kelvin (18SIB02, Real-K)
- New quantities for the measurement of appearance (18SIB03, BxDiff)
- Towards quantum-based realisations of the pascal (18SIB04, QuantumPascal)
- Robust Optical Clocks for International Timescales (18SIB05, ROCIT)
- Advanced time/frequency comparison and dissemination through optical telecommunication networks (18SIB06, TiFOON)
- Graphene impedance quantum standard (18SIB07, GIQS)
- Comprehensive traceability for force metrology services (18SIB08, ComTraForce)
- Traceability for electrical measurements at millimetre-wave and terahertz frequencies for communications and electronics technologies (18SIB09, TEMMT)

- Self-calibrating photodiodes for the radiometric linkage to fundamental constants (18SIB10, chipS•CALe)

Full details of all projects in the 2015 and 2018 Call SI Broader Scope Theme can be found here:



Summary of outputs from EMPIR SI Broader Scope theme.

Fundamental

Metrology and science have a reciprocal relationship, with developments at the frontiers of each feeding into the other. European and international metrology capabilities underpin scientific research and collaboration, while emerging sciences open the door for new measurement standards and methods. Following the redefinition of the SI in 2019, quantum systems emerged as a key area of potential for the development of new primary measurement standards, bolstered by the European Quantum Flagship Programme.

The EMPIR Fundamental projects capitalised on the relationship between science and metrology by addressing research needs in areas like quantum technologies, standardisation, health and sustainability. They also tackled some of the Key Enabling Technologies (KETs) identified by the European Commission, such as nanotechnology, micro/nanoelectronics, photonics, and advanced materials. The NMIs and DIs collaborated with research institutions, end-users, regulatory bodies and industry outside of the metrology community to ensure outputs were suitable for long term uptake. Projects also worked in compliment with existing European and international projects, e.g., those funded through the Quantum Flagship, to maximise impact.

Highlights

Quantum and optical clocks

Optical clocks based on ultra-stable laser radiation are of prominent importance both in scientific and industrial activities. The CC4C project developed the first multi-ion optical clock in the world. This was further improved in the TSCAC project, demonstrating a record-breaking accuracy, the first atomic clock in the world with measurement uncertainties required in the roadmap for the redefinition of the SI second in the future.

Nanotechnology

The MEMQuD project explored quantum conductance and quantum-based resistance standards to create on-chip self-calibrating systems. Project outcomes are contributing to the development of new technologies and advancement of nanoelectronics and nanotechnology.

Micro/nanoelectronics and photonics

Innovative devices, such as nanochips, high-capacity memories and novel materials all rely on our ability to shape matter at the nanoscale. The POLight project developed novel optical methods for nanoscale structures with unprecedented performance, which will help to place the EU at the forefront of advanced and sustainable economies.

Advanced materials

pH is one of the most important chemical properties measured in both science and industry, playing a vital role in health, environmental studies, and material reprocessing. The UnipHied project created a unified absolute pH scale with a strong metrological basis to support and strengthen EU manufacturing and innovation in industries from pharmaceuticals to petrochemicals and semiconductors.

Digital transformation

Smaller, faster, and more efficient electronic devices are a vital part of Europe's economic growth and industrial innovation. The TOPS project undertook fundamental research for the characterisation of topological spin structures, used in digital storage. This new technology will support Europe's continuing expertise and competitiveness in electronic device manufacturing.

