Call for Needs 2021

EURAMET e.V. announces the launch of the 2021 Call for Needs for the following topic areas, within the potential European Partnership on Metrology. Please note that the European Commission has published its candidates for European Partnerships under Horizon Europe, including the proposal submitted by EURAMET. To read the proposal and find out more about our goals for a European Partnership on Metrology, visit the European Commission's webpage.

2021 Call for Needs for the following topic areas:

- **Research Potential related to the Green Deal**
- **Metrology support for the Green Deal**
- **Metrology support for Regulation and Standards**

The Call is in general a two-stage process for joint research projects. As the partnership is still pending and subject to decision, we announce only the Call for Needs:

- **Call for Needs (Stage 1)** of the Call is for potential research topics and is open to any interested party, and opens 13 January 2021: **Deadline 22 February 2021, 23:59 CET.**
- The outcome of the Call for Needs could serve as a basis for a potential partnership call later in 2021 for joint research projects and is subject to eligibility criteria which may open in the third quarter of 2021.

Details are available on the dedicated website **https://msu.euramet.org**

Contact: Programme Manager, empir.msu@euramet.org

European Partnership on Metrology
Call 2022

EURAMET e.V. announces the launch of the 2022 call for needs for the following topic areas within the European Partnership on Metrology:

- **Metrology support for the Health**
- **Integrated European Metrology**
- **Metrology support for Digital Transformation**
- **Metrology support for Regulation and Standards**
- **Research Potential**

The Call is a two-stage process for joint research projects.

- **Stage 1** of the Call is for potential research topics (Call for Needs) and is open to any interested party, and opens 12 January 2022: **Deadline 21 February 2022, 23:59 CET.**
- **Stage 2** of the Call is for joint research projects and is subject to eligibility criteria, and opens on 23 June 2022: **Deadline: 03 October 2022, 23:59 CEST.**

Details are available on the dedicated website **www.metpart.eu**

Contact: Programme Manager, part.msu@euramet.org

European Partnership on Metrology Work Programme

Call 2021 - Budget and Features

Document: P-PRG-GUI-085 Version: 1.0
Approved: Programme Manager 2021-08-19

The European Partnership on Metrology Call Process Guides are written generically to apply to all programme calls. Where there are particular numbers, dates, or options that apply to a particular call then those details are given in the table below. Readers should start with the Guides for an explanation of the call process and refer to this table when directed for the specific information on an individual TP or call.

	Joint Research Projects TP Green Deal	**Joint Research Projects TP NRM**
Indicative budget (EU Contribution)	22.0 M€	4.0 M€
Average EU Contribution per project	2.2 M€	0.8 M€
Maximum EU Contribution per project	2.7 M€	1.0 M€
Expected EU Contribution to the external funded partners (% of total EU Contribution)	35 %	30 %
Maximum number of project partners	-	-
Duration	Up to 36 months	Up to 36 months
Call Process	Two stage – PRT, SRT, JRP	Two stage – PRT, SRT, JRP
Call for PRTs	2021-01-13 to 2021-02-22	2021-01-13 to 2021-02-22
Call for JRPs	2021-08-24 to 2021-10-11	2021-08-24 to 2021-10-11
Proposal guide and template	4	4

EURAMET MSU
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Evaluation process	The referees meet the proposers at a Review Conference before finalising their evaluation scores and producing a ranked list.	The referees meet the proposers at a Review Conference before finalising their evaluation scores and producing a ranked list.
Weighting for Excellence criteria	1.25	1.25
Weighting for Impact criteria	1.75	1.75
Weighting for Implementation criteria	1	1
Expected formal announcement of selected projects	2022-01-18	2022-01-18
Expected contract signature	2022-06-10 (8 months after stage 2 close)	2022-06-10 (8 months after stage 2 close)
Specific call requirements	-	-
Guardian	Joern.Stenger@ptb.de	ddelcampo@cem.es
Facilitator	Beatrice.Lalere@lne.fr	Eveline.Domini@lne.fr

European Partnership on Metrology
Work Programme – Call Scope
Research Potential related to the Green Deal (2021)

Document: P-PRG-GUI-084 Version: 0.5
Approved: EMPIR Committee 2020-09-22

EURAMET intends that the European Partnership on Metrology will develop a balanced and integrated metrology system in the participating countries. In addition to the main call in 2021 related to the Green Deal[1], EURAMET intends to support those countries that have emerging metrology research needs with "Research Potential" projects that will enable their development of scientific and technical research capabilities, related to the objectives of the main call. Potential Research Topics (PRTs) submitted in response to this call should be aligned with the challenges tackled in the Green Deal, such as those defined by major European regulation.

Potential Research Topics (PRTs) submitted for this call should identify:

- the particular metrology needs of stakeholders committed to work towards the objectives described in the Green Deal,
- the research capabilities that should be developed (as clear technical objectives) as a response to the Green Deal,
- national needs and any strategic priorities of a region with respect to the Green Deal, where relevant
- the impact this will have on the industrial competitiveness and societal needs laid out in the Green Deal, and
- how the research capability will be sustained and further developed after the project ends.

The development of the Research Potential should be to a level that would enable participation in the main calls during the timeframe of the Partnership. Proposers should note that the programme funds the activity of researchers to develop the capability, not the required infrastructure and capital equipment, which must be provided from other sources. While PRTs can focus on national needs, the Joint Research Proposals must combine the strategic priorities of several countries and develop an integrated and coordinated response ("smart specialisation") at a regional or European level.

[1] COM (2019) 640 final

European Partnership on Metrology
Work Programme – Call Scope

Metrology support for the Green Deal (2021)

Document: P-PRG-GUI-082 Version: 0.6
Approved: EMPIR Committee 2020-09-22

The "European Green Deal", launched in December 2019, sets out the comprehensive, highest-priority objectives of the European Union to tackle climate and environment-related challenges[1]. The Green Deal requires progress in:

- Increasing the EU's Climate ambition for 2030 and 2050
- Supplying clean, affordable and secure energy
- Mobilising industry for a clean and circular economy
- Building and renovating in an energy and resource efficient way
- Accelerating the shift to sustainable and smart mobility
- From 'Farm to Fork': a fair, healthy and environmentally friendly food system
- Preserving and restoring ecosystems and biodiversity
- A zero-pollution ambition for a toxic-free environment

The Horizon Europe Clusters "5. Climate, Energy and Mobility" and "6. Food, Bioeconomy, Natural Resources, Agriculture and Environment" in Pillar 2 "Global challenges and European Industrial Competitiveness" are closely related to the Green Deal.

The Green Deal is also intended to be a key pillar of the post-Covid-19 economic recovery plan for Europe.

This policy framework sets the context for the call "Metrology support for the Green Deal" in 2021. The European Partnership on Metrology aims at comprehensive, sustainable contributions to this policy framework by mobilising, pooling and developing the European metrology capabilities.

Potential Research Topics (PRTs) submitted in response to this call should describe research and development needs for metrology solutions in support of the Green Deal objectives. They should include the scientific and technological approaches required of academic and industrial stakeholders, and metrological approaches to underpin regulation and support standardisation.

The scope of this call goes beyond the scopes of earlier calls related to environment and energy under EMRP and EMPIR. Stakeholders increasingly ask for efficiencies and environmental impacts of whole cycles and systems. PRTs should respond to this with research needs to support the challenges addressed in the Green Deal, and how the stakeholders would benefit if those needs were met. Research to address these needs will require cross-disciplinary approaches such as combining metrological support for the development of clean energy technologies including generation, conversion, transport, storage and use in combination with metrology for their environmental impact assessment. With respect to environmental monitoring and climate/ocean challenges, cycles of matter, cross-compartment interactions and holistic methods for the assessment of impacts on the environment must be considered.

EURAMET is developing a sustainable integrated and coordinated metrological infrastructure through the European Metrology Networks, EMNs. If appropriate, PRTs should include a description how their objectives fit under the scope of one or more EMNs.

The Green Deal requires regulation. If appropriate, PRTs should describe how they support the development and/or the implementation of regulation.

The EU intends that activities in support of the Green Deal should also contribute to post-Covid-19 economic recovery. PRTs should describe the economic benefits that could result from the work they outline.

[1] COM (2019) 640 final

The Green Deal requires cooperation not only in Europe, but worldwide. EURAMET wishes to strengthen liaisons with partners such as other Partnerships and other key European stakeholders. The NMIs and DIs in Europe are very active under the Metre Convention, which provides a framework for metrology institutes of more than 100 countries representing 98 % of the world's GDP. Metrology is an interdisciplinary methodology and has a fundamental role in the European quality infrastructure. Traditionally and very successfully, it brings together various stakeholders and know-how providers such as research institutes, instrument manufacturers, metrology service providers, standardisation organisations, monitoring networks, regulators and policy makers. PRTs should describe how European and international partners could be involved in meeting the needs described.

European Partnership on Metrology
Work Programme – Call Scope

Metrology support for Regulation and Standards (2021)

Document: P-PRG-GUI-083 Version: 0.3
Approved: EMPIR Committee 2020-09-22

A wide variety of industry needs to access facilities that enable it to test, validate, and ensure compliance with regulation. The National Metrology Institutes were originally established to provide this infrastructure. Within the EU, European Standards and accreditation are key to providing public confidence that measurements made in support of regulation can be relied upon.

This framework sets the context for the call "Metrology support for Regulation and Standards" in 2021. The European Partnership on Metrology aims at comprehensive, sustainable contributions in this area by mobilising, pooling and developing the European metrology capabilities.

Potential Research Topics (PRTs) submitted in response to this call should describe research and development needs for metrology solutions required for standardisation, regulation and conformity assessment. Proposed topics should address one of the following strands:

1. Specific documented demands of European and international Standards Developing Organisations (SDOs) for metrological research in any area. Proposals may address the development of traceable measurement methods or the provision of validated data sets, which are required for documentary standards. The demand for the research shall be demonstrated by clear reference to the measurement needs within strategic documents published by the SDO (Technical Committee(s) (TCs) or Working Group(s), (WGs), (e.g. in the Business Plans or Work Programmes) or by a letter signed by the convenor of the respective TC/WG). Proposals in this strand are expected to address actual standardisation development work.
2. The metrological background of EU regulation, by either responding to documented requirements or by exploring the background and feasibility of expected possible future regulation. Proposals may address the development of traceable measurement methods or the provision of validated data sets, which are required for these purposes.

For both strands it is expected that projects selected for funding will have fewer partners and lower eligible costs than Joint Research Projects selected under other calls.

EURAMET encourages proposals that include representatives from industry, regulators and standardisation bodies for their active participation in the projects, specifically to ensure that the project outputs are acknowledged by the SDO TC/WG or regulatory authority. EURAMET would welcome proposals reflecting standardisation needs related to pan European research initiatives (such as the Quantum Flagship or the Graphene Flagship).

EURAMET wishes to generate benefit for European and international SDOs whilst exploiting the unique capabilities of its member National Metrology Institutes and Designated Institutes. This call is intended to enable and promote collaborative research going beyond the state of the art and strengthen the mutual cooperation of European NMIs, leading to coordinated European metrology infrastructures where appropriate.

European Partnership on Metrology Work Programme

Call 2022 - Budget and Features

Document: P-PRG-GUI-125 Version: 1.1
Approved: Partnership Committee 2022-06-02

The European Partnership on Metrology Call Process Guides are written generically to apply to all programme calls. Where there are particular numbers, dates, or options that apply to a particular call then those details are given in the table below. Readers should start with the Guides for an explanation of the call process and refer to this table when directed for the specific information on an individual TP or call.

	Joint Research Projects **TP HLT**	**Joint Research Projects** **TP IEM**	**Joint Research Projects** **TP DIT**	**Joint Research Projects** **TP NRM**	**Joint Research Projects** **TP RPT**
Indicative budget (EU Contribution)	15.5 M€	15.0 M€	6.0 M€	4.5 M€	2.0 M€
Average EU Contribution per project	1.9 M€	1.9 M€	1.7 M€	0.8 M€	0.5 M€
Maximum EU Contribution per project	2.6 M€	2.6 M€	2.4 M€	1.2 M€	0.9 M€
Expected EU Contribution to the external funded partners (% of total EU Contribution)	35 %	25 %	35 %	30 %	20 %
Maximum number of project partners	-	-	-	-	-
Duration	Up to 36 months	Up to 36 months	Up to 36 months	Up to 36 months	Up to 36 months
Call Process	Two stage – PRT, SRT, JRP	Two stage – PRT, SRT, JRP	Two stage – PRT, SRT, JRP	Two stage – PRT, SRT, JRP	Two stage – PRT, SRT, JRP
Call for PRTs	2022-01-12 to 2022-02-21	2022-01-12 to 2022-02-21	2022-01-12 to 2022-02-21	2022-01-12 to 2022-02-21	2022-01-12 to 2022-02-21
Call for JRPs	2021-06-23 to 2021-10-03	2021-06-23 to 2021-10-03	2021-06-23 to 2021-10-03	2021-06-23 to 2021-10-03	2021-06-23 to 2021-10-03
Proposal guide and template	4	4	4	4	4

Evaluation process	The referees meet the proposers at a Review Conference before finalising their evaluation scores and producing a ranked list.	The referees meet the proposers at a Review Conference before finalising their evaluation scores and producing a ranked list.	The referees meet the proposers at a Review Conference before finalising their evaluation scores and producing a ranked list.	The referees meet the proposers at a Review Conference before finalising their evaluation scores and producing a ranked list.	The referees meet the proposers at a Review Conference before finalising their evaluation scores and producing a ranked list.
Weighting for Excellence criteria	1.25	1.75	1.25	1.25	1.25
Weighting for Impact criteria	1.75	1.25	1.75	1.75	1.5
Weighting for Implementation criteria	1	1	1	1	1.25
Expected formal announcement of selected projects	2023-01-10	2023-01-10	2023-01-10	2023-01-10	2023-01-10
Expected contract signature	2023-06-02 (8 months after stage 2 close)	2023-06-02 (8 months after stage 2 close)	2023-06-02 (8 months after stage 2 close)	2023-06-02 (8 months after stage 2 close)	2023-06-02 (8 months after stage 2 close)
Specific call requirements	-	-	-	-	-
Guardian	mpieksma@vsl.nl	erkki.ikonen @aalto.fi	rado.lapuh@gov.si	ddelcampo @cem.es	Paul.Hetherington @nsai.ie
Facilitator	kweberova@cmi.cz	Thekla.Kiffmeyer @ptb.de	dana.vlad@ economie.fgov.be	Eveline.Domini@ @lne.fr	Tanasko.Tasic @euramet.org

European Partnership on Metrology
Work Programme – Call Scope
Metrology support for Digital Transformation (2022)

Document: P-PRG-GUI-122 Version: 1.0
Approved: Board of Directors 2021-12-01

The European Partnership on Metrology aims at a self-sustaining and effective system for metrology at a European level, that ensures Europe has a world-class metrology system that:

- Provides metrology solutions and fundamental metrological reference data and methods.
- Offers fit-for-purpose measurement solutions, supporting and stimulating European innovation.
- Responds to industrial and societal challenges.
- Supports and enables effective design and implementation of regulations and standards, that underpin public policies addressing these challenges.

The European Partnership on Metrology foresees a sequence of calls over seven years to deliver these aims.

Aligned with the priorities of Horizon Europe, EURAMET has identified the digital transformation as one of the highest-priority technological challenges. In fact, it affects almost all technological areas with manifold implications for metrology. Measurement standards and metrological services must be kept updated and new metrological solutions must be developed for complex, digital measurement scenarios. Data generation, processing, transmission and storage becomes more and more digital, complex sensor networks require systemic approaches, and algorithms based on methods of artificial intelligence and machine learning require completely new methods for quality assurance of measurement results.

The Targeted Programme on **Metrology for Digital Transformation** complements other planned calls targeting metrology challenges in the areas of Green Deal, Health, Industrial Innovation, Fundamental Metrology, Integrated European Metrology, and Standardisation/Regulation. It addresses specific digital topics that have a generic or cross-disciplinary character.

Proposed topics may address metrological methods and solutions both for digitised measurement scenarios and for data as such, including:

- Generic approaches to metrology-based quality-secured data generation, processing and storage that underpin different measurement applications, and for which common, harmonised methods are needed. Data clouds and smart metering in regulated areas are examples.
- Metrology for large sensor networks and "big-data", including modelling of systems.
- Generic in-situ methods for the Internet of Things (IoT) use cases, including in-situ traceability in fully-digital sensor scenarios.
- Assessing and understanding robustness, functionality, reliability and quality of measurement scenarios that include artificial intelligence, machine learning or deep learning.
- Development of fundamental requirements for reference data for the validation of digital measurement scenarios and algorithms, which may include artificial intelligence. Expected outputs include guidelines and standards for metadata and protocols supporting the reliable, trusted and unambiguous communication of data in digital infrastructures.
- Methods for the (automated) assessment of data quality and data quality assessment tools, which is key for their interpretability and usability.

The proposed generic methods and solutions shall be developed starting from concrete applications with documented stakeholder interest, and if possible, from different areas of application. Simultaneously, proposals shall describe the generalisability of the approaches.

The international harmonisation of standards is a key priority of metrology. Proposals shall describe links and relations to key organisations on European and international level that develop digital standards or have introduced de-facto standards. Other European Partnerships, e. g. EOSC, are among those key stakeholders. Industrial stakeholders, which have an interest to use digital data from testing and calibration in their processes, are another group of key stakeholders.

European Partnership on Metrology
Work Programme – Call Scope
Metrology support for Health (2022)

Document: P-PRG-GUI-120 Version: 1.0
Approved: Board of Directors 2021-12-01

The European Partnership on Metrology aims at a self-sustaining and effective system for metrology at a European level, that ensures Europe has a world-class metrology system that:

- Provides metrology solutions and fundamental metrological reference data and methods.
- Offers fit-for-purpose measurement solutions, supporting and stimulating European innovation.
- Responds to industrial and societal challenges.
- Supports and enables effective design and implementation of regulations and standards, that underpin public policies addressing these challenges.

The European Partnership on Metrology foresees a sequence of calls over seven years to deliver these aims.

The call on **Metrology for Health** is to support more reliable and efficient diagnostic and therapeutic techniques through metrological research and development. The call also addresses the development of new techniques to improve healthcare at lower cost, to improve patient quality of life, as well as to support the competitiveness of European medical industries and services.

To enhance the impact of the R&D work and to include world leading expertise, the involvement of the larger health community, such as (academic) hospitals, (medical) universities and centres, medical products and equipment manufacturers, healthcare providers and insurers, decision makers, regulators and patient advocacy groups is expected (including subsidiary services). If appropriate, proposals should address specific demands of standards related to the health field and/or clinical guidelines.

Healthcare increasingly relies on personalised medicine and monitoring, multi-parametric medical treatments and measurements, medical devices and active implants, applications of nanotechnology, multi-modality imaging data, (big) data analysis, and applications of artificial intelligence (AI) and machine learning.

Topics could include, but are not limited to:

- Metrological methods to ensure efficacy and safety for diagnostics, including remote diagnostics, and therapeutics, also on cell and molecular levels.
- Procedures, analytical methods and statistical models to underpin epidemiology and strengthen disease prevention and protection of public health, including preparedness for future pandemics and resilience to medication.
- Metrological methods for digital technologies applied in the health sector, such as in medical devices, image analysis and personalised medicine.
- Metrological methods for advanced (multi-modal) radiotherapy, nanomedicine and theranostics (therapy in combination with diagnostics).
- Quality assurance of test procedures, test kits and vaccines for infectious diseases such as Covid-19, but also other virus- or bacteria-induced diseases, as well as non-infectious and non-transmissible diseases.
- Metrological methods for drug delivery, microfluidic applications and nanotoxicology, including engineering solutions such as closed-loop therapeutic drug delivery and sensing solution technologies.