Nuclear science

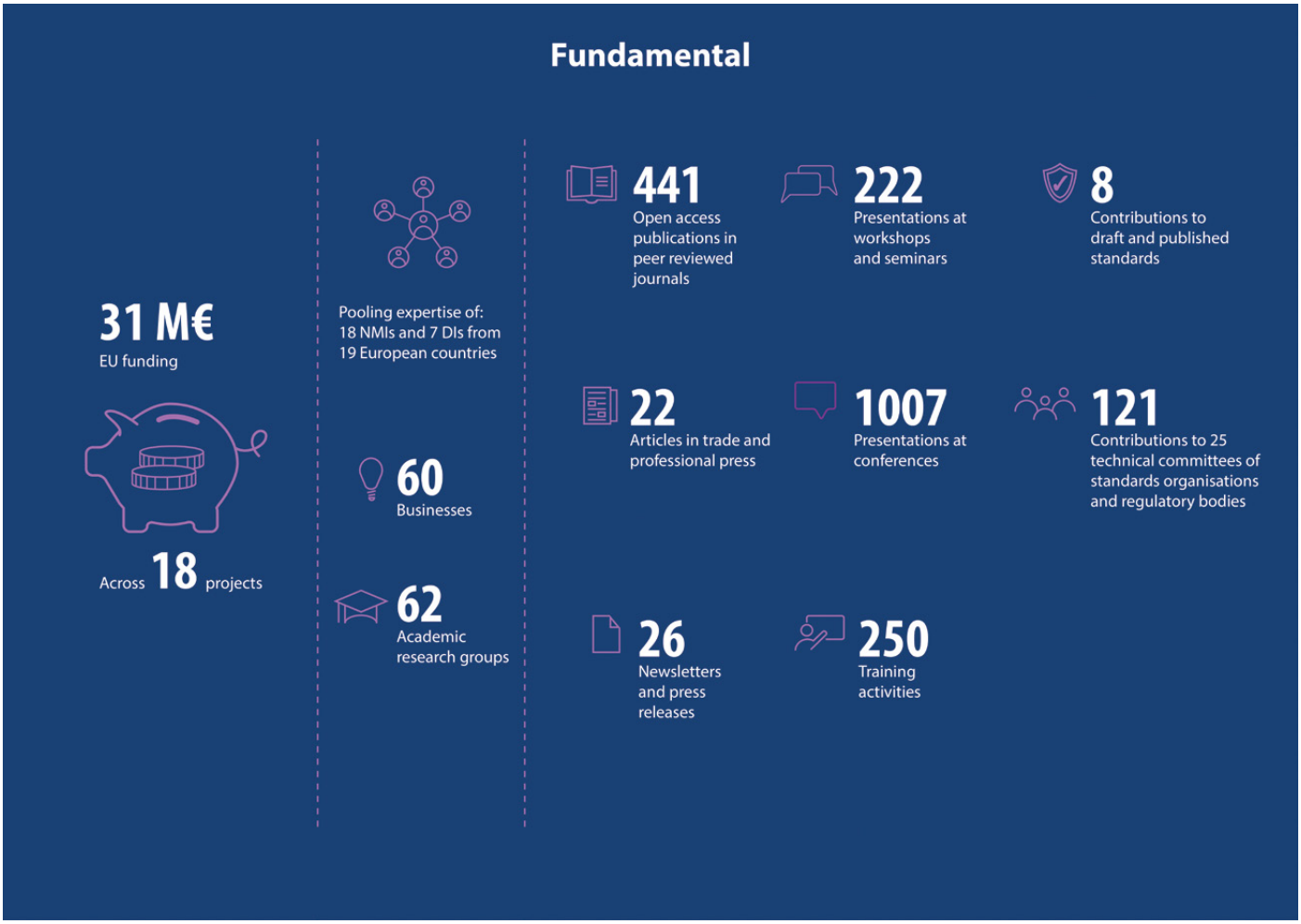
Accurate knowledge of radioactive decay is vital in areas such as nuclear industry, cancer therapy and astronomy. The MetroMMC project developed novel detection techniques and theoretical models to understand better the behaviour of radioactive elements undergoing decay. One output was improved code for nuclides undergoing beta radiation decay that is now used by the nuclear industry.

Annex: Full list of projects

- Light-matter interplay for optical metrology beyond the classical spatial resolution limits (17FUN01, BeCOMe)
- Measurement of fundamental nuclear decay data using metallic magnetic calorimeters (17FUN02, MetroMMC)
- Ultra-stable optical oscillators from quantum coherent and entangled systems (17FUN03, USOQS)
- Single-electron quantum optics for quantum-enhanced measurements (17FUN04, SEQUOIA)
- Photonic and Optomechanical Sensors for Nanoscaled and Quantum Thermometry (17FUN05, PhotOQuant)
- Single-photon sources as new quantum standards (17FUN06, SIQUST)
- Coulomb Crystals for Clocks (17FUN07, CC4C)
- Metrology for topological spin structures (17FUN08, TOPS)
- Realisation of a Unified pH Scale (17FUN09, UnipHied)
- Josephson travelling wave parametric amplifier and its application for metrology (17FUN10, ParaWave)