Proposed topics should indicate where metrology makes a difference and should address clear stakeholder needs. To enhance the impact of the R&D work, the involvement of the larger community, such as the European Metrology Networks, as appropriate, is expected.

Proposals should also describe, where appropriate, how the gender dimension (i.e. sex and/or gender analysis) is taken into account in the project's research and innovation priorities, methods and content.

European Partnership on Metrology
Work Programme – Call Scope
Integrated European Metrology (2022)

Document: P-PRG-GUI-121 Version: 1.0
Approved: Board of Directors 2021-12-01

The European Partnership on Metrology aims at a self-sustaining and effective system for metrology at a European level, that ensures Europe has a world-class metrology system that:

- Provides metrology solutions and fundamental metrological reference data and methods.
- Offers fit-for-purpose measurement solutions, supporting and stimulating European innovation.
- Responds to industrial and societal challenges.
- Supports and enables effective design and implementation of regulations and standards, that underpin public policies addressing these challenges.

The European Partnership on Metrology foresees a sequence of calls over seven years to deliver these aims.

The call on **Integrated European Metrology** complements other planned calls targeting metrology challenges in the areas of Green Deal, Health, Industrial Innovation, Fundamental Metrology, Digital Transformation and Standardisation/Regulation. It specifically aims at the development of integrated, self-sustaining European metrology structures. The call supports the joint research and development of new advanced techniques for providing traceability of measurement results to the users of metrology services. All technological disciplines and metrological fields may be addressed if stakeholder needs are documented or can be convincingly anticipated.

The metrological capabilities and infrastructures of the NMIs and DIs should be jointly developed to address these needs, should demonstrate a high level of integration and coordination, and aimed to be internationally leading.

Proposals must describe:

1. Concrete metrology needs, such as related documents published by the stakeholders.
2. Contributions that the joint, self-sustaining research and service capabilities will make in underpinning regulation, EU policies that address societal challenges, or industrial needs.
3. The added value provided through coordination and integration of capabilities of several institutes beyond capabilities of a single institute.

Engagement of existing European research infrastructures may produce advantages for selected metrology areas. The call will support establishment of research networks aimed at elaborating and proposing metrological research topics to large international infrastructures. To enhance the impact of the R&D work and to include world leading expertise, the involvement of the larger community such as the metrology R&D resources outside Europe, as appropriate, is expected.

As part of the project proposal stage, it is expected that the consortia develop a plan for smart specialisation in research and for the structured provision of sustainable measurement services in the area of the project idea. Proposals should allow and encourage the participation of small and emerging institutes. This is especially relevant for proposals underpinning EU regulation or other challenges with an inherent interest of stakeholders of all European countries. Partners should support each other and coordinate the contributions as far as possible aligned with the stakeholder needs.

European Partnership on Metrology
Work Programme – Call Scope
Metrology support for Regulation and Standards (2022)

Document: P-PRG-GUI-123 Version: 1.0
Approved: Board of Directors 2021-12-01

EURAMET intends that the European Partnership on Metrology will support and enable effective design and implementation of regulation and standards that underpin public policies that address societal challenges.

This sets the context for the call "**Metrology support for Regulation and Standards**" in 2022. The European Partnership on Metrology aims at comprehensive, sustainable contributions in this area by mobilising, pooling and developing the European metrology capabilities.

Potential Research Topics (PRTs) submitted in response to this call should describe research and development needs for metrology solutions required for standardisation, regulation and conformity assessment. Proposed topics should address one of the following strands:

1. Specific documented demands of European and international Standards Developing Organisations (SDOs) for metrological research in any area. Proposals may address the development of measurement methods to ensure traceability, the provision of validated data sets, which are required for documentary standards. The demand for the research shall be demonstrated by clear reference to the measurement needs within strategic documents published by the SDO, by a letter signed by the convenor of the respective SDO TC/WG or by their co-authorship of the PRT.
2. The metrological background of EU regulation, by either responding to documented requirements or by exploring the background and feasibility of expected possible future regulation. Proposals may address the development of traceable measurement methods or the provision of validated data sets, which are required for these purposes.

Aligned with EU's strategy on "Shaping Europe's digital future", EURAMET's strategy 2030 describes digitalisation as a key priority. This is relevant for both strands, and therefore proposals are encouraged that respond to challenges associated with the digital transformation.

EURAMET encourages proposals that include representatives from industry, regulators, and standardisation bodies for their active participation in the projects, specifically to ensure that the project outputs are taken up by the SDO or regulatory authority. EURAMET would welcome proposals reflecting standardisation needs related to pan European research initiatives (such as Flagships) or to support other Partnerships under Horizon Europe.

EURAMET wishes to generate benefit for European and international stakeholders whilst exploiting the unique capabilities of its member National Metrology Institutes (NMI) and Designated Institutes (DI). This call is intended to enable and promote collaborative research going beyond the state of the art and strengthen the mutual co-operation of European NMIs and DIs, leading to coordinated European metrology infrastructures where appropriate.

For both strands it is expected that projects selected for funding will have fewer partners and lower eligible costs than Joint Research Projects selected under other calls.

European Partnership on Metrology
Work Programme – Call Scope
Metrology support for Research Potential (2022)

Document: P-PRG-GUI-124 Version: 1.0
Approved: Board of Directors 2021-12-01

EURAMET intends that the European Partnership on Metrology will develop a balanced and integrated metrology system in the participating countries. In addition to the main calls in 2022 related to Health, Integrated European Metrology, Digital transformation and Normative, EURAMET intends to support those countries that have emerging metrology research needs with "**Research Potential**" projects that will enable their development of scientific and technical research capabilities across all areas covered by the main Partnership calls. Potential Research Topics (PRTs) submitted in response to this call should be designed to tackle relevant research and development in metrology, such as: develop new techniques and measurement capabilities, develop measurement or digital transformation solutions being too limited or specialised for a main call, or develop specific research capabilities that would be necessary to underpin research on a potential future main call topic.

Potential Research Topics (PRTs) submitted for this call should identify:

- the research capabilities that should be developed (as clear technical objectives),
- the area for which the capabilities are built (Green Deal, Digital Transformation, Health, Integrated European Metrology, Industry, Normative or Fundamental Metrology),
- in which future main call the developed research capabilities are planned to be employed,
- the particular metrology needs of stakeholders and the difference that the metrology research will make,
- national needs and any strategic priorities of a region with respect to the specified area proposed,
- the impact this research will have on those countries' NMI/DI that have emerging metrology research needs,
- how the developed research capability of the participating NMIs/DIs will be sustained and further developed after the project ends.

The development of the Research Potential should be to a level that would enable participation in the main calls during the timeframe of the Partnership. Proposers should note that the programme funds the activity of researchers to develop the capability, not the required infrastructure and capital equipment, which must be provided from other sources. While PRTs can focus on national needs, the Joint Research Proposals must combine the strategic priorities of several countries and develop an integrated and coordinated response ("smart specialisation") at a regional or European level.

Potential Partnership for Metrology - Call 2021
AGENDA - timings are Central European Time (CET)
DAY 3 - 24th November (Green Deal)

Time		Referees	JRP representatives
08:30	CET	**Virtual registration for referees and JRP representatives**	
09:00	CET	**WELCOME SESSION: ALL DELEGATES ▲**	
		Welcome Plenary *Speaker: Programme Manager*	
09:30	CET	**Break to change MS Teams sessions**	
09:35	CET	**REFEREE SESSION ▲**	**JRP REPRESENTATIVE SESSION ▲**
		Evaluation guidance for referees *Speaker: Programme Manager*	**What to expect at the review conference** *Speaker: EURAMET MSU*
10:15	CET	**Referees break to change MS Teams sessions**	
10:20	CET	**BREAKOUT SESSION: REFEREES ▲**	**JRP REPRESENTATIVE SESSION ▲**
		GROUP 1 | GROUP 2 | GROUP 3 | GROUP 4	**What to expect if your proposal is successful** *Speaker: EURAMET MSU*
		Referees introduction *Chaired by the EURAMET MSU facilitators*	
10:45	CET	**Coffee break referees** **10:45-11:15am**	
11:00	CET		**Coffee break JRP representatives** **11:00-11:15am**
11:15	CET	**BREAKOUT SESSION: REFEREES & JRP REPRESENTATIVES▲**	
		GROUP 1 | GROUP 2	GROUP 3 | GROUP 4
		Presentation session The session is comprised of pre-allocated presentation sessions of 25 minutes for each proposal/representative. Representatives have been assigned their pre-allocated session in ascending proposal number order within their respective groups. Representatives should join the MS Teams session at least 5 minutes before the start time for their pre-allocated session as shown in the timings below, and will be held in a lobby until the referees are ready for them. Each pre-allocated session comprises: • A 10 minute presentation from the proposal representative. • 15 minutes of informal questions from the referees. Referees within the group who were asked to focus on the proposal will ask their questions first. Then questions from the remaining referees in the group can be asked. Please end promptly to ensure fairness to all proposals/representatives.	
11:25	CET	Presentation session begins for the first proposal/representative within the group	
11:50	CET	Presentation session begins for the second proposal/representative within the group	
12:15	CET	Presentation session begins for the third proposal/representative within the group	
12:40	CET	**Lunch break all**	
13:40	CET	Presentation session begins for the fourth proposal/representative within the group	
14:05	CET	Presentation session begins for the fifth proposal/representative within the group (if applicable)	
14:05 - 14:30	CET	**Coffee break referees**	**DAY 1 ends for JRP representatives** **DAY 2 continues with the Formal Q&A session**
14:35 - 15:00	CET	**BREAKOUT SESSION: REFEREES** GROUP 1 | GROUP 2 | GROUP 3 | GROUP 4 **Referees' development of questions** The referees will discuss their first impressions of the proposals and develop questions for each proposal. The questions will be asked to the JRP representatives in the formal question and answer session the following day.	
16:00 - 16:10	CET	**Coffee break referees**	
16:30	CET	**BREAKOUT SESSION CONTINUED: REFEREES** GROUP 1 | GROUP 2 | GROUP 3 | GROUP 4 Referees' development of questions continued	
17:15 - 17:30	CET	**DAY 1 ends for referees** **DAY 2 continues @08:45 CET with registration**	

Potential Partnership for Metrology - Call 2021
AGENDA - timings are Central European Time (CET)
DAY 4 - 25th November (Green Deal)

08:45	CET	**Virtual registration for referees**			
09:00	CET	**BREAKOUT SESSION: REFEREES & JRP REPRESENTATIVES ▲**			
		GROUP 1	**GROUP 2**	**GROUP 3**	**GROUP 4**
		Formal question and answer session Each representative will be asked the questions the referees have developed in the previous session. Representatives will be questioned individually in ascending proposal number order within their respective groups. Representatives should join the MS Teams session at least 5 minutes before the start time for their Q&A session as shown in the timings below, and will be held in a lobby until the referees are ready for them. Each representative's Q&A session has been allocated 5 minutes maximum for the representative's declaration and 15 minutes maximum for their questions and answers.			
09:10	CET	Q&A session begins for the first proposal/representative within the group			
09:30	CET	Q&A session begins for the second proposal/representative within the group			
09:50	CET	Q&A session begins for the third proposal/representative within the group			
10:10	CET	Q&A session begins for the fourth proposal/representative within the group			
10:30	CET	Q&A session begins for the fifth proposal/representative within the group (if applicable)			
10:30 - 10:50	CET	**Coffee break referees**		**Meeting ends for JRP representatives**	
11:00 - 11:15	CET	**BREAKOUT SESSION: REFEREES**			
		GROUP 1	**GROUP 2**	**GROUP 3**	**GROUP 4**
		A reminder of the tasks *Speaker: EURAMET MSU facilitator*			
11:15 - 11:30	CET	**Marking session** Referees agree a consensus mark for each proposal against the evaluation criteria, and complete one marking sheet for each proposal. The referees who concentrated on the proposal under discussion should make the most comments, but all referees may comment on a proposal. Referees should establish a ranked list of all proposals in their group. This list and the marking sheets are then submitted to the EURAMET MSU.			
12:40 - 13:10	CET	**Lunch break referees**			
13:40 - 13:55	CET	**BREAKOUT SESSION CONTINUED: REFEREES**			
		GROUP 1	**GROUP 2**	**GROUP 3**	**GROUP 4**
		Marking session continued.			
15:30	CET	**Coffee break referees**			
16:15	CET	**REFEREE DISCUSSIONS: ALL REFEREES ▲**			
		Discussion of the single ranked list *Chaired by the Programme Manager* During the coffee break, the EURAMET MSU will establish a preliminary single ranked list of proposals. They will identify those that fall near the funding cut-off point and these will be the focus of this session's discussions. The referees will discuss the preliminary single ranked list of proposals in order to establish their final single ranked list of all proposals. The Programme Manager will provide procedural advice and capture the results including the decision for each proposal.			
17:15	CET	**Meeting ends**			

The EMPIR Chair and Deputy Chair may observe sessions marked ▲

Potential Partnership for Metrology - Call 2021
AGENDA - timings are Central European Time (CET)
DAY 1 - 22nd November (Normative)

08:30	CET	**Virtual registration for referees and JRP representatives**		
09:00	CET	**WELCOME SESSION: ALL DELEGATES ▲**		
		Welcome Plenary *Speaker: Programme Manager*		
09:30	CET	**Break to change MS Teams sessions**		
09:35	CET	**REFEREE SESSION ▲**		**JRP REPRESENTATIVE SESSION ▲**
		Evaluation guidance for referees *Speaker: Programme Manager*		**What to expect at the review conference** *Speaker: EURAMET MSU*
10:15	CET	**Referees break to change MS Teams sessions**		
10:20	CET	**BREAKOUT SESSION: REFEREES ▲**		**JRP REPRESENTATIVE SESSION ▲**
		GROUP 1	**GROUP 2**	**What to expect if your proposal is successful** *Speaker: EURAMET MSU*
		Referees introduction *Chaired by the EURAMET MSU facilitators*		
10:45	CET	**Coffee break referees** **10:45-11:15am**		
11:00	CET			**Coffee break JRP representatives** **11:00-11:15am**
11:15	CET	**BREAKOUT SESSION: REFEREES & JRP REPRESENTATIVES ▲**		
		GROUP 1		**GROUP 2**
		Presentation session The session is comprised of pre-allocated presentation sessions of 25 minutes for each proposal/representative. Representatives have been assigned their pre-allocated session in ascending proposal number order within their respective groups. Representatives should join the MS Teams session at least 5 minutes before the start time for their pre-allocated session as shown in the timings below, and will be held in a lobby until the referees are ready for them. Each pre-allocated session comprises: • A 10 minute presentation from the proposal representative. • 15 minutes of informal questions from the referees. Referees within the group who were asked to focus on the proposal will ask their questions first. Then questions from the remaining referees in the group can be asked. Please end promptly to ensure fairness to all proposals/representatives.		
11:25	CET	Presentation session begins for the first proposal/representative within the group		
11:50	CET	Presentation session begins for the second proposal/representative within the group		
12:15	CET	Presentation session begins for the third proposal/representative within the group		
12:40	CET	**Lunch break all**		
13:40	CET	Presentation session begins for the fourth proposal/representative within the group		
14:05	CET	Presentation session begins for the fifth proposal/representative within the group		
14:30	CET	Presentation session begins for the sixth proposal/representative within the group (if applicable)		
14:30 - 14:55	CET	**Coffee break referees**		**DAY 1 ends for JRP representatives** **DAY 2 continues with the Formal Q&A session**
15:00 - 15:15	CET	**BREAKOUT SESSION: REFEREES**		
		GROUP 1	**GROUP 2**	
		Referees' development of questions The referees will discuss their first impressions of the proposals and develop questions for each proposal. The questions will be asked to the JRP representatives in the formal question and answer session the following day.		
16:10 - 16:25	CET	**Coffee break referees**		
16:30 - 16:45	CET	**BREAKOUT SESSION CONTINUED: REFEREES**		
		GROUP 1	**GROUP 2**	
		Referees' development of questions continued		
17:30 - 18:05	CET	**DAY 1 ends for referees** **DAY 2 continues @08:45 CET with registration**		

Potential Partnership for Metrology - Call 2021
AGENDA - timings are Central European Time (CET)
DAY 2 - 23rd November (Normative)

08:45	CET	**Virtual registration for referees**	
09:00	CET	**BREAKOUT SESSION: REFEREES & JRP REPRESENTATIVES ▲**	
		GROUP 1	**GROUP 2**
		Formal question and answer session Each representative will be asked the questions the referees have developed in the previous session (at the end of Day 1). Representatives will be questioned individually in ascending proposal number order within their respective groups. Representatives should join the MS Teams session at least 5 minutes before the start time for their Q&A session as shown in the timings below, and will be held in a lobby until the referees are ready for them. Each representative's Q&A session has been allocated 5 minutes maximum for the representative's declaration and 15 minutes maximum for their questions and answers.	
09:10	CET	Q&A session begins for the first proposal/representative within the group	
09:30	CET	Q&A session begins for the second proposal/representative within the group	
09:50	CET	Q&A session begins for the third proposal/representative within the group	
10:10	CET	Q&A session begins for the fourth proposal/representative within the group	
10:30	CET	Q&A session begins for the fifth proposal/representative within the group	
10:50	CET	Q&A session begins for the sixth proposal/representative within the group (if applicable)	
10:50 - 11:10	CET	**Coffee break referees**	**Meeting ends for JRP representatives**
11:15 - 11:30	CET	**BREAKOUT SESSION: REFEREES**	
		GROUP 1	**GROUP 2**
		A reminder of the tasks *Speaker: EURAMET MSU facilitator*	
11:30 - 11:45	CET	**Marking session** Referees agree a consensus mark for each proposal against the evaluation criteria, and complete one marking sheet for each proposal. The referees who concentrated on the proposal under discussion should make the most comments, but all referees may comment on a proposal. Referees should establish a ranked list of all proposals in their group. This list and the marking sheets are then submitted to the EURAMET MSU.	
13:30	CET	**Lunch break referees**	
14:10 - 14:30	CET	**BREAKOUT SESSION CONTINUED: REFEREES**	
		GROUP 1	**GROUP 2**
		Marking session continued.	
16:15	CET	**Coffee break referees**	
17:00	CET	**REFEREE DISCUSSIONS: ALL REFEREES ▲**	
		Discussion of the single ranked list *Chaired by the Programme Manager* During the coffee break, the EURAMET MSU will establish a preliminary single ranked list of proposals. They will identify those that fall near the funding cut-off point and these will be the focus of this session's discussions. The referees will discuss the preliminary single ranked list of proposals in order to establish their final single ranked list of all proposals. The Programme Manager will provide procedural advice and capture the results including the decision for each proposal.	
18:00	CET	**Meeting ends**	