- Two-species composite atomic clocks (20FUN01, TSCAC)
- Pushing boundaries of nano-dimensional metrology by light (20FUN02, POLight)
- Two dimensional lattices of covalent- and metal-organic frameworks for the Quantum Hall resistance standard (20FUN03, COMET)
- Towards new primary activity standardisation methods based on low-temperature detectors (20FUN04, PrimA-LTD)
- Single- and entangled photon sources for quantum metrology (20FUN05, SEQUME)
- Memristive devices as quantum standard for nanometrology (20FUN06, MEMQuD)
- Microwave metrology for superconducting quantum circuits (20FUN07, SuperQuant)
- Next generation ultrastable lasers: reducing thermal noise limit and overcoming technical limitations with new materials and technologies (20FUN08, NEXTLASERS)

Full details of all projects in the 2017 and 2020 Call Fundamental Theme can be found here:



Summary of outputs from EMPIR Fundamental theme.

Standardisation

Standardisation is the foundation of regulation, ensures quality and enables fair trade. Through standards, products and services across Europe are made safer and more reliable, ensuring EU competitiveness and improving quality of life. By increasing efficiency and compatibility between products, standards reduce waste and minimise costs. Standards also have a profound social impact, improving the quality of healthcare, safeguarding the environment and protecting citizens' welfare at home, in public and in the workplace.

The EMPIR Standardisation (also referred to as 'Pre- and co-normative research') projects provided the metrological basis required to underpin the development of European and International documentary standards. They supported the Europe 2020 strategy for smart, sustainable and inclusive growth, addressing needs across key areas like health, energy, digital transformation and industry. To maximise impact, projects addressed the specific demands of European and International Standards Developing Organisations (SDOs), such as CEN-CENELEC and the ISO.

Highlights

Environmental monitoring and emissions

Some industrial processes result in toxic emissions from stacks and flues, which must meet strict levels. The project Heroes advised on best practice and validated instruments that enabled better regulation of hydrogen gas emissions. This will help to minimise the impact of pollution on people's health and the environment.

Advanced manufacturing

Research into fundamental physics, the manufacture of advanced pharmaceuticals, semiconductors and electronics all require an environment free of atmospheric contaminants, provided by high or ultra-high vacuums. The project Ion gauge developed the first instrument for measuring vacuums with a design specification capable of incorporating into normative standards. In the follow-on project ISO Gauge this was realised with the publication of the first international standard in this area.

Healthcare

The project iMET-MRI developed improved metrology for quantitative MRI, which enables the measurement of properties indicative of disease progression. This work lead to the development of two new facilities for improved MRI device measurements, realising the full benefit of decades of research work by the MRI community. Microfluidics are used in medical applications for on-the-spot diagnosis. The project MFMET developed new international standards to accelerate the use of these devices in medical and pharmaceutical applications. These advancements will help establish a metrology basis for microfluidics.

Security

With the advent of quantum computers previously unbreakable security codes could be decrypted. The MeTISQ project developed new methods for characterising quantum key distribution (QKD) hardware and assessed counter-measures to attacks on these systems. As a part of this project a commercial QKD system was validated which has since been used in the first industrial deployments of a quantum-secure networks in the UK and France.

Lighting and optics

Road lighting must provide sufficient light for road safety, however recent advances in lighting meant that international standards were out of date. The project SURFACE provided updated data on the minimum luminance levels for night-time roads which will reduce energy consumption and improve safety.

Energy and power systems

The project UHV improved methods and standards for detecting nano-second electrical surges caused by removing power loads, which can cause grid failures. This will protect the power network from electrical faults and ensure the performance and stability of instrumentation used in the more efficient power grids of the future.

Advanced materials and nanosystems

Graphene's structure gives it unique properties including high electrical and thermal conductivity, making it suitable to underpin a new generation of electronics. The project GRACE contributed to five documentary standards as well as developing a new method for graphene characterisation, enabling customers to reliably identify suitable graphene products for their applications.