The EMPIR Chair and Deputy Chair may observe sessions marked ▲

Call 2022 – Normative

AGENDA

Tuesday 8th November

<table>
<tr><td>08:00</td><td colspan="2">Registration (Atrium Level 0)</td></tr>
<tr><td rowspan="2">09:00</td><td colspan="2">WELCOME SESSION: ALL DELEGATES▲ (ON AIR + BACK STAGE LEVEL 0)</td></tr>
<tr><td colspan="2">Speaker: Programme Manager</td></tr>
<tr><td rowspan="2">09:30</td><td>REFEREE SESSIONS▲
(ON AIR + BACK STAGE LEVEL 0)</td><td>JRP REPRESENTATIVE SESSIONS ▲
(TALK SHOW LEVEL 0)</td></tr>
<tr><td>Referees introduction
Chaired by the MSU facilitators</td><td>What to expect at the review conference
Speaker: Programme Manager</td></tr>
<tr><td>10:00</td><td>Evaluation guidance for referees
Speaker: Programme Manager</td><td>What to expect if your proposal is successful
Speaker: Deputy Programme Manager</td></tr>
<tr><td>10:45</td><td colspan="2">Coffee break (Atrium Level 0)</td></tr>
<tr><td rowspan="2">11:15</td><td colspan="2">POSTER SESSION: ALL DELEGATES▲ (ON AIR, BACK STAGE LEVEL 0)</td></tr>
<tr><td colspan="2">The poster session is comprised of pre-allocated poster presentation sessions of 20 minutes. Please see the poster timetable provided. Each pre-allocated session comprises:
• A 5 minute presentation from the proposal representative.
• 15 or 20 minutes of informal questions from the referees.
• A maximum of 3 referees at each poster during a pre-allocated session.
• A bell will signal the end of each pre-allocated session. Please end promptly.</td></tr>
<tr><td>12:15</td><td colspan="2">Lunch break (Atrium Level 0)</td></tr>
<tr><td rowspan="2">13:00</td><td colspan="2">POSTER SESSION CONTINUED: ALL DELEGATES▲ (ON AIR, BACK STAGE LEVEL 0)</td></tr>
<tr><td colspan="2">Poster session continued.
JRP representatives will also be required for an open session for any further questions from referees from other groups. Please note that during the open session the number of referees has not been scheduled and so may vary.</td></tr>
<tr><td>14:30</td><td colspan="2">Coffee break (Atrium Level 0)</td></tr>
<tr><td rowspan="3">14:45</td><td colspan="2">BREAKOUT SESSION: REFEREES</td></tr>
<tr><td>GROUP 1 (L'INTERVIEW LEVEL 3)</td><td>GROUP 2 (LE STUDIO LEVEL 3)</td></tr>
<tr><td colspan="2">Referees' development of questions
The referees will discuss their first impressions of the proposals and develop questions for each proposal. The questions will be asked to the JRP representatives in the formal question and answer session.</td></tr>
<tr><td>17:00</td><td colspan="2">Coffee break (Level 3)</td></tr>
<tr><td rowspan="3">17:15</td><td colspan="2">BREAKOUT SESSION: REFEREES & JRP REPRESENTATIVES▲</td></tr>
<tr><td>GROUP 1 (L'INTERVIEW LEVEL 3)</td><td>GROUP 2 (LE STUDIO LEVEL 3)</td></tr>
<tr><td colspan="2">Formal question and answer session
JRP representatives will have a maximum of 15 minutes to answer questions that the group of referees have formulated for them, in the previous session.
Each JRP representative will be called into the room individually, in ascending numerical order for the proposals within the group. Each JRP representative will sit in the room in front of the referees whilst being questioned.
Each JRP representative will be recorded by the EURAMET MSU as a record of their answers. All recordings will be kept securely by EURAMET.
After this session JRP representatives may leave.</td></tr>
<tr><td>18:55</td><td colspan="2">Meeting Ends</td></tr>
<tr><td>19:30</td><td colspan="2">Conference dinner: referees and EURAMET (Restaurant Level 1)</td></tr>
</table>

Call 2022 – Normative

AGENDA
Wednesday 9th November

08:45	**REFEREES▲ (ON AIR + BACK STAGE LEVEL 0)**	
	A reminder of the tasks *Speaker: Programme Manager*	
09:00	**MARKING SESSION: REFEREES**	
	GROUP 1 (L'INTERVIEW LEVEL 3)	**GROUP 2 (LE STUDIO LEVEL 3)**
	Referees agree consensus marks for each proposal against the evaluation criteria, and complete one marking book for each proposal. The referees who were asked to focus on the proposal under discussion should lead the discussions, but all referees may contribute. Referees should establish a ranked list of all proposals in their group. This list and the marking books are captured by the MSU.	
11:00	**Coffee break (Level 3)**	
11:30	**MARKING SESSION CONTINUED: REFEREES**	
	GROUP 1 (L'INTERVIEW LEVEL 3)	**GROUP 2 (LE STUDIO LEVEL 3)**
	Marking session continued.	
13:15	**Lunch break (Restaurant Level 1)**	
14:15	**SINGLE RANKED LIST & CLOSING SESSION▲ (ON AIR + BACK STAGE LEVEL 0)**	
	Chaired by the Programme Manager During lunch, the MSU will have established a preliminary single ranked list of proposals. They will identify those that fall near the funding cut-off point and these will be the focus of this session's discussions. The referees will discuss the preliminary single ranked list of proposals in order to establish their final single ranked list of all proposals. The Programme Manager will provide procedural advice and capture the results.	
15:30	**Meeting Ends**	

The EMPIR Chair and Deputy Chair may observe sessions marked ▲

Call 2022 – Integrated European Metrology

AGENDA

Thursday 10th November

EURAMET

08:00	**Registration (Atrium Level 0)**
09:00	**WELCOME SESSION: ALL DELEGATES▲ (ON AIR + BACK STAGE LEVEL 0)** *Speaker: Programme Manager*
09:30	**REFEREE SESSIONS▲ (ON AIR + BACK STAGE LEVEL 0)** **Referees introduction** *Chaired by the MSU facilitators* **JRP REPRESENTATIVE SESSIONS ▲ (TALK SHOW LEVEL 0)** **What to expect at the review conference** *Speaker: Programme Manager*
10:00	**Evaluation guidance for referees** *Speaker: Programme Manager* **What to expect if your proposal is successful** *Speaker: Deputy Programme Manager*
10:45	**Coffee break (Atrium Level 0)**
11:15	**POSTER SESSION: ALL DELEGATES▲ (ON AIR, BACK STAGE, TALK SHOW LEVEL 0)** The poster session is comprised of pre-allocated poster presentation sessions of 20 minutes. Please see the poster timetable provided. Each pre-allocated session comprises: • A 5 minute presentation from the proposal representative. • 15 or 20 minutes of informal questions from the referees. • A maximum of 3 referees at each poster during a pre-allocated session. • A bell will signal the end of each pre-allocated session. Please end promptly.
12:15	**Lunch break (Atrium Level 0)**
13:00	**POSTER SESSION CONTINUED: ALL DELEGATES▲ (ON AIR, BACK STAGE, TALK SHOW LEVEL 0)** Poster session continued. JRP representatives will also be required for an open session for any further questions from referees from other groups. Please note that during the open session the number of referees has not been scheduled and so may vary.
14:15	**Coffee break (Atrium Level 0)**
14:30	**BREAKOUT SESSION: REFEREES** GROUP 1 (L'INTERVIEW LEVEL 3) | GROUP 2 (LE STUDIO LEVEL 3) | GROUP 3 (L'EMISSION LEVEL 3) **Referees' development of questions** The referees will discuss their first impressions of the proposals and develop questions for each proposal. The questions will be asked to the JRP representatives in the formal question and answer session.
16:45	**Coffee break (Level 3)**
17:00	**BREAKOUT SESSION: REFEREES & JRP REPRESENTATIVES▲** GROUP 1 (L'INTERVIEW LEVEL 3) | GROUP 2 (LE STUDIO LEVEL 3) | GROUP 3 (L'EMISSION LEVEL 3) **Formal question and answer session** JRP representatives will have a maximum of 15 minutes to answer questions that the group of referees have formulated for them, in the previous session. Each JRP representative will be called into the room individually, in ascending numerical order for the proposals within the group. Each JRP representative will sit in the room in front of the referees whilst being questioned. Each JRP representative will be recorded by the EURAMET MSU as a record of their answers. All recordings will be kept securely by EURAMET. After this session JRP representatives may leave.
18:25	**Meeting Ends**
19:00	**Conference dinner: referees and EURAMET (Restaurant Level 1)**

Call 2022 – Integrated European Metrology

AGENDA

Friday 11th November

08:45	**REFEREES ▲ (ON AIR + BACK STAGE LEVEL 0)**		
	A reminder of the tasks *Speaker: Programme Manager*		
09:00	**MARKING SESSION: REFEREES**		
	GROUP 1 (L'INTERVIEW LEVEL 3)	**GROUP 2 (LE STUDIO LEVEL 3)**	**GROUP 3 (L'EMISSION LEVEL 3)**
	Referees agree consensus marks for each proposal against the evaluation criteria, and complete one marking book for each proposal. The referees who were asked to focus on the proposal under discussion should lead the discussions, but all referees may contribute. Referees should establish a ranked list of all proposals in their group. This list and the marking books are captured by the MSU.		
11:00	**Coffee break (Level 3)**		
11:30	**MARKING SESSION CONTINUED: REFEREES**		
	GROUP 1 (L'INTERVIEW LEVEL 3)	**GROUP 2 (LE STUDIO LEVEL 3)**	**GROUP 3 (L'EMISSION LEVEL 3)**
	Marking session continued.		
13:15	**Lunch break (Restaurant Level 1)**		
14:15	**SINGLE RANKED LIST & CLOSING SESSION ▲ (ON AIR + BACK STAGE LEVEL 0)**		
	Chaired by the Programme Manager During lunch, the MSU will have established a preliminary single ranked list of proposals. They will identify those that fall near the funding cut-off point and these will be the focus of this session's discussions. The referees will discuss the preliminary single ranked list of proposals in order to establish their final single ranked list of all proposals. The Programme Manager will provide procedural advice and capture the results.		
15:30	**Meeting Ends**		

The EMPIR Chair and Deputy Chair may observe sessions marked ▲

Call 2022 – Health

AGENDA

Monday 14th November

08:00	**Registration (Atrium Level 0)**		
09:00	**WELCOME SESSION: ALL DELEGATES▲ (ON AIR + BACK STAGE LEVEL 0)**		
	Speaker: Programme Manager		
09:30	**REFEREE SESSIONS▲ (ON AIR + BACK STAGE LEVEL 0)**	**JRP REPRESENTATIVE SESSIONS ▲ (TALK SHOW LEVEL 0)**	
	Referees introduction *Chaired by the MSU facilitators*	**What to expect at the review conference** *Speaker: Programme Manager*	
10:00	**Evaluation guidance for referees** *Speaker: Programme Manager*	**What to expect if your proposal is successful** *Speaker: Deputy Programme Manager*	
10:45	**Coffee break (Atrium Level 0)**		
11:15	**POSTER SESSION: ALL DELEGATES▲ (ON AIR, BACK STAGE, TALK SHOW LEVEL 0)**		
	The poster session is comprised of pre-allocated poster presentation sessions of 20 minutes. Please see the poster timetable provided. Each pre-allocated session comprises: • A 5 minute presentation from the proposal representative. • 15 or 20 minutes of informal questions from the referees. • A maximum of 3 referees at each poster during a pre-allocated session. • A bell will signal the end of each pre-allocated session. Please end promptly.		
12:15	**Lunch break (Atrium Level 0)**		
13:00	**POSTER SESSION CONTINUED: ALL DELEGATES▲ (ON AIR, BACK STAGE, TALK SHOW LEVEL 0)**		
	Poster session continued. JRP representatives will also be required for an open session for any further questions from referees from other groups. Please note that during the open session the number of referees has not been scheduled and so may vary.		
14:15	**Coffee break (Atrium Level 0)**		
14:30	**BREAKOUT SESSION: REFEREES**		
	GROUP 1 (L'INTERVIEW LEVEL 3)	**GROUP 2 (LE STUDIO LEVEL 3)**	**GROUP 3 (L'EMISSION LEVEL 3)**
	Referees' development of questions The referees will discuss their first impressions of the proposals and develop questions for each proposal. The questions will be asked to the JRP representatives in the formal question and answer session.		
16:45	**Coffee break (Level 3)**		
17:00	**BREAKOUT SESSION: REFEREES & JRP REPRESENTATIVES▲**		
	GROUP 1 (L'INTERVIEW LEVEL 3)	**GROUP 2 (LE STUDIO LEVEL 3)**	**GROUP 3 (L'EMISSION LEVEL 3)**
	Formal question and answer session JRP representatives will have a maximum of 15 minutes to answer questions that the group of referees have formulated for them, in the previous session. Each JRP representative will be called into the room individually, in ascending numerical order for the proposals within the group. Each JRP representative will sit in the room in front of the referees whilst being questioned. Each JRP representative will be recorded by the EURAMET MSU as a record of their answers. All recordings will be kept securely by EURAMET. After this session JRP representatives may leave.		
18:25	**Meeting Ends**		
19:00	**Conference dinner: referees and EURAMET (Restaurant Level 1)**		

Call 2022 – Health

AGENDA

Tuesday 15th November

08:45	**REFEREES▲ (ON AIR + BACK STAGE LEVEL 0)**		
	A reminder of the tasks *Speaker: Programme Manager*		
09:00	**MARKING SESSION: REFEREES**		
	GROUP 1 (L'INTERVIEW LEVEL 3)	**GROUP 2 (LE STUDIO LEVEL 3)**	**GROUP 3 (L'EMISSION LEVEL 3)**
	Referees agree consensus marks for each proposal against the evaluation criteria, and complete one marking book for each proposal. The referees who were asked to focus on the proposal under discussion should lead the discussions, but all referees may contribute. Referees should establish a ranked list of all proposals in their group. This list and the marking books are captured by the MSU.		
11:00	**Coffee break (Level 3)**		
11:30	**MARKING SESSION CONTINUED: REFEREES**		
	GROUP 1 (L'INTERVIEW LEVEL 3)	**GROUP 2 (LE STUDIO LEVEL 3)**	**GROUP 3 (L'EMISSION LEVEL 3)**
	Marking session continued.		
13:15	**Lunch break (Restaurant Level 1)**		
14:15	**SINGLE RANKED LIST & CLOSING SESSION▲ (ON AIR + BACK STAGE LEVEL 0)**		
	Chaired by the Programme Manager During lunch, the MSU will have established a preliminary single ranked list of proposals. They will identify those that fall near the funding cut-off point and these will be the focus of this session's discussions. The referees will discuss the preliminary single ranked list of proposals in order to establish their final single ranked list of all proposals. The Programme Manager will provide procedural advice and capture the results.		
15:30	**Meeting Ends**		

The EMPIR Chair and Deputy Chair may observe sessions marked ▲

Call 2022 – Research Potential
AGENDA
Wednesday 16th November

08:00	**Registration (Atrium Level 0)**	
09:00	**WELCOME SESSION: ALL DELEGATES▲ (ON AIR + BACK STAGE LEVEL 0)**	
	Speaker: Programme Manager	
09:30	**REFEREE SESSIONS▲ (ON AIR + BACK STAGE LEVEL 0)**	**JRP REPRESENTATIVE SESSIONS ▲ (TALK SHOW LEVEL 0)**
	Referees introduction *Chaired by the MSU facilitators*	**What to expect at the review conference** *Speaker: Programme Manager*
10:00	**Evaluation guidance for referees** *Speaker: Programme Manager*	**What to expect if your proposal is successful** *Speaker: Deputy Programme Manager*
10:45	**Coffee break (Atrium Level 0)**	
11:15	**POSTER SESSION: ALL DELEGATES▲ (ON AIR + BACK STAGE LEVEL 0)**	
	The poster session is comprised of pre-allocated poster presentation sessions of 20 minutes. Please see the poster timetable provided. Each pre-allocated session comprises: • A 5 minute presentation from the proposal representative. • 15 or 20 minutes of informal questions from the referees. • A maximum of 3 referees at each poster during a pre-allocated session. • A bell will signal the end of each pre-allocated session. Please end promptly.	
12:15	**Lunch break (Atrium Level 0)**	
13:00	**POSTER SESSION CONTINUED: ALL DELEGATES▲ (ON AIR + BACK STAGE LEVEL 0)**	
	Poster session continued.	
14:00	**Coffee break (Atrium Level 0)**	
14:15	**BREAKOUT SESSION: REFEREES (LE STUDIO LEVEL 3)**	
	Referees' development of questions The referees will discuss their first impressions of the proposals and develop questions for each proposal. The questions will be asked to the JRP representatives in the formal question and answer session.	
16:30	**Coffee break (Level 3)**	
16:45	**BREAKOUT SESSION: REFEREES & JRP REPRESENTATIVES▲ (LE STUDIO LEVEL 3)**	
	Formal question and answer session JRP representatives will have a maximum of 15 minutes to answer questions that the group of referees have formulated for them, in the previous session. Each JRP representative will be called into the room individually, in ascending numerical order for the proposals within the group. Each JRP representative will sit in the room in front of the referees whilst being questioned. Each JRP representative will be recorded by the EURAMET MSU as a record of their answers. All recordings will be kept securely by EURAMET. After this session JRP representatives may leave.	
18:25	**Meeting Ends**	
19:00	**Conference dinner: referees and EURAMET (Restaurant Level 1)**	

Call 2022 – Research Potential

AGENDA

Thursday 17th November

08:45	**REFEREES▲ (ON AIR + BACK STAGE LEVEL 0)**
	A reminder of the tasks *Speaker: Programme Manager*
09:00	**MARKING SESSION: REFEREES (LE STUDIO LEVEL 3)**
	Referees agree consensus marks for each proposal against the evaluation criteria, and complete one marking book for each proposal. The referees who were asked to focus on the proposal under discussion should lead the discussions, but all referees may contribute. Referees should establish a ranked list of all proposals in their group. This list and the marking books are captured by the MSU.
10:45	**Coffee break (Atrium Level 0)**
11:15	**MARKING SESSION CONTINUED: REFEREES**
	Marking session continued.
13:15	**Lunch break (Restaurant Level 1)**
14:15	**SINGLE RANKED LIST & CLOSING SESSION▲ (ON AIR + BACK STAGE LEVEL 0)**
	If the previous session requires more time this session will be used The referees will discuss and establish their final single ranked list of all proposals. The Programme Manager will provide procedural advice and capture the results.
15:30	**Meeting Ends**

The EMPIR Chair and Deputy Chair may observe sessions marked ▲

Call 2022 – Digital Transformation

AGENDA

Wednesday 16th November

08:00	**Registration (Atrium Level 0)**	
09:00	**WELCOME SESSION: ALL DELEGATES▲ (ON AIR + BACK STAGE LEVEL 0)**	
	Speaker: Programme Manager	
09:30	**REFEREE SESSIONS▲ (ON AIR + BACK STAGE LEVEL 0)**	**JRP REPRESENTATIVE SESSIONS ▲ (TALK SHOW LEVEL 0)**
	Referees introduction *Chaired by the MSU facilitators*	**What to expect at the review conference** *Speaker: Programme Manager*
10:00	**Evaluation guidance for referees** *Speaker: Programme Manager*	**What to expect if your proposal is successful** *Speaker: Deputy Programme Manager*
10:45	**Coffee break (Atrium Level 0)**	
11:15	**POSTER SESSION: ALL DELEGATES▲ (TALK SHOW LEVEL 0)**	
	The poster session is comprised of pre-allocated poster presentation sessions of 20 minutes. Please see the poster timetable provided. Each pre-allocated session comprises: • A 5 minute presentation from the proposal representative. • 15 or 20 minutes of informal questions from the referees. • A maximum of 3 referees at each poster during a pre-allocated session. • A bell will signal the end of each pre-allocated session. Please end promptly.	
12:15	**Lunch break (Atrium Level 0)**	
13:20	**POSTER SESSION CONTINUED: ALL DELEGATES▲ (TALK SHOW LEVEL 0)**	
	Poster session continued.	
13:40	**Coffee break (Atrium Level 0)**	
14:00	**BREAKOUT SESSION: REFEREES (L'INTERVIEW LEVEL 3)**	
	Referees' development of questions The referees will discuss their first impressions of the proposals and develop questions for each proposal. The questions will be asked to the JRP representatives in the formal question and answer session.	
16:00	**Coffee break (Level 3)**	
16:30	**BREAKOUT SESSION: REFEREES & JRP REPRESENTATIVES▲ (L'INTERVIEW LEVEL 3)**	
	Formal question and answer session JRP representatives will have a maximum of 15 minutes to answer questions that the group of referees have formulated for them, in the previous session. Each JRP representative will be called into the room individually, in ascending numerical order for the proposals within the group. Each JRP representative will sit in the room in front of the referees whilst being questioned. Each JRP representative will be recorded by the EURAMET MSU as a record of their answers. All recordings will be kept securely by EURAMET. After this session JRP representatives may leave.	
17:40	**Meeting Ends**	
19:00	**Conference dinner: referees and EURAMET (Restaurant Level 1)**	

Call 2022 – Digital Transformation

AGENDA

Thursday 17th November

08:45	**REFEREES▲ (ON AIR + BACK STAGE LEVEL 0)**
	A reminder of the tasks *Speaker: Programme Manager*
09:00	**MARKING SESSION: REFEREES (L'INTERVIEW LEVEL 3)**
	Referees agree consensus marks for each proposal against the evaluation criteria, and complete one marking book for each proposal. The referees who were asked to focus on the proposal under discussion should lead the discussions, but all referees may contribute. Referees should establish a ranked list of all proposals in their group. This list and the marking books are captured by the MSU.
10:45	**Coffee break (Level 3)**
11:15	**MARKING SESSION CONTINUED: REFEREES**
	Marking session continued.
13:15	**Lunch break (Restaurant Level 1)**
14:15	**SINGLE RANKED LIST & CLOSING SESSION▲ (TALK SHOW LEVEL 0)**
	If the previous session requires more time this session will be used The referees will discuss and establish their final single ranked list of all proposals. The Programme Manager will provide procedural advice and capture the results.
15:30	**Meeting Ends**

The EMPIR Chair and Deputy Chair may observe sessions marked ▲

Potential European Partnership on Metrology

<u>Call 2021</u>

Normative
Green Deal

Report of the Independent Observer Joseph Prieur

December 2021

Contents

1. Introduction

1.1 Terms of Reference

This report provides the observations of the Independent Observer IO (Joseph Prieur), following completion of the virtual Review Conference held via MS Teams on 22, 23, 24 and 25 November 2021.

The role of the Independent Observer is described in Section 4.2 of the EURAMET document Potential Partnership on Metrology Call Process Guide 6 “Evaluating Partnership Proposals” (https://msu.euramet.org/current_calls/documents/Guide6.pdf), as follows:

The European Commission may send an independent observer …. to the review conferences. The independent observer … will not participate directly in the evaluation procedure.
The independent observer will have access to all areas of the evaluation process and will report their observations and opinions to the European Commission and EURAMET

The IO main function is therefore to ensure that the Joint Research Project (JRP) proposal evaluation process is being implemented in accordance and compliance with the rules that are set out in this Guide 6. It can be seen as a Quality Assurance measure in the proposal evaluation process.

The specific tasks of the Independent Observer were defined in his appointment letter dated 21 October 2021, as follows:

- To act as an independent observer during the EURAMET Partnership 2021 selection process.
- To prepare and review the Call and Selection documentation.
- To attend a preparatory joining session prior to the virtual review conferences.
- To attend the virtual review conferences 22nd – 25th November 2021.
- To provide a draft report to the Programme Manager for factual checking by 5th December 2021.
- To take due regard of comments made by the Programme Manager on the draft. EURAMET comments will be limited to factual matters, the opinions remaining those of the observer.
- To produce a final report by the end of December 2021 (subject to timely response to the draft by EURAMET).
- The report may be produced in two parts, the first part reporting on the process and in a form that could be made public, while recommendations to EURAMET on improvements to the process that could be made in future years could be reserved for a second part which would not be made generally available.

It was noted that:

- The final report of the IO will be provided - unabridged - to the European Commission by EURAMET and shall be of a suitable quality for this purpose.
- All relevant personnel, including the Referees, will be instructed to provide full cooperation with the IO to enable completion of his task.
- Full and unfettered access will be provided to all relevant aspects of the call and selection process to enable the IO to complete his task.
- The IO is bound by confidentiality, and will be required to sign a copy of Form 6a: Code of Conduct and Declaration, available at https://msu.euramet.org/current_calls/documents/Form6a.docx and provide this to the EURAMET MSU. The IO signed the code of conduct on 1 November 2021, before being given access to any confidential information.
- The IO shall only discuss the outcome and provide the report to those who have a legitimate right of access (which includes, should they so choose to contact directly the IO, the relevant Unit of the European Commission). Please note that EURAMET reserves the right to publish the report.
- This call 2021 is being held ahead of any agreement from the Commission that the relevant funding will be available. At present the relevant legislation is still under discussion in both Council and Parliament,

and there is no certainty on the detailed arrangements for funding selected projects. Due to this circumstances EURAMET would like to highlight that all published guides and templates are subject to amendment by the EC and EURAMET as further information becomes known.

This report therefore deals with the process that was carried out to implement the Review Conference and arrive at Single Ranked lists of proposals submitted for each of the two European Partnership 2021 Calls (Normative and Green Deal). The recommendations to EURAMET are included in a separate report. Both reports follow the format of the previous years' reports to ensure consistency of approach.

1.2 Approach

The IO's observations are based on the following inputs:

- Exchange of e-mails, telephone conversations or virtual meetings (via MS Teams) with the MSU team in charge of the call 2021 evaluation
- Review of copies (received by mail from MSU on 1 November 2021) of the procedural e-mails and attachments sent to referees
- Various guides, templates and forms, and other relevant documents, namely
    a. Form 6a: Referee Code of Conduct and Declaration
    b. Referee joining instructions for virtual review conferences 2021
    c. The Selected Research Topics (SRT) for both Normative and Green Deal calls, against which Joint Research Projects (JRP) were to be submitted
    d. Note 1 - Referee selection process.
    e. Note 2 – Security of EURAMET referee data.
    f. Note 18 – MSU duties at virtual review conferences (used also for training purposes).
    g. Guide 6 – guidance for evaluating Partnership proposals for the new Partnership programme
    h. Form 6a – referee code of conduct form for the new Partnership programme.
    i. Form 6b – the payment form for referees for the new Partnership programme.
    j. Form 6c – the JRP evaluation form for the new Partnership programme

  These documents were updated from earlier existing versions as necessary to adapt to virtual conferences and to Horizon Europe changes (essentially from EMPIR under Horizon 2020, to Partnership on Metrology under Horizon Europe)
- Review of Independent Observer reports and recommendations produced after the review conferences of earlier EMPIR Calls
- Review of Call 2021 documentation and briefing materials delivered during the virtual review Conference;
- Attendance at the virtual Review Conference via MS Teams (22-25November, 2021), involving:
    - Days 1and 2: Normative (22 and 23 November)
    - Days 3 and 4: Green Deal (24 and 25 November)
- Informal exchanges by mail or MS Teams during the Review Conference with some referees, the EMPIR Chair, the Programme Manager and members of the Management Support Unit (MSU)

As independent observer, I am fully satisfied that I had free and open access to all information, presentations and discussions that constituted the evaluation of the call 2021 proposals and that throughout the complete evaluation process all my questions received prompt, clear and complete answers

1.3 Structure of the Report

The report aims to cover the whole of the 2021 Stage 2 process from launch of the Calls to the decision on the projects that will be funded. It therefore covers the period from the opening of the Calls (24 August 2021 for both Normative and Green Deal calls) to the Metrology Partnership Committee meeting of November 30, 2021 following the Review Conferences held via MS Teams from 22 to 25 November 2021.

The report comprises sections on the background/scope of the Call for proposals, selection of referees, the remote evaluation, and all stages/sessions of the Review Conference. The report concludes with my fin regarding compliance with the rules and quality of the process.

A separate report has been prepared for EURAMET with comments and suggestions for improvement of the process.

2. Call for Proposal

In 2021 EURAMET issued calls for proposals for Joint Research Projects (JRP) for 2 Targeted Programmes (TP), namely Green Deal and Normative, following a two-stage process. Stage 1 (call for needs) was launched on 11 January 2021 and closed on 22 February 2021. Stage 2 (call for JRP proposals) was launched on 24 August 2021 and closed on 11 October 2021.

JRP Proposals

For both Targeted Programmes Normative and Green Deal, Stage 1 offers the chance for all stakeholders from any country to influence the R&D projects undertaken by the European metrology community by identifying the challenges, problems or opportunities for potential research topics.

Stage 1 invites interested parties to submit Potential Research Topics (PRT). This consultation phase is an open bottom-up driven identification process for metrology research needs. From PRTs submitted at stage 1, the EMPIR Committee (now Metrology Partnership Committee) defines a number of SRT (Selected Research Topics) which are considered to be of the highest priority and will provide the basis for Stage 2 calls for JRPs in each of the 2 Targeted Programmes (Green Deal and Normative). Each SRT may contain inputs from more than one single PRT as similar ideas may be combined as appropriate. Stage 2 calls, for both TPs, were published on 24 August 2021 and closed on 11 October 2021.
From the 72 PRTs suitable for prioritisation submitted at stage 1 (56 Green Deal, 16 Normative) the Metrology Partnership Committee selected 31 SRTs (20 for Green Deal and 11 for Normative). These 31 SRTs were the basis of the call for proposals for Joint Research Project (JRP) which consortia were invited to submit in stage 2 of the call 2021. From the 31 published SRTs, 1 did not generate any JRP proposal. The number of eligible JRP proposals received in response to stage 2 of the call 2021 was thus 30, distributed as follows:

- Green Deal 19
- Normative 11

All 30 eligible JRP proposals were put forward to be evaluated at the Review Conference (22-25 November 2021). Due to the current Covid 19 pandemic situation it was a virtual Review Conference, as in 20020, held via MS Teams. Participants to the Review Conferences were the selected referees, proposers' representatives (1 representative for each JRP proposal), MSU staff, EURAMET and EC representatives as observers and the IO.

Green Deal

The "European Green Deal", launched in December 2019, sets out the comprehensive, highest priority objectives of the EU to tackle climate and environment-related challenges. The Green Deal is also intended to be a key pillar of the post-Covid-19 economic recovery plan for Europe.

The call for this TP aims at comprehensive, sustainable contributions to this Green Deal policy framework by mobilising, pooling and developing the European metrology capabilities.

The research proposed to address these needs will require cross-disciplinary approaches such as combining metrological support for the development of clean energy technologies including generation, conversion, transport, storage and use in combination with metrology for their environmental impact assessment. Cycles of matter, cross-compartment interactions and holistic methods for the assessment of impacts on the environment should be considered with respect to environmental monitoring and climate/ocean challenges.

Normative

Overall strategic aim of this TP is to develop metrological methods and techniques required for standardisation, regulation and conformity assessment. Proposed topics should address one of the following strands:

- Specific documented demands of European and international Standards Developing Organisations (SDOs) for metrological research in any area. Proposals in this strand are expected to be mostly "co-normative" in nature.
- Specific documented demands of European Regulators and Conformity Assessment bodies for metrological research in any area.

Proposals that include representatives from industry, regulators and SDOs for their active participation in the projects are encouraged, specifically to ensure that the project outputs are acknowledged by the SDO TC/WG or regulatory authority.

These are JRPs so they have to undertake research – but research aimed at standardisation. Proposals may address topics such as the development of traceable measurement methods or the provision of validated data sets

3. Selection of Referees

EURAMET maintains and updates a Referee Database initially set up in January 2014 for the EMPIR Programme. All potential referees for EMPIR are required to register with EURAMET in accordance with Guide 8 (Registering as a Referee for EMPIR) http://msu.euramet.org/downloads/documents/Guide_8_Register_as_a_Referee.pdf.

EURAMET also maintains privileged access to the European Commission's Horizon Europe Expert Database which may be used in certain circumstances to identify potential referees. In such a case, selected referees have also to register on the EURAMET Referee Database.

To evaluate the proposals submitted, EURAMET compiles, from the Referee Database, a pool of appropriate referees and then selects referees from the pool. A proposal will be evaluated by at least three appropriate referees. In practice, 5 referees are assigned to each proposal to allow for possible referee drop out and also because an odd number is preferable in case a majority voting would be required. Referees are tasked to focus on a maximum of 3 proposals (ideally only 2 proposals for first time referees) per TP, to take into account their workload. First time referees are used for 1 TP, while experienced referees may be involved in up to 2 TPs (in such case they are not involved in more than 5 proposals in total). In each evaluation group the number of referees does not exceed twice the number of proposals to be evaluated by the group.
When selecting referees EURAMET looks for a high level of skill, experience and knowledge in the relevant areas, with a proper balance of specialists and generalists assigned to each proposal. Providing this condition can be satisfied, EURAMET then seeks a balance in terms of geographical diversity, gender, private and public sectors (where appropriate), and an appropriate turnover of referees from year to year
.
The selection process started immediately after issuing the call for stage 2 proposals, by checking willingness and availability to participate and relevant areas of expertise from potential referees. Potential referees were provided with detailed information about the calls, about their expected role and involvement, and practical information about the logistics of the evaluation process, and they were invited to declare promptly any possible conflict of interest which may arise, should they be selected. The final selection process for the call 2021 involved the matching of referees to the 2021 SRTs based on the use of keywords in their profiles and confirmation of availability for the Review Conference and absence of conflict of interest.

Referees evaluate the JRPs on a personal capacity, not as representatives of their employer, their country or any other entity or affiliation. They must act independently, impartially and objectively. They may not delegate another person to carry out the work or be replaced by any other person. They must maintain the confidentiality of the documents before, during and after the Review Conferences. They must declare any links to a particular consortium. All referees must abide by a Code of Conduct and sign Form 6a: Code of Conduct and Declaration prior to beginning any evaluation
The Independent Observer signed also the Form 6a (Code of Conduct and Declaration) on 1 November 2021, prior to commencement of his involvement in the process.

The referees are responsible for evaluating each proposal in a fair way. They assist EURAMET to the best of their abilities, professional skills, knowledge and applying the highest ethical and moral standards. They must follow any instructions and time-schedules given by EURAMET and deliver consistently high quality work. They evaluate the merits of each application against the given evaluation criteria.

The statistical analysis of referees for the present Review Conference was provided for review:

Male	40	65.6%
Female	21	34.4%
Average age	53	
Age <30	0	0.0%
Age 30-34	2	3.3%
Age 35-39	3	4.9%
Age 40-44	7	11.5%
Age 45-49	11	18.0%
Age 50-54	16	26.2%
Age 55-59	6	9.8%
Age 60-64	6	9.8%
Age 65-69	8	13.1%
Age 70-75	2	3.3%
Age >75	0	0.0%
Consultancy firms	0	0.0%
Higher Education Establishments	30	49.2%
Non-research Commercial sector including SMEs	12	19.7%
Non-research International Organisations (Association of States)	2	3.3%
Non-research Public Sector	0	0.0%
Private / Commercial Research Centres	8	13.1%
Private Non-profit Research Centres	1	1.6%
Public Research Centres	8	13.1%
Other	0	0.0%
No information given	0	0.0%
Previous EURAMET referee	48	78.7%
Previous EC evaluator	39	63.9%

Nationalities	25	
Austria	2	3.3%
Belgium	0	0.0%
Bosnia and Herzegovina	0	0.0%
Bulgaria	1	1.6%
Croatia	2	3.3%
Czech Republic	1	1.6%
Denmark	0	0.0%
Finland	2	3.3%
France	4	6.6%
FYR Macedonia	1	1.6%
Germany	4	6.6%
Greece	3	4.9%
Hungary	1	1.6%
Ireland	1	1.6%
Iceland	1	1.6%
Israel	0	0.0%
Italy	5	8.2%
Lebanon	1	1.6%
Lithuania	1	1.6%
Malta	0	0.0%
Netherlands	3	4.9%
Other	0	0.0%
Poland	6	9.8%
Portugal	2	3.3%
Romania	3	4.9%
Serbia	3	4.9%
Slovakia	1	1.6%
Slovenia	2	3.3%
Spain	6	9.8%
Sweden	0	0.0%
Switzerland	0	0.0%
Turkey	2	3.3%
United Kingdom	3	4.9%

There were 61 referees in total, from 25 different nationalities. The above table shows a wide variety of referees with due consideration of previous evaluation experience (about 21% of referees are newcomers to this Review Conference, a turn over similar to the European Commission practice for the Research Framework Programmes Horizon 2020 and now Horizon Europe), background (type of organisation), nationality and age. The combined representation of Higher Education Establishments and Public Research Organisations is just below 2/3. As far as gender is concerned, about 1/3 of referees were female referees. In terms of geographical balance, there was a wide and well distributed range of nationalities, none of them exceeding 10% of the total number of referees. No referee participated to more than 1 TP.

4. Remote Evaluation

The closing date for phase 2 proposal submission was 11 October 2021 for both TPs (Green Deal and Normative).

Potential referees for JRPs had already been invited on 24 June 2021 (i.e. ahead of the launch of stage 2 calls) to submit their availability, areas of expertise and absence of known possible conflicts of interest (CoI) not later than 30 July 2021. The selected referees were informed about their selection on 10 and 11 September 2021 and requested to confirm their availability and absence of CoI by 24 September 2021 and to return their completed and signed declaration 6a (code of conduct). On 13 October 2021, selected referees were provided with joining instructions for their participation at the virtual Review Conference. They were also requested to attend a mandatory Preparatory Joining Session. Several Preparatory Joining Sessions were held for different referee groups and also, separately, for JRP representatives. The Independent Observer attended 2 such sessions (one for referees and one for representatives) on 12 November 2021.

Remote evaluation for JRPs commenced early November with an e-mail to the referees from the EMRP-MSU, customised for each of the 2 Targeted Programmes and provided the referees with the following information:

● Evaluation group they would join;
● Full list of proposals that they would evaluate in each group;
● Link to a password-protected web-page containing the Information for referees, including all the proposals for their Targeted(s) Programme(s) within their group
● Matrix showing which proposals each person would specifically focus on at the Review Conference;
● Preview of what they would be required to do at the Review Conferences (and what documentary material would be provided);
● Guidance on selective reading;
● Concluding remarks on what they should do if they discover a conflict of interest;
● E-mail address and telephone number for the EMRP-MSU.