Measurement standards

The project EMUE developed uncertainties for many complex measurement areas leading to input into a revision of the Guide to the Expression of Uncertainty in Measurement. This widely used guide supports

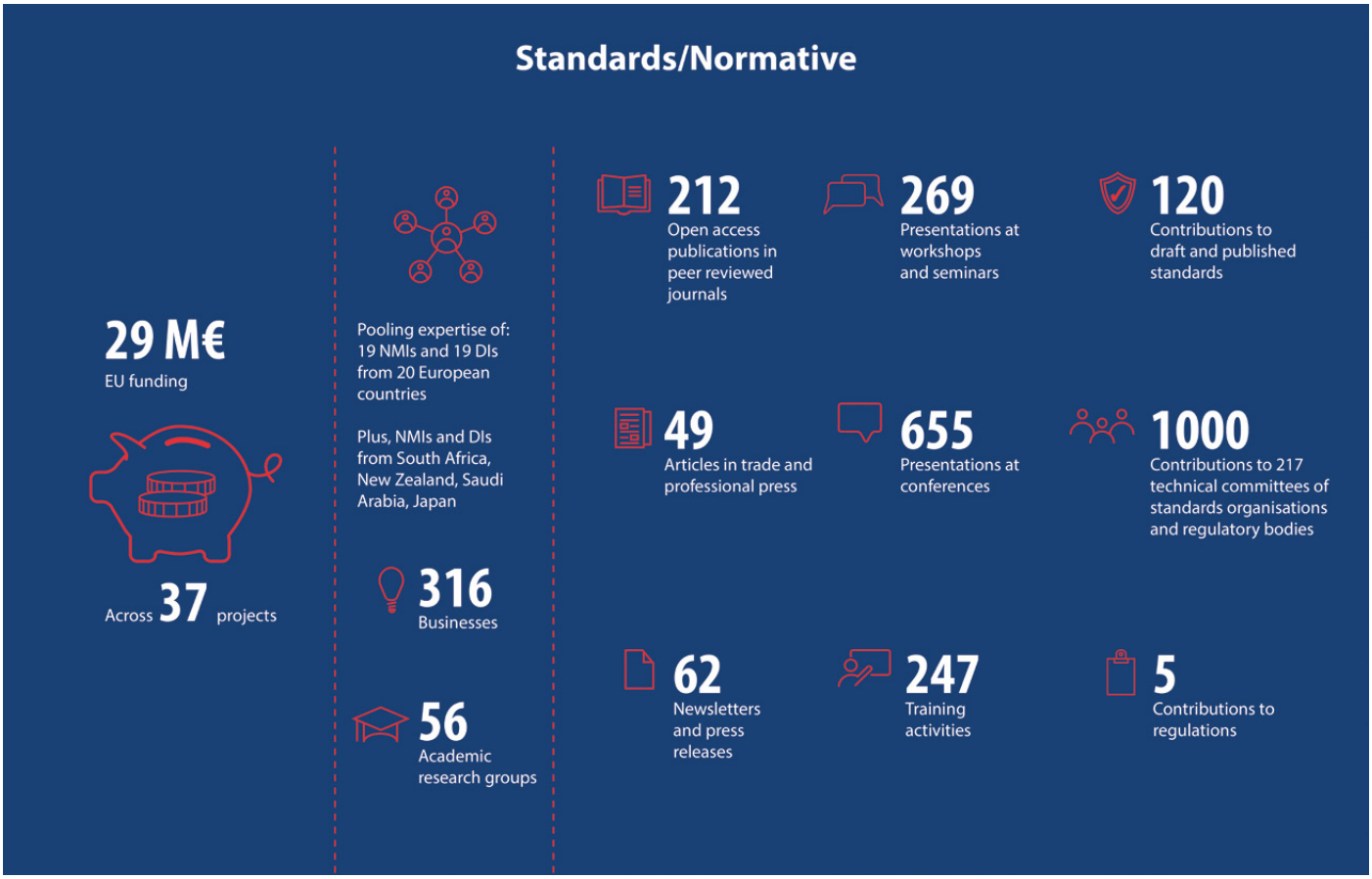
the scientific community in making confident and trusted measurements. The project also inputted into making a new form of MRI more quantitative.