The observer noted that in each referee group, each proposal was assigned to 5 referees (3 "specialists" and 2 "generalists"), well above the required minimum; this meets EC requirements, aiming to balance the tendency of specialists to mark their favourite subjects slightly higher. Although these 5 referees were instructed to focus specifically on their assigned proposals, they were also invited/encouraged to familiarise themselves with the other proposals within their group to facilitate meaningful discussions later at the final plenary session when all proposals of all groups would be compared and ranked, for each TP

Password-protected web-pages specific to each Targeted Programme were available to referees and contained more detailed information, including:

● Guide 4: Writing Joint Research Projects (JRPs): a set of instructions given to the proposers on what to include in their proposal.
● Guide 6: Evaluating JRP Proposals: explains how the evaluation process will work, explains role and gives marking guidance for JRPs.
    •Form 6a: Code of Conduct and Declaration;
    •Form 6b: Payment to referees;
    •Form 6c: JRP Evaluation (marking sheet).
● Call Budget and Features: EMPIR Call 2021.
● JRP Proposals in zip files: documents submitted by the proposers together with the SRT supporting document published by EURAMET listed by Group.
● Logistics information for the Review Conference including agenda and joining information.
● Link to the Call web page so that they could see the briefing information for the proposers.

5. Virtual Review Conference: Preliminaries

As already mentioned, mandatory preparatory joining sessions were organised ahead of the virtual Review conference, separately for the selected referees and for representatives (for confidentiality reasons).

The Review Conferences were scheduled over 4 days from22 to 25 November 2021 to cover the complete 2021 Call evaluation for both TPs. A specific document (book) providing all relevant information was given to the participants. The independent observer was given his own book, detailing the complete agenda for the Review Conference and providing all details about the schedules of all sessions (briefings, JRP proposal presentations and informal Q & A sessions, development of formal questions, formal Q & A sessions, marking /consensus sessions, ranked list discussions, etc.), participants, logistics, as well as the various relevant guides and forms.

Participants to the Conference were the EMPIR Chair and deputy Chair, the EURAMET Programme Manager and Deputy Programme Manager, an EU Commission representative, the MSU staff (16 persons), the referees, the JRP representatives and the Independent Observer.

Two days (22 and 23 November 2021) were dedicated to the TP Normative, and the two next 2 days (24 and 25 November 2021) were dedicated to the TP Green Deal. The schedule of the 2 days was identical for the 2 TPs:

- Day 1 for Normative and Day 3 for Green Deal
    - Registration (Referees and JRP Representatives)
    - Welcome session (Referees and JRP Representatives)
    - Briefing for Referees & Briefing for JRP Representatives (separate sessions)
    - Presentations to Referees by JRP representatives and informal discussions, informal Q&A for each group (2 parallel groups for Normative, 4 parallel groups for Green Deal)
    - Development/Preparation of questions for the formal Q & A session of Day 2 for Normative (or Day 4 for Green Deal), in each group (Referees only)

- Day 2 for Normative and Day 4 for Green Deal
    - Registration (Referees)
    - Formal Q & A sessions with referees and JRP representatives in each group
    - Marking/consensus sessions (agree comments and scores against each criterion) for all proposals within each group (Referees)
    - Establishment and agreement on a single ranking list with separation of equal scored proposals (if needed). Recording of the evaluation final result (Referees of all groups, for each TP)

The registration session of Day 1 (and Day 3) was designed to ensure that all participants could register, while ensuring also that no anonymous, uninvited or unrecognisable participants would join and attend.

For each TP, the Programme Manager delivered a welcome address to all participants (referees and JRP representatives), a general introduction of EURAMET, of the European Partnership on Metrology and its general & specific objectives and its funding, the general description of Normative and Green Deal calls, their budgets, the call process, the expected outcome of the review conference, the requirements for confidentiality and other referee obligations, and the programme of the day.

This was followed, on Day1 and Day 3, by 2 parallel and separated dedicated briefing sessions, one for the referees (see Section 5.1), another one for the JRP representatives (see Section 5.2).

Day 1 and Day 3 continued with the presentation sessions (see Section 5.3) where each JRP representative was invited to present and discuss his (her) proposal with the relevant referee group and

The final session of Day 1 (and Day) was for the development of questions which would be asked on Day 2 (and Day 4) to the JRP representatives (see Section 5.4)

Day 2 (and Day 4) started with a registration session for referees and a brief reminder of the tasks ahead, followed by the formal Q & A sessions (see Section 5.5).

On Day 2 (and Day 4) the formal Q & A sessions were followed by marking/consensus sessions (see Section 6.1) for each evaluation group. This was then followed by the plenary session (see Section 6.2) where all JRPs (from all evaluation groups related to the same TP) were ranked.

5.1 Briefing for the Referees

Following the Welcome address and general presentation by the Programme Manager on Days 1 & 3, all referees were briefed about the main aspects of the evaluation process and of their involvement in this process: the oversubscription rate (requested budget/ available budget), the inputs and expected outputs of the conference, the need for the experts to act “ad personam” (not representing any country nor organisation), the code of conduct they had agreed to abide by.
They were also reminded about

- all major principles of independence, fairness, impartiality and objectivity and absence of conflict of interest in carrying out their work.
- The need not to talk to the JRP representatives (outside the sessions planned for that purpose)
- the evaluation sequence and their tasks in each session (presentations and informal discussions with JRP representatives, preparation of formal questions, formal Q & A session, marking/consensus session, final ranking session).
- the evaluation criteria, the thresholds, the weighing factors, the score interpretation table, and guidance on marking/commenting
- The need of “commenting before scoring”: scores have to support comments and not the other way around
- the need to ignore all proposal pages beyond the maximum page limit.
- the novel aspects to be taken into account under Horizon Europe compared to Horizon 2020
- the need to evaluate proposals as submitted (not suggesting any change nor improvements) and to evaluate them only against the 3 criteria
- the need to ensure consistency between scores and comments and not to penalise twice a proposal for the same reason under 2 different criteria
- the need to assess the conformity of the proposal with the SRT, and to assess the merits of the proposals and not the quality of the SRT

The observe believes that the briefing was complete and clear to enable all referees to undertake their tasks in full knowledge of what was expected from them and with all necessary guidance to perform their work.

5.2 Briefings for the JRP Representatives

In parallel with the briefing session for referees, a briefing session in 2 parts was organised for the JRP Representatives.

The first part explained to the Representatives how the review conference will be sequenced over the 2 days. The Representatives were informed about the evaluation process and what they should expect at the Review Conference. The representatives were informed about:

- the oversubscription ratio (requested budget/available budget)
- the purpose, inputs and outputs of the review conference
- the involved participants (referees, programme owners, applicant representatives, observer) and their respective roles and obligations
- the decision making process and responsibilities
- the JRP presentation and informal questions /questions sessions
- the formal Q &A sessions
- The marking /consensus sessions and final ranking session
- the evaluation criteria and score interpretation
- the purpose and importance of referee comments : clear feedback to applicants (for all proposals) and assistance to EURAMET during grant preparation (for successful proposals)

The second briefing was to explain to the representatives what to expect if their proposal was successful and selected for funding. This included the grant preparation phase required to agree a contract with EURAMET, the exchanges between the successful consortium and EURAMET and MSU, including the timescales, protocol updates (in terms of content, deliverables, impact, budget), the consortium agreement, and lessons from previous years.

The representatives were also reminded the specific strict rules in place for the formal virtual Q & A session of the next day in order to ensure equal opportunity for all. They are requested to be available 5 minutes before their scheduled admittance into the session. They will be requested to confirm their agreement that the session will be recorded and to declare that they are alone during the full session without any other person with them when responding to the questions (failing that, the formal Q & A session would be immediately discontinued).

5.3 Presentation Sessions with the JRP Representatives

For Normative TP the referees were split into 2 Groups, with 10 referees in the group having 5 proposals and 12 referees in the group having 6 proposals. For Green Deal TP, referees were split in 4 groups having 10 referees each in the 3 groups with 5 proposals, and only 9 referees for the group with 4 proposals. Each group had a facilitator, a note-taker, and an additional support person from the MSU staff.

As already mentioned, in each referee group each proposal had been pre- assigned to 5 referees (3 “specialists” and 2 “generalists”) at the remote individual evaluation stage. Before starting the presentations, referees were reminded that priority for questions would be given to those referees who were specifically asked to focus on the proposal under discussion, but they were all entitled to participate actively in the session in order to familiarise themselves with the other proposals within their group to facilitate meaningful discussions later at the final plenary session when all proposals of all groups would be compared and ranked, for each TP.

In order to ensure equal treatment for all proposers, the total maximum duration of the presentation session was set at 25 minutes

Before the presentation by JRP representatives, the facilitator had designated one particular referee as a Chair, selected by the MSU staff on the basis of his/her competences in terms of communication skills and facilitation of discussions. The role of the Chair is to initiate the discussion within the group during the preparation of the formal Q & A session and also during the marking session, and to assist the facilitator in clarifying, if needed, the formal questions to the JRP representatives. Referees acting as Chairs cannot be first-time referees, and they are not designated as Chairs for more than 1 proposal. All referees within the group were clearly informed that they are all equal referees, i.e. all referees’ comments are valid and of equal importance.

Each JRP representative, in a prescribed order, is then invited to present his (her) proposals to the relevant referee group in order to:
- Present the key aspects of the proposal in a clear and concise manner (10 minutes)
- Have interactive discussions with the referees (15 minutes)

At the end of the discussion with referees the JRP representative leaves the session until the next day for the formal Q & A session. From that moment, neither referees nor MSU staff have access anymore to the presentation. However, during this session, referees (but not MSU staff) are free to take notes if they wish. This may help them to prepare their formal questions for the Q & A session. This presentation session, along with the interactive discussion, is also an opportunity for the JRP representative to anticipate possible questions and get prepared, within his own organisation/consortium, for the formal Q & A session of the next day.

5.4 Preparation for Formal Interviews

The preparation for formal questions took place on Day 1 (and Day 3) and was devoted to exchanging views on the proposals between referees (based on their reading of the written proposal as well as on the presentation session) and, above all, formulating formal questions to be asked on the next day to the JRP representatives on each proposal.

The MSU facilitator was assisted by an MSU note taker during each of these sessions in order to write down the questions, for each evaluation group. It was made clear to all referees that only those questions which were developed jointly by referees would be raised, as these were to be “consensus” questions: no other questions would be allowed. The facilitator indicated that a list of about 8 to 10 such questions would seem appropriate for the limited duration of the Q &A session (15 minutes maximum). Referees were also advised that they should formulate clearly understandable questions and avoid multi-part questions. At the end of the development of questions, these were prioritized. Again, in order to have equal treatment of all proposals, the total duration of this session was limited to 20 minutes to elaborate questions for each proposal

The nominated Chair referee was invited to initiate the process by suggesting the first question(s). The facilitator contributed to ensure that the questions were adequately formulated and written down by the note taker. All referees were then invited to participate in the elaboration of the questions either by formulating questions themselves or discussing and agreeing on the clarity, relevance and content of questions raised by their co-referees, and contributing to the prioritization of the questions.

The observer noted that, on several occasions, questions raised were dealing with the alignment of the JRP with the SRT, and/or perceived differences between the written proposal and the oral presentation of the representative

At the end of the session, the agreed questions were not made available to the referees

5.5 Formal Interviews with JRP Representatives

The formal Q&A sessions took place on Day 2 for the normative TP, and Day 4 for the Green Deal TP. In each group they were chaired by the MSU facilitator, assisted by a note taker. The note taker managed the virtual attendance of the JRP representatives (in the prescribed order).

Each representative was admitted into the session and asked to agree on the session being recorded in order to provide evidence of the answers given by the representative and evidence of the declaration that the representative understood clearly that:

- he/she was the only person, from the representative side, allowed to attend the session and answer questions
- the representative camera will be kept on during the whole session
- if a voice was heard participating to or interfering with the answers of the representative, the session would be immediately discontinued

The facilitator informed the representative about the total duration of the session (15 minutes), the number of questions to be expected in order for him/her to make his/her own judgement about the time he/she would spend to answer, and indicated that, should the Q&A be finished before the allocated slot of 15 minutes was over, the representative was entitled to use the time left to to make a statement or to come back to a previous question to correct or complete his answer.
The facilitator then raised the questions in the order defined in the question elaboration session. If needed, the Chair referee was invited to clarify the question. During the session, the facilitator acted also as a time keeper. At the end of this session the facilitator thanked the representative for his /her participation to the conference. The participation of the representative to the Review Conference was terminated from that moment.

The referees were then reminded again that they should not interact with the JRP Representatives after the session.

The observer noted that, indeed, on some occasions, there was time left after the questions, and several representatives took this opportunity to clarify, correct or complement the information delivered to the referees during the presentation session or in response to earlier questions of this Q & A session

6. Review Conference: Evaluation

6.1 Marking the JRPs

Within each group, the facilitator acted as a Chair and reminded the referees about their tasks for the marking session, and the "rules of the game": 35 minutes par proposal, commenting before scoring, ensuring that comments are directed to the right criterion, ensuring that a proposal is not penalised twice for the same reason, the scores and score interpretation table, the individual criterion threshold and the global threshold and their significance in terms of "killing" or not a proposal, the weighting factors, the need to avoid recommendations for changes /improvements of the proposal, the need to ignore information contained in the proposal pages beyond the page limit, etc

Referees were also reminded that:

- their comments may be as blunt as they wish. They will be 'polished' afterwards and expressed in adequate language by EURAMET/MSU, without changing the meaning.
- comments have to help applicant to understand the reasons for their scores, especially for those who will not be funded, and therefore referees should pay a particular attention to the comments for those proposals having low scores
- comments are also to help EURAMET during the grant preparation phase for those JRPs that will be funded

Before commenting and scoring, referees were also invited to agree on whether the proposals conform fully, partially or not at all with the SRTs, and whether deviations, if any, are justified. This was also the occasion for the facilitator to remind the referees that they are to assess the proposals and not the SRT.

In contrast with last year practices (under Horizon 2020) the operational capacity of the project partners to perform the work is now to be assessed under the criterion" implementation". Likewise, the gender dimension and open science aspects are now to be taken into account under the criterion "excellence"

The facilitators initiated the discussion by inviting, on each criterion, one of the referees (Chair referee or another primary reader of the proposal) to express his (her) comments resulting from all inputs received (remote reading of the proposal, presentation by representatives , Q & A session). Other referees could then contribute to the discussion and express their comments. An agreed set of comments was then obtained with positive and negative comments against which a mark was proposed for each criterion. At times, facilitators had to remind referees that scores should properly reflect and support their comments. There were some situations when a provisional score was noted, subject to reconsideration at the end of the marking session when all proposals of the group had been dealt with. This allowed referees to make a comparative assessment of the proposals. After reviewing all proposals within the group, the scores were finalized. At the end of each marking session, referees were asked to formally expressed their agreement with the results of the session (scores, comments and ranking) and the results were formally recorded before being transmitted to the MSU for the preparation of the final plenary session. Also recorded was the commitment of all referees to delete, destroy or dispose of all electronic or printed documents related to the evaluation of the call 2021.

During the marking sessions the Programme Manager circulated virtually between the groups to check emerging scores, to obtain a preliminary view of the single ranked list and to prepare for the subsequent final plenary session and presentation of the list to all referees.

6.2 Single Ranked List

Once all marking sessions of all groups for a given TP were completed and the results of each group passed over to MSU, EURAMET MSU developed a Single Ranked List for the JRPs by the using a pre-defined Excel template for ease of review and data sorting.

The explanations given by the Programme Manager on the ranking, the procedure to untie proposals with equal scores, and the line where the cumulated requested funding reached the available budget (the funding line) were all very clear and understood by all referees. It was indicated that the ranking of proposals close to the funding line need to be carefully looked at.

For each TP, the first draft of the Single Ranked List was presented to the plenary meeting of the referees by the Programme Manager. The initial ranking was done by ordering proposals by the highest weighted total score. Proposals with equal weighted total score were untied and ranked by the highest weighted score for the highest weighted criterion (i.e. Impact for both Normative and Green Deal TPs), and then, if necessary, by how close the external participation value would be to the TP target. There was no discussion nor suggestion from any referee to depart from the proposed ordering of equal score proposals untied in accordance with this method

All referees were quickly in agreement with the proposed ranking. It was agreed that proposals near the funding line did not require further differentiation.

The referees were then asked to agree and give their approval, one by one, on the ranked list and their approval was recorded. They also formally approved the list of proposals not suitable for funding.

The Programme manager explained that the proposed ranked lists for both TPs were to be submitted to the Metrology Partnership Committee for approval on 30 November 2021.

The referees were thanked by the Programme Manager as well as by the EURAMET Chair and Deputy Chair. The opportunity was also taken to introduce to all participants the incoming new EURAMET Chair and thank the outgoing Chair.

7. Conclusions

The main conclusions that I can draw from review of the 2021 EMPIR Call documentation, the process and my attendance at the Review Conferences include the following:

- The evaluation process and procedures were carried out in accordance with all the rules derived from the applicable current legislation. All documents, guides, forms, templates were updated from previous calls to reflect the current status of adoption of the new legislation concerning the future European Partnership on Metrology, knowing that some of these documents may require further updating and possible amendments once the legislation comes into force

- Due to the continuing COVID-19 pandemic, the review conference for Call 2021 was held virtually. This particular circumstance, already prevailing last year, requires very carefully prepared planning and specific arrangements for all participants to the evaluation, notably in terms of logistics. Every organisational aspect was extremely well prepared by EURAMET and the MSU, including detailed instructions, preparatory joining sessions with computer testing via MS Teams platform prior to the beginning of the Review Conference. Further to this, during the Review Conference the MSU team, perfectly trained, was always available to assist the participants in case technical issues would be experienced, and to answer promptly any question from participants. The IO considers that all the preparation, procedures and assistance were of very high quality. This remarkable preparation led to a very smooth running of the whole evaluation process

- The overall evaluation process was conducted in a very efficient manner and the referees carried out their work in full compliance with the guiding principles of independence, impartiality, accuracy, objectivity and consistency. The security and confidentiality aspects of the process, which are more difficult to handle with a virtual review conference, were perfectly dealt with.

- The Call documentation and all correspondence with the referees were comprehensive, of a very high standard, in keeping with the maturity of the EURAMET & MSU teams and their procedures which have been developed, refined as needed, and well proven over the call evaluations of the last 7 years

- The Review Conference was organised in a highly professional manner, ranging from the logistics to the facilitation of the individual sessions (time efficiency, technical competency and unbiased nature), taking into consideration all the necessary requirements concerning security, confidentiality, transparency and fairness. All constraints and technical aspects resulting from the virtual character of the Review Conference were successfully taken into account.

- The Call outcomes (Single Ranked Lists) were of high quality and suitable for submission to the Metrology Partnership Committee for timely approval.

As an independent observer, I am convinced that all proposals received adequate and equal treatment, that the whole evaluation process was conducted to high standards of diligence, fairness and professionalism, in accordance with established principles of independence, impartiality, objectivity, accuracy and consistency at all stages and in full compliance with established rules, and that the resulting ranked lists reflected, for those projects above the funding line, the best projects which should be funded.

The organisational and logistical aspects were excellent.

8. Acknowledgments

In closing this report, I would like to thank the EMPIR Chair and Deputy Chair, the EURAMET Programme Manager and deputy Programme Manager, and the entire Management Support Unit team for their excellent support before, during and after the Review Conference. Every effort was made to assist me, to explain the relevant context and to provide me free and unrestricted access to all information and documents, and to answer promptly and fully any question, thus demonstrating a high degree of transparency. Their support, their assistance and their kindness throughout the entire process were outstanding and contributed greatly to making the observation work not only a smooth but also a very enjoyable exercise.

European Partnership on Metrology

Call 2022

Normative
Integrated European Metrology
Health
Digital Transformation
Research Potential

Report of the Independent Observer

Joseph Prieur

December 2022

Contents

1. Introduction

1.1 Terms of Reference

This report provides the observations of the Independent Observer (IO) Joseph Prieur, following completion of the Review Conferences held at Novotel Monte Carlo, 16 Boulevard Princesse Charlotte, 98000 Monaco, from 8 to 17 November 2022.

The role of the Independent Observer is described in Section 4.2 of the EURAMET document Partnership on Metrology Call Process Guide 6 "Evaluating Partnership Proposals" (http://www.metpart.eu/referees.html) as follows: *The European Commission may send an independent observer…to the review conferences. The independent observer… will not participate directly in the evaluation procedure. The independent observer will have access to all areas of the evaluation process and will report his observations and opinions to the European Commission and EURAMET".*

The IO main function is therefore to ensure that the Joint Research Project (JRP) proposal evaluation process is being implemented in accordance and compliance with the rules that are set out in this Guide 6. It can be seen as a Quality Assurance measure in the proposal evaluation process.

The specific tasks of the Independent Observer were further defined in his appointment letter dated 22 September 2022, as follows:

- To act as an independent observer during the EURAMET Partnership 2022 selection process.
- To prepare and review the Call and Selection documentation.
- To attend the review conferences in Monaco 8th-17th November 2022.
- To provide a draft report to the Programme Manager for factual checking by 09.12.2022.
- To take due regard of comments made by the Programme Manager on the draft. EURAMET comments will be limited to factual matters, the opinions remaining those of the observer.
- To produce a final report by the end of December 2022 (subject to timely response to the draft by EURAMET).
- The report may be produced in two parts, the first part reporting on the process and in a form that could be made public, while recommendations to EURAMET on improvements to the process that could be made in future years could be reserved for a second part which would not be made generally available

The appointment letter also stipulates that:

- The final report of the IO will be provided - unabridged - to the European Commission by EURAMET and shall be of a suitable quality for this purpose.
- All relevant personnel, including the Referees, will be instructed to provide full cooperation with the IO to enable completion of his task.
- Full and unfettered access will be provided to all relevant aspects of the call and selection process to enable the IO to complete his task.
- The IO is bound by confidentiality, and will be required to sign a copy of Form 6a: Code of Conduct and Declaration, available at http://www.metpart.eu/referees.html and provide this to the EURAMET MSU. The IO signed the code of conduct on 22 September 2022, before being given access to any confidential information.
- The IO shall only discuss the outcome and provide the report to those who have a legitimate right of access (which includes, should they so choose to contact directly the IO, the relevant Unit of the European Commission). EURAMET reserves the right to publish the report.

This report therefore deals with the process that was carried out to implement the Review Conferences and arrive at a Single Ranked list of proposals submitted for each of the 5 specific European Partnership Calls 2022

(Normative, Integrated European Metrology, Health, Digital Transformation, Research Potential). The recommendations to EURAMET are included in a separate report. Both reports follow the format of the previous years' reports to ensure consistency of approach.

1.2 Approach

The IO's observations are based on the following inputs:

- Exchange of e-mails, telephone and/or face to face conversations with the MSU team in charge of the call 2022 evaluation before or during the review conferences
- Review of copies (received by mail from MSU on 21 October 3 November, 2022) of the procedural e-mails and attachments sent to referees
- Review of the statistical information on referees (received on 3 November 2022)
- Review of documents available to applicants (http://www.metpart.eu/applicants) and to referees (http://www.metpart.eu/referees) and documents available on the EURAMET review conferences Share Point (forms, guides, FAQ, etc.). Amongst these, the main documents reviewed by the IO were:
    a. Form 6a: Referee Code of Conduct and Declaration (also signed by the IO)
    b. A sample of Selected Research Topics (SRT) for the 5 Targeted Programmes (TPs), against which Joint Research Projects (JRP) were to be submitted
    c. Note 1 - Referee selection process. An example of how specific Conflicts of Interest are handled, in compliance with the procedure described in Note 1, was also provided.
    d. Note 2 – Security of EURAMET referee data.
    e. Guide 6 – Evaluating Partnership Proposals
    f. Form 6a – Referee Code of Conduct and Declaration
    g. Form 6b – Payment to Referees.
    h. Form 6c – JRP Evaluation
    i. The Call 2022 Work Plan (Work Programme 2022)

  In contrast with the 2021 review conferences, conducted in a virtual mode due to the Covid 19 pandemic, the 2022 conferences were held physically and therefore there was no need for specific preparatory joining sessions and related instructions for virtual review conferences. This appears to be a significant simplification of the evaluation process.

- Review of the Independent Observer report and recommendations produced after the virtual review conferences for the European Partnership on Metrology calls of the previous year (2021)
- Review of the Call 2022 documentation and briefing materials delivered to the referees as well as to the applicant representatives during the virtual review Conferences;
- Attendance at the virtual Review Conferences (8-17 November, 2022), including:
    - Normative (8 and 9 November)
    - Integrated European Metrology (10 and 11 November)
    - Health (14 and 15 November)
    - Digital Transformation and Research Potential (16 and 17 November)
- Informal exchanges during the Review Conferences with some referees, some applicant representatives, the European Metrology Partnership Chair, the Programme Manager and Deputy Manager, the members of the Management Support Unit (MSU), and the EC officer

As there were a significant number of sessions held in parallel over the conference period, I was unable to attend them all. My approach was to cover, at least partially, as many referee groups as possible, as many facilitators as possible, and to attend, part time, almost all poster sessions.

As independent observer, I am fully satisfied that I had free and unfettered access to all relevant information, presentations and discussions that constituted the evaluation of the call 2022 proposals and that throughout

the complete evaluation process all my questions received prompt, clear and complete answers from all participants, thus demonstrating a high degree of openness and transparency

1.3 Structure of the Report

The report aims to cover the whole of the 2022 Stage 2 process from launch of the Calls to the decision on the projects that will be funded. It therefore covers the period from the opening of the Calls (23 June 2022 for all 5 calls) to the European Metrology Partnership Committee meeting of November 22, 2022.

The report comprises sections on the background/scope of the Calls, selection of referees, the remote evaluation, and all stages of the Review Conferences. The report concludes with my findings regarding compliance with the rules and quality of the process.

As requested in my appointment letter, I will submit to EURAMET a separate report with my comments and suggestions for improvement of the process.

2. Calls for Proposal

In 2022, EURAMET issued calls for proposals for Joint Research Projects (JRP) for 5 Targeted Programmes (TP), namely Normative, Integrated European Metrology, Health, Research Potential, and Digital Transformation (a very new TP in this call 2022) following a two-stage process:

- Stage 1 (call for needs) was open on 12 January 2022 and closed on 21 February 2022. Stage 1 generated 104 PRTs (Potential Research Project) deemed suitable for prioritisation. These PRTs were selected and formed the basis of the 55 SRTs (Selected Research Topics) against which the Joint Research Projects (JRPs) could be submitted at stage 2
- Stage 2 (call for JRP proposals) was open on 23 June 2022 and closed on 03 October 2022 for all TPs. Eventually, 52 JRPs were submitted at the closing date, whereas 3 SRTs did not generated any JRP.

For all 5 Targeted Programmes, Stage 1 offers an opportunity for all stakeholders from any country to influence the R&D projects undertaken by the European metrology community by identifying the challenges, problems or opportunities for potential research topics. Any interested party may submit Potential Research Topics (PRTs). This consultation phase is an open bottom-up driven identification process for metrology research needs. From these PRTs, the Metrology Partnership Committee defines a number of SRTs (Selected Research Topics) which are considered to be of the highest priority and provide the basis for Stage 2 calls for JRPs in each TP. Each SRT may contain inputs from more than one single PRT as similar ideas may be combined as appropriate. The following table summarizes the overall outcome of the process in terms of number and distribution of submitted ideas (PRTs), selected topics (SRTs), and submitted proposals (JRPs).

All 52 submitted JRP proposals were considered eligible and therefore put forward to be evaluated at the Review Conferences (8-17 November 2022). Participants to the Review Conferences were the selected referees, proposers' representatives (1 for each JRP proposal), MSU / EURAMET staff, the Partnership Chair, one EC representative and the IO.

TP Targeted Programmes	PRT Potential Research Topics	SRT Selected Research Topics	JRP Joint Research Projects	Available Budget (€ M)	Oversubscription rate (requested/available)
	Stage 1 (from idea to SRT)				
		Stage 2 (from SRT to JRP)			
Normative (NRM)	19	12	12	4.5	2.8

Integrated European Metrology (IEM)	29	15	15	15	2.2
Health (HLT)	31	15	15	15.5	2.2
Research Potential (RPT)	13	7	6	2	2.1
Digital Transformation (DIT)	12	6	4	6	1.5
Total	104	55	52	43	About 2.2

All actions covered by the 2022 stage 2 call are of the type "Research and Innovation Actions (RIAs)"

As can be seen from the above table, each SRT generated 1 (and only 1) JRP for Normative, Integrated European Metrology and Health TPs. One single SRT on Research potential did not generate a JRP. For Digital Transformation 2 out of 6 SRTs (33%) did nor generate any JRP. A tentative explanation for this seemingly relatively low interest may be that DIT is a very new topic in the European Metrology Partnership and therefore the potential applicants are not yet familiar with this subject being a topic for a call.

Having served also as Independent Observer for other evaluations of proposals submitted in response to Horizon 2020 and Horizon Europe programmes, I find interesting to observe that for the metrology sector, every SRT generates not more than 1 proposal, in contrast with most of Horizon 2020 or Horizon Europe programmes in which each so called "topic" (approximately equivalent to an SRT) generates usually many (sometimes several tens) competing proposals. This may be due, to some extent, to the fact that the European Metrology community is a rather closed, well-coordinated, and specialized community where most of the stakeholders/potential applicants know each other and prefer, quite understandably, organize themselves in a concerted attempt not to waste their efforts in submitting competing proposals. However, the competition between proposals, within each TP, does exist as can be seen clearly from the oversubscription rate indicated in the above table. This rate ranges from 1.5 for DIT (low because only 4 proposals out of 6 SRTs were submitted) to 2.8 for Normative, in all cases much lower than the usual high oversubscription rates (typically from 6 to 10) often seen in the Horizon Europe programme

3. Selection of Referees

EURAMET maintains, updates and expands a Referee Database initially set up in January 2014 for the EMPIR Programme. All potential referees are required to register in the Database in accordance with Guide 8 (Registering as a EURAMET Referee) available on https://metpart.eu/referees.html . EURAMET has also access to the European Commission's Horizon Europe Expert Database which may be used, if needed, to identify potential referees. In such a case, selected referees have also to register on the EURAMET Database.

To evaluate the proposals submitted, EURAMET compiles, from the Referee Database, a pool of appropriate referees and then selects them from the pool. A proposal must be evaluated by at least three appropriate referees. On the basis of recent past years' experience, in practice 6 referees are assigned to each proposal to allow for possible referee unforeseen unavailability (illness, travel restrictions due to covid, or whatever other reason) although it is recognized that an odd number is preferable in case a majority voting would be required. Each referee is tasked to focus on a maximum of 3 proposals (ideally only 2 proposals for first time referees) per TP, to take into account their workload. First time referees are used for 1 TP, while experienced referees may be involved in up to 2 TPs (in such case they are not involved in more than 5 proposals in total). In each evaluation group the number of referees does not exceed twice the number of proposals to be evaluated by the group.
When selecting referees EURAMET looks for a high level of skill, experience and knowledge in the relevant areas, with a proper balance of specialists and generalists assigned to each proposal. Providing this condition can be satisfied, EURAMET then seeks a balance in terms of geographical diversity, gender, private and public sectors (where appropriate), and an appropriate turnover of referees from year to year

.
The selection process started immediately after issuing the call for stage 2 proposals, by checking the willingness and availability to participate and relevant areas of expertise from potential referees. Potential referees were

provided with detailed information about the calls, their expected role and involvement, and practical information about the schedule and logistics of the evaluation process. They were also invited to declare promptly any possible conflict of interest which may arise, should they be selected. The final selection process for the stage 2 evaluation involves the matching of referees to the SRTs using keywords in their profiles and confirmation of availability for the Review Conferences and absence of CoI. Throughout the process, referees do not know who their co-referees are until they meet physically at the review conferences, and in any case, they are clearly instructed not to disclose the names of their co-referees. It would be advisable also to request that they do not disclose their own selection as referees on social networks, at least until after the final decision about the proposals selected for funding has been made

Referees are also clearly instructed that they must evaluate the JRPs on a personal capacity, not as representatives of their employer, their country or any other entity or affiliation. They must act independently, impartially and objectively. They may not delegate the work nor be replaced by another person. They must maintain the confidentiality of the documents and of the identity of the participants to the evaluation process before, during and after the Review Conferences. They must declare any links to a particular consortium. All referees must abide by a Code of Conduct and sign Form 6a: Code of Conduct and Declaration prior to having access to confidential information or starting any evaluation activity.

As Independent Observer, I also signed the Form 6a (Code of Conduct and Declaration) on 22 September 2022, in parallel with receiving my appointment letter as Independent Observer, prior to commencement of my involvement in the process.

The referees are responsible for evaluating each proposal in a fair way. They assist EURAMET to the best of their abilities, professional skills, knowledge and applying the highest ethical and moral standards. They must follow any instructions and time-schedules given by EURAMET and deliver consistently high-quality work. They must evaluate the merits of each application against the given evaluation criteria, and nothing else.

The statistical analysis of referees for the present Review Conferences was provided to the Independent Observer for review:

Male	81	74.3%
Female	28	25.7%
Average age	54	
Age <30	0	0.0%
Age 30-34	1	0.9%
Age 35-39	9	8.3%
Age 40-44	7	6.4%
Age 45-49	20	18.3%
Age 50-54	26	23.9%
Age 55-59	11	10.1%
Age 60-64	15	13.8%
Age 65-69	7	6.4%
Age 70-75	8	7.3%
Age >75	5	4.6%
Consultancy firms	3	2.8%
Higher Education Establishments	55	50.5%
Non-research Commercial sector including SMEs	14	12.8%
Non-research International Organisations (Association of States)	2	1.8%
Non-research Public Sector	0	0.0%
Private / Commercial Research Centres	9	8.3%
Private Non-profit Research Centres	3	2.8%
Public Research Centres	18	16.5%
Other	5	4.6%
No information given	0	0.0%
Previous EURAMET referee	79	72.5%
Previous EC evaluator	67	61.5%

Nationalities	28	
Austria	1	0.9%
Belgium	3	2.8%
Bosnia and Herzegovina	0	0.0%
Brazil	1	0.9%
Bulgaria	1	0.9%
Croatia	4	3.7%
Czechia	1	0.9%
Denmark	1	0.9%
Finland	2	1.8%
France	13	11.9%
FYR Macedonia	1	0.9%
Germany	8	7.3%
Greece	4	3.7%
Hungary	0	0.0%
Ireland	0	0.0%
Israel	3	2.8%
Italy	17	15.6%
Lithuania	2	1.8%
Malta	1	0.9%
Netherlands	1	0.9%
Other	1	0.9%
Poland	4	3.7%
Portugal	0	0.0%
Romania	1	0.9%
Serbia	5	4.6%
Slovakia	1	0.9%
Slovenia	2	1.8%
Spain	8	7.3%
Sweden	5	4.6%
Switzerland	2	1.8%
Türkiye	4	3.7%
United Kingdom	12	11.0%

There were 109 referees in total, from 28 different nationalities. The above table shows a wide variety of referees with due consideration of previous evaluation experience. About 28% of referees are newcomers to this Review Conference, a turn over slightly higher than the European Commission practice for the current on -

going Research Framework Programme Horizon Europe with a turn over often between 20 and 25%. Many experienced referees have also experience in other EC evaluations. The background (type of organisation), nationality and age of the referees are very diverse. The combined representation of Higher Education Establishments and Public Research Organisations is about2/3. As far as gender is concerned, about 1/4 of referees were female referees, a smaller proportion than last year (1/3). The range of nationalities is very wide, and referees from Italy, UK and France are totalling not far from 40% of the total number.

4. Remote Evaluation

Phase 2 opening date was on 23 June 2022 and the deadline for proposal submission was 03 October 2022. Potential referees for JRPs were invited on 24 June 2022 (one day after the calls were launched) to submit their willingness, availability, areas of expertise and absence of CoI not later than 22 July 2022. Selected referees were then informed about their selection by 30 August 2022 and requested to confirm their availability by 14 September 2022 and to return their completed and signed declaration 6a (code of conduct). Should referees discover a CoI, they should immediately declare it to EURAMET and resubmit a new form 6a.

Referees were informed about their selection on 20 October 2022 with an e-mail from MSU, customised for each TP for which they were selected. Referees were then provided with the following information:

- TP(s) for which they were selected (a few referees were selected for up to 2 TPs);
- Evaluation group they would join;
- Full list of proposals that they would evaluate in each group;
- Protected access (on a specific webpage of the Share Point site for the review conferences) to all the proposals for their TP(s) within their group(s)
- Matrix showing which proposals each referee should specifically focus on at the Review Conference;
- Additional relevant material forms and guides to assist referees in planning and performing their evaluation work (such as Forms 6a, 6b, 6c, and Guides 6, 4, budget information).
- Logistics information and agenda for the upcoming Review Conferences.
- Contact data for the MSU team

For each TP, referees were organised in groups with 4 to 6 proposals per group. There were 1 to 3 groups per TP. Within each group, referees had access to all proposals and to the corresponding SRTs but were requested to focus on up to 3 specific proposals. Referees were able to start immediately their reading and individual evaluation of the proposals assigned to them, upon being informed of their selection. Not knowing who their co-referees were, over the individual evaluation period, referees were able to perform fully independently their individual proposal reading/evaluation. No specific feed-back from individual readings/evaluations was requested from referees ahead of the review conferences.

In each referee group, each proposal was assigned to 6 referees with a balanced distribution between 3 “specialists” and 3 “generalists”, i.e., well above the required minimum. This provides allowance in case a referee has to be withdrawn or drops out (for reasons such as uncovering a CoI situation, or illness, or any other force majeure unavailability situation). The presence of generalists also contributes to balance the tendency of specialists to mark their favourite subjects slightly higher.

With 3 readings per referee, 5 to 6 referees per proposal and 4 to 6 proposals per group, the number of referees per group was ranging from 10 to 13, I e. about twice the number of proposals pertaining to the group.

Referees were instructed to focus specifically on their assigned proposals, but were also invited/encouraged to familiarise themselves with the other proposals within their group to facilitate meaningful discussions later at the review conference stage (during poster sessions, development of questions, marking sessions, final plenary session when all proposals of all groups would be compared and ranked, for each TP). In that respect, from informal discussions I had with several referees during coffee breaks or lunch/diners at the review conferences I came to the conclusion that referees do indeed read **all** proposals within their groups. They reckon that they spend 4 to 6 times more time on their assigned proposals (8 to 12 hours) than on the other proposals within their groups (typically 2 hours). They all indicated that, in their opinion, not reading at all a proposal would be clearly and quickly noticed at the poster session through the behaviour of the concerned referees and the probable poor relevance (or lack) of questions/comments from them.