Annex: Full list of projects

- Metrology for sampling and conditioning SO2 emissions from stacks (15NRM01, Sulf-Norm)
- Techniques for ultra-high voltage and very fast transients (15NRM02, UHV)
- Metrology for sustainable hydrogen energy applications (15NRM03, Hydrogen)
- Standard tests and requirements for rate-of-change of frequency measurements in smart grids (15NRM04, ROCOF)
- Developing electrical characterisation methods for future graphene electronics (16NRM01, GRACE)
- Pavement surface characterisation for smart and efficient road lighting (16NRM02, SURFACE)
- kQ factors in modern external beam radiotherapy applications to update IAEA TRS-398 (16NRM03, RTNORM)
- Towards an ISO standard for magnetic nanoparticles (16NRM04, MagNaStand)
- Towards a documentary standard for an ionisation vacuum gauge (16NRM05, Ion gauge)
- Improvement of emissivity measurements on reflective insulation materials (16NRM06, EMIRIM)
- SAR measurement using vector probes (16NRM07, Vector SAR)
- Bidirectional reflectance definitions (16NRM08, BiRD)
- Loss Measurements on Power Transformers and Reactors (17NRM0, TrafoLoss)
- Electromagnetic Interference on Static Electricity Meters (17NRM02, MeterEMI)
- Standards for the evaluation of the uncertainty of coordinate measurements in industry (17NRM03, EUCoM)
- Improved traceability chain of nanoparticle size measurements (17NRM04, nPSize)
- Advancing measurement uncertainty - comprehensive examples for key international standards (17NRM05, EMUE)
- Metrology for monitoring endocrine disrupting compounds under the Water Framework Directive (18NRM01, EDC-WFD)
- Primary standards and traceable measurement methods for X-ray emitting electronic brachytherapy devices (18NRM02, PRISM-eBT)
- Calibration and accuracy of non-catching instruments to measure liquid/solid atmospheric precipitation (18NRM03, INCIPIT)
- Determining new uncertainty requirements for increasingly stringent legislative HCl industrial emission limits (18NRM04, Heroes)
- Grid measurements of 2 kHz - 150 kHz harmonics to support normative emission limits for mass-market electrical goods (18NRM05, SupraEMI)
- Flow metering of renewable gases (biogas, biomethane, hydrogen, syngas and mixtures with natural gas) (18NRM06, NEWGASMET)
- Measurement of the focal spot size of X-ray tubes with spot sizes down to 100 nm (18NRM07, NanoXSpot)
- Traceable dosimetry for small fields in MR-guided radiotherapy (19NRM01, MRgRT-DOS)
- Revision and extension of standards for test methods for LED lamps, luminaires and modules (19NRM02, RevStdLED)
- Metrology for traceable protocols for elemental and oxidised mercury concentrations (19NRM03, SI-Hg)

- Standardisation of structural and chemical properties of graphene (19NRM04, ISO-G-SCoPe)
- Measurement methods and test procedures for assessing accuracy of instrument transformers for power quality measurements (19NRM05m, IT4PQ)
- Metrology for testing the implementation security of quantum key distribution hardware (19NRM06, MeTISQ)
- Support for standardisation of high voltage testing with composite and combined wave shapes (19NRM07, HV-com^2)
- Metrology for temporal light modulation (20NRM01, MetTLM)
- Establishing metrology standards in microfluidic devices (20NRM02, MFMET)
- Standardisation of measurements for DC electricity grids (20NRM03, DC grids)
- Metrology for the determination of emissions of dangerous substances from building materials into indoor air (20NRM04, MetrIAQ)
- Improved metrology for quantitative MRI (20NRM05, iMET-MRI)
- Metrology for standardised seawater pHT measurements in support of international and European climate strategies (20NRM06, SApHTIES)
- Gauge Developing an ISO Technical Specification 'Characteristics for a stable ionisation vacuum gauge' (20SIP01, ISO Guage)

Full details of all projects in the Pre- and co-normative research Theme can be found here:



Summary of outputs from EMPIR Standardisation theme.

Capacity Building

Ensuring a balanced and integrated metrology infrastructure is vital to the future of European metrology and has a significant impact on the entire quality infrastructure. Reducing metrological capability gaps in areas of national and regional priority, as informed by both European regulations and the needs of stakeholders, enables competition, improves research capacity and contributes to increased economic welfare.