5. Review Conferences: Preliminaries

The Review Conferences were scheduled over 8 working days from 8 to 17 November 2022 to cover the complete 2022 Call evaluation for all 5 TPs. A specific document (book) providing all relevant information was given to the participants (referees and representatives). As independent Observer I was provided with my own specific book, detailing the complete agenda for the Review Conferences and providing all details about the schedules of all sessions: welcome sessions, briefings for referees, briefing for JRP representatives, poster sessions (JRP proposal presentations and informal Q & A sessions), development of formal questions, formal Q & A sessions, marking sessions, single ranked list and closing sessions, participants, logistics, as well as the various relevant guides and forms.
I was also provided with examples of the specific book for referees and the specific book for JRP representatives, illustrating clearly that each type of participant was provided with the strictly necessary information on a "need to know" basis. For example, the referee book does not disclose the representative names, and the representative book does not disclose the names of the referees. The books for referees and JRP representatives contained also a specific questionnaire inviting them to express their opinions about the review conferences (and the overall evaluation process for referees)

Participants to the Conferences (full time or part time) were the European Metrology Partnership Chair, the Programme Manager and Deputy Programme Manager, an EU Commission representative, the MSU staff (15 persons), the referees, the JRP representatives and the Independent Observer.

Two days were dedicated to each TP (with Research Potential and Digital Transformation being held in parallel over the same 2 days due to the fact that these evaluations required one single referee group each). The session schedule, common to all 5 TPs, of the 2 days, was as follows:

- Day 1
    - Registration (Referees and JRP Representatives)
    - Welcome session (Referees and JRP Representatives)
    - Briefing for Referees & Briefing for JRP Representatives (separate sessions)
    - Poster sessions: presentations to Referees by JRP representatives and informal discussions, informal Q&A within each group (3 parallel groups for IEM and Health, 2 parallel groups for Normative, and 1 single group for Digital and PRT)
    - Development/Preparation of questions for the formal Q & A session in each group
    - Q & A session in each group

- Day 2
    - Reminder of tasks
    - Marking sessions (agree comments and scores against each criterion) for all proposals within each group (Referees)
    - Establishment and agreement on a single ranking list with separation of equal scored proposals (if needed). Recording of the evaluation final result (Referees of all groups, for each TP)

The welcome address of Day 1 was delivered by the Programme Manager to all participants (referees and JRP representatives), It covered a general introduction of EURAMET, the European Partnership on Metrology and its general & specific objectives, its funding, the general description of calls, their budgets, the call process, the general scope and call budget for each TP, the expected outcome of the review conference, the requirements for confidentiality, and the programme of the day.

This was followed by 2 parallel and separated dedicated briefing sessions, one for the referees (see Section 5.1), another one for the JRP representatives (see Section 5.2).

Day 1 continued with the poster sessions, (see Section 5.3) where each JRP representative was invited to present and discuss his (her) proposal with the relevant referee group (2 or 3 persons each time, except for the final open poster session for multi group TP where any referee from any group for the concerned TP is welcome to attend)

The next session of Day 1 was for the development of questions (see Section 5.4) which would be asked to the JRP representatives in the following session on the same day (see Section 5.5)

At the end of Day 1, referees are invited to a conference diner (without JRP representatives) where they can continue to exchange freely their views on the different proposals evaluated on that day, before the marking sessions of Day 2

Day 2 started with a brief briefing/reminder of the tasks ahead for the referees, and then continued with parallel marking sessions (see Section 6.1) for each evaluation group. This was then followed by the plenary session (see Section 6.2) where all JRPs (from all evaluation groups related to the same TP) were ranked (which includes also untying and ranking equal score proposals)

In terms of work distribution, as observer, I believe the review conferences were very well organised with, for each conference, a long working day (day 1) followed by a shorter working day (day 2) which is very reasonable as far as the workload is concerned. It also allows to have JRP representatives in attendance for only one day (day 1) thus minimizing the risk of occurrence of undue interferences between referees and representatives during the evaluation

5.1 Briefing for Referees (Referees, Review Conference Day 1)

Following the Welcome address and general presentation by the Programme Manager on Day 1 for each TP, all referees were briefed about the main aspects of the evaluation process and of their involvement in this process. The briefing was made of 2 parts.

- The first part is specific for each group of referees for the proposals to be evaluated over days 1 and 2; it is under the control of MSU facilitator for each group. Those referees with a conflict of interest with one or more proposals within their group are requested to attend the concerned poster session(s) in a passive mode (just listening) without disclosing their CoI situation, and they are requested to absent themselves from the discussions on proposals for which a CoI was detected (and, if applicable, competing proposals as well) during the development of questions, marking session and plenary closing session (by remaining silent or leaving the session)
- The second part is a briefing delivered by the Programme manager to all referees for all groups dealing with proposals pertaining to the TP under consideration. It is meant to provide general information and guidance about their evaluation work.

Referees are informed about the oversubscription rate (requested budget/ available budget), in order to make them clearly aware that the process is very selective, and therefore they are expected to make their best judgments to help EURAMET to select the very best proposals

Referees are clearly informed about all participants to the evaluation process during the review conferences and the role of each of them (referees, JRP representatives, Partnership Chair, Programme manager and deputy manager, MSU staff, EC observer, independent observer). They are informed/reminded about the inputs and expected outputs of the conference, the decision-making process and responsibility, and the code of conduct they have agreed to abide by.

They are also reminded about

- the need for the experts to act “ad personam” (not representing any country nor employer nor any entity/organisation
- all major principles of independence, fairness, impartiality and objectivity
- the need to declare any possible conflict of interest
- the need not to talk to the JRP representatives (outside the sessions planned for that purpose)
- the evaluation sequence and their tasks in each session (poster sessions and informal discussions with JRP representatives, preparation of formal questions, formal Q & A session, marking session, final ranking session).
- the evaluation criteria, the thresholds, the weighing factors (specific for each TP), the score interpretation table, and guidance on marking/commenting
- The need of “commenting before scoring”: scores have to support comments and not the other way around
- the need to ignore all proposal pages beyond the maximum page limit.
- the novel aspects to be taken into account under Horizon Europe compared to Horizon 2020 (gender dimension, open science and research data/output management under Excellence criterion, and operational capacity under Implementation criterion)
- the need to evaluate proposals as submitted (not suggesting any change nor improvements) and to evaluate them only against the 3 criteria
- the need to ensure consistency between scores and comments and not to penalise twice a proposal for the same reason under 2 different criteria
- the need to assess the conformity of the proposal with the SRT (Yes, No or Partially, with justification)
- the need to assess the merits of the proposals and not the quality of the SRT (in other words assess the quality of the proposal and not of the topic description, to use Horizon Europe jargon)

The observe believes that the briefing was comprehensive, and clear to enable all referees to undertake their tasks in full knowledge of what was expected from them and with all necessary guidance to perform their work. The briefing was also an opportunity for each referee to ask questions and obtain clarifications on any aspect of the evaluation process.

Of particular significance and importance this year was the question of UK participation to the JRPs after the Brexit. Currently, for UK participants, it is still possible to be considered as external funded partners (i.e., funded from the call budget), but this may possibly change at any time in the near future in such a way that UK participants could then only be funded from their own government and not from the “common pot”. If this would happen, more budget in the common pot would become available for funding one or more additional projects, in such a way that the funding line may eventually go further down the ranked list. Therefore, in order to cover all possible scenarios, it was agreed that some proposals below the “normal” funding line should also be ranked (and therefore equal score proposals below this “normal “funding line should be untied) during the proposal ranking session for each TP to provide sufficient flexibility in the final setting of the funding line and therefore on the final list of projects selected for funding. Referees were reminded that in any case UK participants are not allowed to coordinate a project.

5.2 Briefings for Representatives (JRP representatives, Review Conference Day 1)

In parallel with the briefing session for referees, a briefing session in 2 parts was organised for the JRP Representatives on Day 1 for each TP

The first part explained to the Representatives the sequencing of the review conference over Day 1 of the review conference. The Representatives were informed about the evaluation process and what they should expect at the Review Conference. They were informed about:

- the oversubscription ratio (requested budget/available budget), as a reminder that JRPs were competing against each other

- the basic principles for their participation to the review conference (defence of their proposal in front of their judges and competitors under strict rules ensuring equal opportunity and fairness for all)
- the inputs and outputs of the review conference
- the involved participants (referees, programme owners, applicant representatives, observer) and their respective roles and obligations
- the decision-making process and responsibility
- the sequencing of the poster sessions (presentations and informal questions sessions attended by 3 referees…or possibly more for the open session (for multi-group TPs)
- the possibility for representatives to get in touch with their home base, before the Q & A sessions, to get assistance for difficult questions raised during the poster sessions.
- The formal Q &A sessions
- the need to refrain from talking to any referee after the end of their Q & A sessions
- The marking sessions and final ranking session
- the evaluation criteria and score interpretation
- the purpose and importance of referee comments: clear feedback to applicants (for all proposals) and assistance to EURAMET during grant preparation (for successful proposals)

The second part of the briefing was to explain to the representatives what to expect if their proposal was successful and selected for funding. This included information on the grant preparation phase (including timescales), recent changes in the model grant agreement, exchanges between the successful consortium and EURAMET/ MSU, protocol updates (in terms of content, deliverables, outcomes, impact, budget, open access, Dissemination/Communication/Exploitation Plan), consortium agreement, and lessons from previous years.

The representatives were reminded about the specific strict "rules of the game" in place for the formal virtual Q & A session in order to ensure equal opportunity for all. They are requested to be available 5 minutes before their scheduled admittance into the session. They are informed that the session will be recorded and the records kept securely by EURAMET.

5.3 Poster Sessions (Referees and Representatives, Review Conference Day 1)

For each TP the referees were split into groups, as explained in section 4 with 2 groups for Normative, 3 groups for IEM and Health, and one single group for Digital and RPT. Each group had a facilitator and a note-taker from the MSU staff.

As already mentioned, in each referee group each proposal had been pre- assigned to 6 referees (3 specialists and 3 generalists) at the remote individual evaluation stage. At the briefing stage, referees were reminded that priority for questions would be given to those referees who were specifically asked to focus on the proposal under discussion, but they were all entitled to participate actively in the session in order to familiarise themselves with the other proposals within their group in order to allow them to contribute to the subsequent development of questions within their group.

In addition, for multigroup TPs, a final open session was planned for the benefit of any referee of any group for the TP under consideration. This is to facilitate meaningful discussions later at the final plenary session when all proposals of all groups would be compared and ranked, for each TP

In order to ensure equal treatment for all proposers, the total maximum duration of the presentation sessions was set at 20 minutes

Each JRP representative, in a prescribed order, is then invited to present his (her) proposals to the relevant referee group in order to:
- Present the key aspects of the proposal in a clear and concise manner (about 5 minutes)
- Have interactive discussions with the referees (about 15 minutes)

During the poster sessions, referees are free to take notes, if they wish, in preparation of the subsequent development of formal questions. Poster sessions are also an opportunity for JRP representatives to anticipate possible questions which may come up in the formal Q & A sessions.
Overall, representatives are repeating the exercise as many times as the number of proposals per group (+1 for the open session in multigroup TPs), i.e., 4 times (for Digital) to 7 times (for Normative)

At the end of the poster sessions, the posters are removed and JRP representatives leave the conference until they are called back later in the afternoon for the formal Q&A sessions. In the meantime, they may, if they wish, prepare themselves for the Q& A sessions by seeking support from their own organisations.

5.4 Preparation for Formal Questions (Referees, Review Conference Day 1)

The preparation for formal questions took place on Day 1 and was devoted to exchanging views on the proposals between referees (based on their reading of the written proposal as well as on the poster sessions) and, above all, formulating formal questions to be asked to the JRP representatives on each proposal.

Prior to this session, the facilitator had designated one particular referee as a Chair, selected by the MSU staff on the basis of his/her competences in terms of communication skills and facilitation of discussions. The role of the Chair is to initiate the discussion within the group during the preparation of formal questions (and also to assist the facilitator in clarifying, only if needed, the formal questions to the JRP representatives during Q & A sessions). Referees acting as Chairs cannot be first-time referees, and they are not designated as Chairs for more than 1 proposal. All referees within the group were clearly informed that they are ALL equal referees, and therefore the Chair is not “more equal than the others”.

For these sessions, the MSU facilitator was assisted by an MSU note taker in order to write down the questions, for each evaluation group. All referees were clearly instructed that only those questions which were developed jointly by referees would be raised, as these were to be “consensus” questions: no other questions would be allowed. The facilitator suggested that, typically, 5 to 10 such questions would seem appropriate for the limited duration of the Q &A session (15 minutes maximum). Referees were also advised that they should formulate clearly understandable questions, and avoid multi-part questions. At the end of the development of questions, these were prioritized. In order to have equal treatment for all proposals, the total duration of this session was limited to 20 minutes to elaborate questions for each proposal

The nominated Chair referee was invited to initiate the process by suggesting the first question(s). The facilitator contributed to ensure that the questions were adequately formulated and written down by the note taker. All other referees, notably those who were asked to focus on the proposal under discussion, were then invited to participate in the elaboration of the questions either by formulating questions themselves or discussing and agreeing on the clarity, relevance and content of questions raised by their co-referees, and contributing to the prioritization of the questions.

At the end of the session, the ranked list of agreed questions was not made available to the referees, but kept by the facilitator. Questions would be read to the JRP representative by the facilitator, and only in case the question would need to be clarified, would the chair referee be invited to provide such clarification.

5.5 Formal Q & A (Referees and Representatives, Review Conference Day 1)

The formal Q&A sessions were the last sessions of Day 1. In each group they were chaired by the MSU facilitator. Each representative was admitted into the session in ascending order of the proposal numbers. In some rare cases, the order was modified to accommodate early departure time of some representatives; this was mutually agreed between representatives and the facilitator. The representative was reminded by the facilitator about:

- the recording of the session (in order to provide evidence of the answers given)

- the total duration of the session (15 minutes),
- the number of questions (in order for him/her to make his/her own judgement about the time he/she would want to spend to answer the questions)
- the option available to the representative, should the Q&A be finished before the allocated slot of 15 minutes was over, to use the time left to to make a statement or come back to a previous question to correct or complete his answer, or decide to terminate the session.

The facilitator then raised the questions in the order defined in the question elaboration session. If needed, the Chair referee was invited to clarify the question. During the session, the facilitator acted also as a time keeper. At the end of this session the facilitator thanked the representative for his /her participation to the conference. The participation of the representative to the Review Conference was fully terminated from that moment.

The JRP representatives were then reminded again that they should not interact with referees after the session. They were also invited to fill in a satisfaction questionnaire regarding their participation to the review conferences

The observer noted that, on some rare occasions, there was time left after the questions, and representatives took this opportunity to clarify, correct or complement the information delivered to the referees during the poster session or in response to earlier questions of this Q & A session. On one particular Q &A session, as there was some time left, the representative invited referees to ask more questions but was reminded by the facilitator that this was not allowed, because questions were to be strictly “consensus” questions and not individual questions. It was also noted that, by default, the clock was not made visible to the representative unless he/she would ask for it.

6. Review Conferences: Evaluation

6.1 Marking the JRPs (Referees, Review Conference Day 2)

Within each group, the facilitator, acting as a Chair, reminded the referees about their tasks for the marking session, and the “rules of the game”: 35 minutes per proposal, commenting before scoring, ensuring that comments are directed to the right criterion, ensuring that a proposal is not penalised twice for the same reason, paying attention to the score interpretation table (displayed in the room), the individual criterion threshold and the global threshold and their significance in terms of “killing” or not a proposal, the weighting factors, the need to avoid recommendations for changes /improvements of the proposal, the need to ignore information contained in the proposal pages beyond the page limit, etc.

Referees were also reminded that:

- comments may be as blunt as they wish. They will be ‘polished’ afterwards and expressed in adequate language by EURAMET/MSU, without changing the meaning. What is needed at this stage is clarity of the comments.
- comments are very important for 2 major reasons
  - comments have to help applicants to clearly understand the reasons for their scores, especially for those who will not be funded and who will end up being just below the funding line.
  - comments have also to help EURAMET during the grant preparation phase for those JRPs that will be funded

Before commenting and scoring, referees were invited to agree on whether the proposals conform fully, partially or not at all with the SRTs, and whether deviations, if any, are properly justified in the proposal. The facilitator reminded also the referees that they are to assess the proposals and not the SRT.

Referees were also reminded that, in contrast with prevailing practices under Horizon 2020, the operational capacity of the project partners to perform the work is now to be assessed under the criterion” implementation”.

Likewise, the gender dimension (not to be confused with gender balance), research data and output management, and open science aspects are now to be assessed under the criterion “excellence”

The facilitators invited, on each criterion, the chair referee to initiate the process by expressing his (her) comments resulting from all inputs received (remote reading of the proposal, poster session, Q & A session). Other referees were invited contribute to the discussion and express their comments. An agreed set of comments was then obtained with positive and negative comments against which a mark was proposed for each criterion. At times, facilitators had to remind referees that scores should properly reflect and support their comments and to draw the referees’ attention to the score interpretation table displayed in the room. There were a significant number of situation when a provisional score (N+ or N-) was noted, subject to reconsideration at the end of the marking session when all proposals of the group had been dealt with. This allowed referees to make a comparative assessment of the proposals. After commenting and marking all proposals within the group, the scores were finalized. At the end of each marking session, referees were asked to formally expressed their agreement with the results of the session by signing the record of comments and scores for each proposal within their group (except those for which a CoI had been identified) and the results were then transmitted to the MSU for the preparation of the final plenary session.

During the marking sessions for each TP, the Programme Manager circulated between the groups (for multigroup TPs) to check emerging scores and to obtain a preview of what the single ranked list might look like, in preparation for the subsequent final plenary session.

6.2 Single Ranked List (Referees, Review Conference Day 2)

Once all marking sessions of all groups for a given TP were completed, the results of each group were passed over to MSU to developed a proposed Single Ranked List of JRPs. For each TP, the first draft of the Single Ranked List was presented to the plenary meeting of the referees by the Programme Manager

The Programme Manager first showed the lower part of the ranked list with proposals being below threshold on one or more criteria or globally. These proposals were simply ranked in descending order of the total weighted scores. As these proposals would not be funded in any case, there was no attempt (and no need) to untie equal score proposals.

Once referees had expressed their agreement on these JRPs not suitable for funding, the programme manager showed the upper part of the ranked list. The initial ranking was also done in descending order of the total weighted score. Proposals with equal total weighted score were untied and ranked first by the highest weighted score for the highest weighted criterion, and then, if necessary, by how close the external participation value would be to the TP target. No referee challenged these default options for untying the equal total weighted score proposals. However, with the current uncertainty on the status of the UK’s association agreement to HE during the grant preparation phase, there is also an uncertainty on the extent of the external participation. Therefore, for those proposals which still needed untying, a referee was invited to briefly explained to his/her co-referees the main features, objectives, strengths and shortcomings of each proposal and then referees were invited to vote. In all cases there was a clear majority view enabling the proposals to be untied without any controversy nor ambiguity.

As explained earlier (section 5.1), the UK association uncertainty makes it also uncertain where should the funding line be eventually positioned down the ranked list. Therefore, some proposals below the “normal” funding line were also untied in order to facilitate the decision-making process in case the funding line would eventually go further down the ranked list

For all TPs, all referees were quickly in agreement with the proposed ranking. Referees were then asked to formally give their approval, one by one, on the ranked list and their approval was recorded. They also formally approved the list of proposals not suitable for funding.