To support this, the Capacity Building (also referred to as 'Research Potential') projects disseminated research expertise to emerging National Metrology Institutes (NMIs) and Designated Institutes (DIs), fostering new and existing collaborations and using smart specialisation for coordinated knowledge transfer. Partners across three projects developed new calibration and measurement capabilities, while partners across five projects developed new measurement services. Projects addressed both industrial competitiveness and societal needs across key areas, including chemical and environmental metrology, materials, and medical metrology and dosimetry, and created long-term research roadmaps to ensure their developments were sustainable beyond the end of any individual project.

Highlights

Chemical and environmental metrology

When old industrial sites are reclaimed for new building projects, robust testing is needed to ensure no contaminants, such as heavy metals, remain in the soil. The ENVCRM project brought together NMIs and DIs from across Europe to create new traceable reference materials for contaminated soil, improving detection and helping share knowledge through collaboration. In addition, the UNAC-LOW project also improved hydrophones to better protect marine animals.

Medical metrology and dosimetry

Globally, over a third of permanent blindness is due to glaucoma, nerve damage caused by high interocular pressure (IOP). The inTense project brought together NMIs and ophthalmologists to develop a new centre for IOP metrology which offers training, type approval and verifications, and performs around 500 IOP calibrations annually to help protect vision across the EU.

Electronic and quantum metrology

During the RFMicrowave project, new tools were created to help address radio- and microwave interference from electronics. The huge boom in consumer electronics has made interference, which can impact other devices, a growing concern. These improved models are vital to develop accurate calibration standards and ensure manufacturers can reduce emissions from products.

Materials measurements

Automatic weighing ensures products made by continuous manufacturing processes, like pre-packaged foods, stay within weight tolerances. The AWICal project developed methods and guidance for calibration and uncertainty evaluation for check weighing instruments, helping manufacturers to improve measurements and ensure consumer confidence in their products.

Temperature and humidity

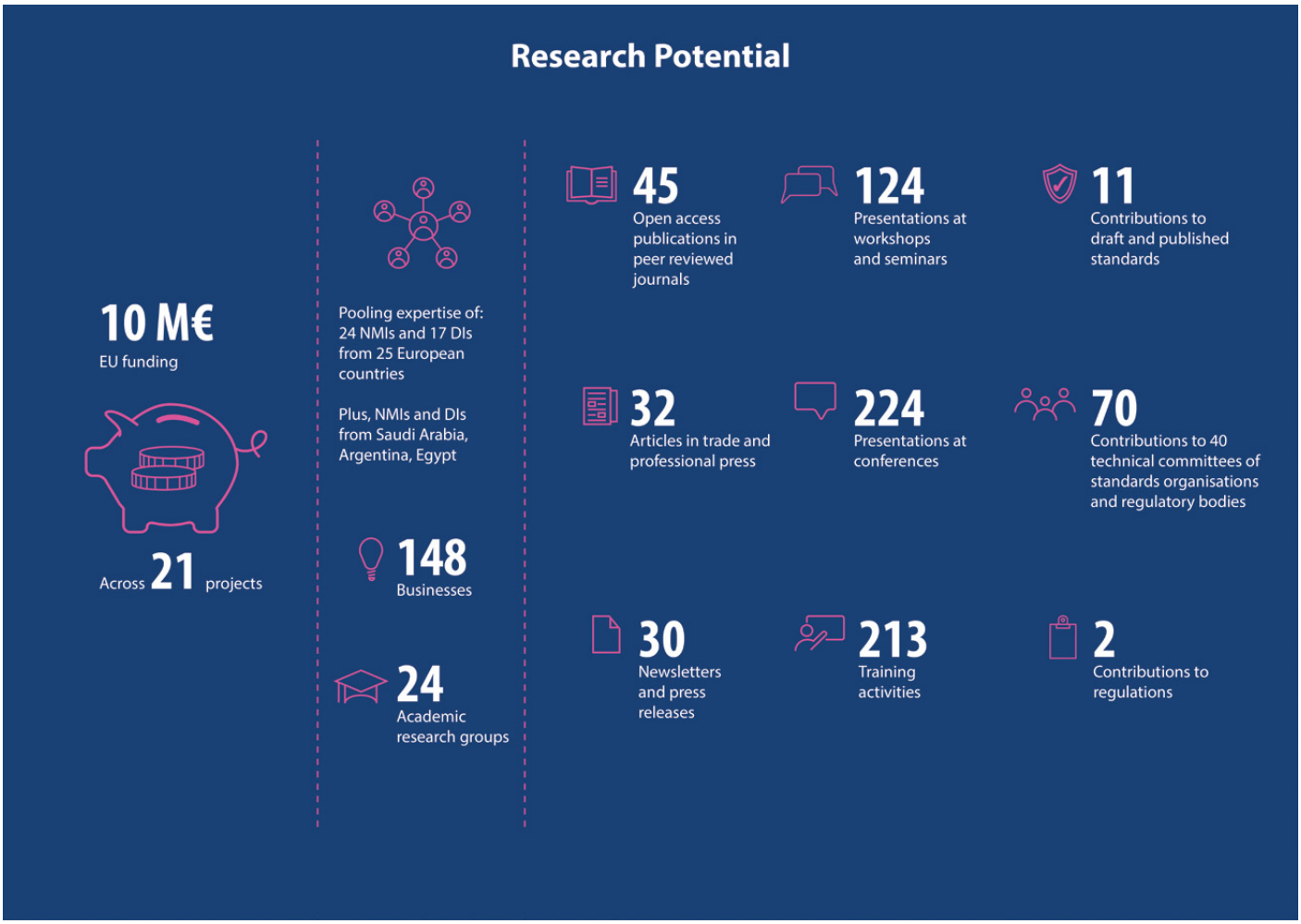
Humidity control is critical to many sensitive manufacturing processes, from semiconductor fabrication to the pharmaceutical industry. In the HUMEA project, 10 institutes from across the EU came together to share expertise, leading to the creation of new measurement procedures as well as a new calibration device, now serving the pharmaceutical and biochemical sectors.

Annex: Full list of projects

- Towards the propagation of ac quantum voltage standards (14RPT01, ACQ-PRO)
- Traceable calibration of automatic weighing instruments operating in the dynamic mode (14RPT02, AWICal)
- Matrix reference materials for environmental analysis (14RPT03, ENVCRM)
- Absorbed dose in water and air (14RPT04, Absorb)
- Developing traceable capabilities in thermal metrology (14RPT05, Eura-Thermal)
- Development of RF and microwave metrology capability (15RPT01, RFMicrowave)
- Underwater acoustic calibration standards for frequencies below 1 kHz (15RPT02, UNAC-LOW)
- Expansion of European research capabilities in humidity measurement (15RPT03, HUMEA)
- Traceability routes for electrical power quality measurements (15RPT04, TracePQM)
- Development of scientific and technical capabilities in the field of chemical analysis (16RPT01, ChemMet-Cap)
- Certified forensic alcohol reference materials (16RPT02, ALCOREF)
- Developing research capabilities for traceable intraocular pressure measurements (16RPT03, inTENSE)
- Research capabilities for radiation protection dosimeters (17RPT01, DOSEtrace)
- Establishing traceability for liquid density measurements (17RPT02, rhoLiq)
- A digital traceability chain for AC voltage and current (17RPT03, DIG-AC)
- A versatile electrical impedance calibration laboratory based on digital impedance bridges (17RPT04, VersICaL)
- Traceability for contact probe and stylus instrument measurements (18RPT01, ProbeTrace)
- Developing an infrastructure for improved and harmonised metrological checks of blood-pressure measurements in Europe (18RPT02, adOSSIG)

- Traceable measurement capabilities for monitoring thermocouple performance (18RPT03, MetForTC)
- Quantum traceability for AC power standards (19RPT01, QuantumPower)
- Improvement of the realisation of the mass scale (19RPT02, RealMass)

Full details of all projects in the Research Potential Theme can be found here:



Summary of outputs from EMPIR Research Potential theme.

The future of metrology in Europe

The EMPIR programme helped address a range of the EU's 'Grand Challenges' in Health, Energy, Environment and Industry, and made significant progress in fundamental measurement science. The European Partnership on Metrology (2021 to 2027) further extends this work to address global challenges, support the European Green Deal, and contribute to the development of self-sustaining, coordinated metrology infrastructures, with the capacity to continue joint research and innovation after 2030.

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