The Programme manager indicated that the ranked lists for all TPs would be submitted to the Metrology Partnership Committee for approval on 22 November 2022.

For security/confidentiality reasons, referees were invited to delete, destroy or dispose of all electronic or printed documents related to the evaluation of the call 2022. To that effect, the MSU staff was available to collect any document that referees wanted to leave before departing. Referees were also invited to fill in and return to MSU staff the satisfaction questionnaire regarding their participation to the review conferences

7. Conclusions

The conclusions that I can draw from the review of the 2022 European Metrology Partnership Call documentation, and from my participation to the evaluation process as IO, and primarily my attendance at the Review Conferences 2022 include the following:

- The evaluation process was carried out in accordance with all applicable rules and procedures. All documents, guides, forms, templates were up to date, clear, and available in due time to all participants to the evaluation process

- The evaluation was organised in an outstanding manner, extremely well planned and prepared by EURAMET and the MSU. During the Review Conferences the MSU team was always available to assist the participants (referees, representatives, and myself as IO) and to answer promptly any question from them. The preparation, procedures and assistance were of very high quality. This remarkable organisation led to a very smooth running of the whole evaluation process

- The overall evaluation process was conducted in a very efficient manner and the referees carried out their work in full compliance with the guiding principles of independence, impartiality, accuracy, objectivity and consistency. The security and confidentiality aspects of the process were perfectly dealt with.

- The Call documentation for the European Metrology Programme and all correspondence and procedures with the referees were comprehensive, of a very high standard. This documentation is now well proven after many years of being used, updated and refined in the predecessor programmes EMRP and EMPIR

- The briefings delivered by the programme manager, deputy manager, and MSU facilitators to the referees and the representatives were comprehensive and of very high quality. The guidance and information provided to referees and representatives in these briefings is absolutely necessary. Although some of this guidance and information are repeated by facilitators at the start or during the various sessions, the experience shows that this repetition is often very much needed (also for the IO!)

- The referee work at the review conferences was intense but the workload was perfectly distributed over 2 days for each conference, with a long day (day 1) and a shorter day (day 2), both with several breaks. The informal exchanges during breaks were also contributing to the quality and richness of the evaluation. For me, as IO, these breaks are excellent occasions to talk to referees and get valuable inputs for my observer work.

- One major difference between this evaluation and other Horizon Europe evaluations is the active participation of applicant representatives in the evaluation process for the metrology partnership. Interestingly, when asked about their views about the relative importance of the written proposals against the poster sessions as inputs into their assessment work, the answers were generally either 70% for written proposals against 30% for the poster sessions, or just the opposite (30% Proposals +70% Posters). Very rarely did I get a balanced view of 50% each. One tentative explanation may be that those referees who are asked to focus on a proposal attach more importance to the written proposal, whereas the other referees rely more on the poster sessions.

- Adhering strictly to the schedule and timing of the numerous conference sessions is a rather difficult exercise, but this is absolutely necessary if one wants to treat equally all proposals. This was remarkably achieved over the full duration of the conferences. In that respect, one virtue the coffee breaks is to offer some buffer time/margin between sessions, thus contributing to keeping closely to the daily schedule.

- The work in tandem (facilitator + note taker) during the question development and the marking sessions was also remarkably well performed, considering that referees do not always make the effort of expressing themselves with sufficient clarity and slowness to facilitate their work. It was more than once necessary for the tandem (mainly the facilitator) to take an active part in the session to rephrase or reinterpret the questions or the comments of the referees in a clear, concise and understandable manner.

- The main call evaluation outcomes are the final ranked lists. They were obtained as a result of a clear, fair and transparent evaluation process supported by carefully selected referees. There was no plenary meeting in which controversy or frustration could be noticed. As IO, I have no doubt that these lists are suitable for the Metrology Partnership Committee to make their decisions on a well-founded basis.

As an independent observer, I am convinced that all proposals received adequate, fair and equal treatment. The whole evaluation process was conducted to high standards of diligence, fairness and professionalism, in accordance with established principles of independence, impartiality, objectivity, accuracy and consistency at all stages and in full compliance with established rules, and that the resulting ranked lists reflected, for those projects above the funding line, the best projects which should be funded.

The organisational and logistical aspects were excellent.

8. Acknowledgments

In closing this report, I would like to thank the European Metrology Partnership Chair, the EURAMET Programme Manager and deputy Programme Manager, and the entire Management Support Unit team for their excellent support before, during and after the Review Conferences. Every effort was made to provide me with free and unrestricted access to all information and documents, and to answer promptly and fully any question, thus demonstrating a high degree of openness and transparency. Their support, their assistance and their kindness throughout the entire process were outstanding and contributed greatly to making the observation work not only a smooth but also a very enjoyable exercise.

Publishable Summary for 21GRD01 OpMetBat
Operando metrology for energy storage materials

Overview

The development of new battery materials is key to improving the performance, lifetime, safety and cost of energy storage technologies such as Li-ion batteries for electric vehicles. However, innovation is hampered by the inability of industry to reliably characterise their structure and chemistry in an operating environment. This project will build a metrological framework supporting traceable *operando* characterisation of state-of-the-art battery materials under dynamic charge / discharge conditions. This includes advancement and validation of *ex situ* methods, establishing new protocols, cells and a best practice guide for *operando* approaches and developing new instrumentation enabling hybrid, multiparameter measurement to inform new materials development.

Need

The European Green Deal targets net zero CO_2 emissions of greenhouse gases in Europe by 2050, specifying zero emissions from new cars by 2035. Electrification of the automotive industry is key to meeting these goals, but rapid advances in energy storage technologies such as lithium-ion batteries are required to realise this. Many new materials combinations for battery electrodes are emerging that can begin to address performance targets, but lifetime issues remain problematic. Hence, there is an urgent need for traceable analytical techniques to decipher structure-behaviour relationships and elucidate degradation and failure mechanisms to improve battery performance by design, rather than empirically.

Quantification of elemental composition, and determination of oxidation and chemical binding states, coordination and phase structure are crucial for an enhanced understanding of battery electrode degradation (Objective 1). Moreover, investigations must be conducted in real-time, allowing aging mechanisms to be linked to battery state of charge (SoC) and state of health (SoH). Currently, degradation studies are performed *post-mortem*, using *ex situ* methods where the cell is disassembled, leading to chemical modification which can distort the result. To avoid that, *operando* methods, where electrode materials are characterised simultaneously during cell charge-discharge, are needed. Whilst some *operando* methods are available, they are not sufficiently reliable or quantitative to allow confident data interpretation (Objective 2). Moreover, there is a need for new hybrid *operando* methods, where multiple measurands are synchronously probed during electrochemical cycling, to establish causal links between materials properties and their impact on cell performance (Objectives 3 and 4). Such advanced measurements bring new challenges as they require special sample environments such as dedicated electrochemical cells with thin probing windows, while ensuring that the electrochemical behaviour remains unperturbed. Hence, there is a need for establishing a robust, validated metrological framework for *operando* metrology, that can be transferred to battery developers and demonstrated through industrial case studies.

Objectives

The project aims to develop *operando* techniques and hybrid (multi-modal) instrumentation, supported by quantitative and validated *ex situ* analysis and electrochemical measurement methods, to enable beyond state-of-the-art materials characterisation for high-capacity energy storage technologies.

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EURAMET. Neither the European Union nor the granting authority can be held responsible for them.

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

European Partnership Co-funded by the European Union

METROLOGY PARTNERSHIP EURAMET

The specific objectives are:

1. To develop traceable chemical, physical and structural analysis methods for ex-situ characterisation of high-capacity energy storage materials (e.g Li-ion and Li-S) and components (e.g. Cobalt, Nickel, Manganese) with a focus on x-ray spectroscopic techniques. This includes the fabrication and qualification of at least 3 calibration samples and verification by interlaboratory studies (post-mortem). A relative uncertainty in elemental composition determined by XRS of below 10 % will be targeted.
2. To establish a Good Practice Guide for current and emerging in operando spectroscopy methods including X-ray and vibrational spectroscopy, validated by ex-situ analysis and round robin tests, in order to establish and, where possible improve, experimental repeatability and accuracy with respect to elemental and species analysis of battery materials. In addition, to develop measurement protocols to assess the influence of cell geometry, electrode configuration, and measurement parameters on observable phenomena, as well as to assess the extent and influence of vacuum ultra-violet (VUV) or X-ray radiation damage.
3. To develop novel dynamic electrochemical approaches combined with in operando spectroscopy and dimensional metrology for the correlative assessment of the relationships between material structure and cell performances.
4. Based on the results of Objectives 1-3, to develop novel in operando instrumentation and hybrid methodologies for multi-parameter spectro-electrochemical characterisation of materials and components for high-capacity energy storage (e.g. in Li-ion and Li-S battery systems). To investigate the causal relationship between electronic/molecular- and microstructure information and charge carrier dynamics as measured with electroanalytical methods, to gain information on the state of health and state of charge.
5. To facilitate – in cooperation with the EMPIR JRP 20NET01 Clean Energy – the take up of the data and measurement infrastructure developed in the project by the measurement supply chain (NMIs, DIs, calibration laboratories), standards developing organisations (e.g. ISO/TC 201) and key end users (materials suppliers and battery manufacturers). To promote technology transfer of the project outputs as lab-based alternatives to synchrotron radiation-based methods, towards industry and manufacturers.

Progress beyond the state of the art and results

Traceable ex situ characterisation of high-capacity energy storage materials (objective 1)
Despite a variety of existing approaches to *operando* characterisation of energy storage materials based on X-ray spectrometry, vibrational spectroscopy and X-ray diffraction, practices vary substantially across academia and industry. There is little agreement and consistency in terms of electrochemical cell geometry, materials handling methods and measurement protocols, leading to a lack of confidence in data comparison.

This project aims to make progress beyond state of the art by establishing a foundation for *traceable* and quantitative *operando* measurement built on *ex situ* methods that are validated by adopting appropriate reference materials. This includes development of new, more reliable, sample transfer protocols that minimise the likelihood of chemical changes as a result of cell disassembly in *post-mortem* studies. Advanced analytical techniques such as X-ray photoelectron spectroscopy (XPS) and secondary ion mass spectrometry (SIMS) will be employed which improve upon current approaches in terms of sensitivity, accuracy and spatial resolution, and new reference data will be generated to support widespread and reliable comparison.

Good practice guide for current operando spectroscopy and diffraction methods (objective 2)
For the first time, this project will develop and disseminate a good practice in the application of operando X-ray and optical techniques such as Raman spectroscopy. This will be achieved by developing cells and protocols validated by physical modelling, performing parametric studies to optimise experimental conditions, and undertaking interlaboratory comparisons to establish the root of uncertainties to improve experimental repeatability.

Novel dynamic electrochemical analysis approaches for combination with operando spectroscopy and dimensional metrology (objective 3)
To develop a completely new and innovative approach to electrochemical impedance spectroscopy (EIS) which can be implemented during galvanostatic cycling. Conventional EIS typically requires cell equilibration which precludes this kind of dynamic measurement, but the new approach to frequency-dependent analysis will for the first time allow EIS to be performed simultaneously alongside operando spectroscopic materials characterisation to uncover the connection between materials property changes and cell performance loss.

Novel operando instrumentation and hybrid methodologies for multi-parameter characterisation (objective 4)
Finally, the new knowledge generated throughout the project will be built upon to develop novel *operando* instrumentation and methodologies that further extend the state of the art by: (i) improving sensitivity compared to current approaches by developing new *operando* cell windows; (ii) allowing advanced X-ray methods normally confined to synchrotrons to be transferred to laboratory-based instrumentation; and (iii) enabling simultaneous, *hybrid*, multiparameter measurement to allow causal links between materials property changes to be established, and their links to cell performance loss to be identified unequivocally.

The new framework for *operando* metrology will be demonstrated by way of industrial case studies, in which the tools developed will be combined to deconvolute some of the most challenging degradation mechanisms currently observed by battery developers and that cannot be resolved by current ex situ characterisation techniques. For this reason, the battery manufacturer Johnson Matthey (JM) and the Fiat Research Center S.C.p.A. (CRF) associated with the large automotive manufacturer Stellantis will carry out three industrial impact case studies that will demonstrate how *operando* and *hybrid* characterisation techniques can overcome these issues. From an industrial perspective, regarding both R&D and quality management, the intended demonstration of transferability from large-scale facilities into the laboratory is highly desirable.

Outcomes and impact
Outcomes for industrial and other user communities
Through various dissemination activities, the protocols and best practice guidance established for the implementation of *operando* X-ray spectroscopy (XRS), Raman spectroscopy and X-ray diffraction (XRD) for energy storage materials characterisation will be adopted by battery manufacturers (e.g. VW, Tesla, CATL) and user communities in Europe (e.g. European Battery Alliance, Battery European Partnership Association, Battery 2030+). The uptake of the good practice guide by battery and materials developers will add value to their materials characterisation by improving the fidelity of *operando* approaches and increasing confidence in data interpretation. The improved depth of time-resolved information gleaned by operando techniques compared to more conventional analytical methods will stimulate innovation, leading to more rapid and efficient materials development for established battery technologies such as Li-ion as well as for emerging chemistries such as lithium-sulphur (Li-S). The uptake of the new know-how will deliver a lasting impact of improving battery performance, durability and safety as fade and failure mechanisms become better understood.
The transfer of synchrotron-based methods to equipment that can be used in a laboratory will have an enormous impact on industrial and other user communities, since the availability of synchrotron beam time is highly limited. Sophisticated lab-based systems can, therefore, be used as standard characterisation methods for battery cells by industrial cell producers.

As quality control in the industry is typically performed with galvanostatic charge/discharge, the EIS measurement protocol and analysis algorithm will be an ideal tool to access valuable information about processes in operating industrial cells, at low cost. The immense output of data will benefit from the use of novel machine learning algorithms to better estimate battery SoH and improve lifetime prediction. Moreover, the dynamic nature of this innovative approach will allow EIS to be performed simultaneously alongside *operando* spectroscopy, enabling much more confident analysis of degradation mechanisms.
Ex situ characterisation continues to be important in battery failure analysis. However, the requirement for cell disassembly and removal of liquid components limits the modes of failure that can be assessed. The project will validate and clarify the limitations of *ex situ* methods and will serve as guidance to industry analysts and increase confidence in ex situ characterisation by providing reliable reference data. This improved metrology framework will accelerate the development of better performing batteries with longer lifetime.

Outcomes for the metrology and scientific communities
The good practice guide developed will benefit the scientific community by improving reliability, repeatability/reproducibility and fidelity of *operando* measurements. By encouraging the uptake of a common set of methods and measurement protocols, the comparability of data across the academic literature will be greatly improved, allowing more conclusive links between materials chemistry/structure and behaviour. The consortium will develop cells for *operando* and *hybrid* (multi-dimensional or multimodal) spectroscopy, which benefits both communities as they can integrate the outputs in their systems and workflows. The project will pioneer *operando* metrology for battery research at several European synchrotron radiation facilities and the transfer into laboratories to support industry and researchers. The provision of accurate atomic fundamental parameters is of substantial interest for the scientific community using X-ray techniques. Electrochemical assessment of capacity fade in battery systems will gain from the novel EIS measurement protocol. As it can be performed in parallel, it opens additional information regarding e.g. charge transfer evolution and solution resistances. The scientific community will benefit from protocols for performing microchemical analysis of batteries in fixed states which will allow for studies of the internal solid-liquid interfaces to obtain mechanistic insights. Such results will further support the interpretation of *operando* spectroscopies widely in the metrological community.

Outcomes for relevant standards
The NMI participants are involved in key international organisations (ISO, BIPM, EURAMET). Many of the techniques to be developed are too immature to consider standardisation at this stage, however activities to support the future development of relevant standards are planned. To achieve this, participants will disseminate project outputs to committees and lead discussions on *operando*-specific challenges. The consortium will also communicate the battery industry's needs to the respective committees to help identify target methods of future standardisation activities.

The most relevant standards committee is ISO TC201, which focuses on surface chemical analysis and includes many of the analytical techniques used in the project. The project will provide input into: Working Group 5 on optical interface analysis (e.g. Raman spectroscopy); subcommittee 6 on SIMS; subcommittee 7 on XPS; subcommittee 10 on X-ray reflectivity (XRR) and X-ray fluorescence (XRF) spectroscopy; subcommittee 2 on general procedures for surface chemical analysis; and subcommittee 1 on terminology. In ISO TC201 SC10 input related to physically traceable XRF methods will be generated. The consortium will also engage with VAMAS on the topics of Raman spectroscopy (technical working area 42) and surface chemical analysis (technical working area 2) to establish a foundation for pre-normative interlaboratory comparison activities. This will establish the current level of repeatability and comparability and provide the basis for future standardisation. Several committees associated specifically with batteries will also be targeted to ensure that the importance of standardisation at the materials level is represented.

Longer-term economic, social and environmental impacts
The transition to hybrid electric vehicles is essential to reduce human impact on air pollution, global warming, and their effects on public health. Improved confidence in measurement is key to the development of next generation energy storage materials with sufficient performance and lifetime for automotive applications, and therefore underpins this energy transition. The improved measurement capabilities and robust traceability chain to be developed in this project will facilitate the required understanding to develop electrochemical viability to meet this rapidly growing need. The improved battery lifetime that results will not only improve the commercial viability of these technologies for use in the automotive sector, but moreover bring down their cost, which is one of the most prohibitive challenges preventing more widespread adoption of electric vehicles. Reducing the cost of electric vehicles will improve their competitiveness against conventional combustion engine vehicles, thus stimulating market growth. Reduced costs will also improve public perception of electric vehicles, further augmenting their uptake within society. More broadly this will lead to significant economic benefits across the EU, with automotive companies prospering, generating wealth and jobs.

The metrology framework and tools developed will support rational materials design concepts in the energy storage sector and more broadly, which will in future pave the way to more efficient development of functional material chemistries with improved sustainability, and smaller CO_2 footprint. Of major concern in the battery industry is reliance on critical raw materials such as cobalt and lithium. These materials are available currently, but a supply risk has been identified and in the long term a fully electrified society will require alternative materials and chemistries. By developing new and advanced tools and methodologies for the reliable *operando* characterisation of these materials, empowering scientists, and industry to develop next generation materials based on more abundant (and therefore cheaper) resources that can also be more easily recycled.

Finally, this project will bring substantial societal benefits. Decarbonisation of the automotive sector will significantly improve air quality whilst reducing noise pollution in urbanised areas, thus improving the overall quality of life of inhabitants as well as their physical and mental health. The latter aspects will decrease pressure on health services, therefore improving wellbeing for wider society.

List of publications
n/a

This list is also available here: https://www.euramet.org/repository/research-publications-repository-link/

Project start date and duration:	1 September 2022, 36 months	
Coordinator: Burkhard Beckhoff, PTB Tel: +49 30 34817170 E-mail: Burkhard.Beckhoff@ptb.de Project website address: https://opmetbat.inrim.it/		
Internal Beneficiaries: 1. PTB, Germany 2. CEA, France 3. CMI, Czechia 4. INRIM, Italy	External Beneficiaries: 5. CRF, Italy 6. HZB, Germany 7. JSI, Slovenia 8. MEU, Türkiye 9. TUB, Germany 10. UNG, Slovenia 11. UNIROMA1, Italy 12. WWU, Germany	Unfunded Beneficiaries: 13. OG, Germany
Associated Partners: 14. ELECTRO, United Kingdom, 15. Empa, Switzerland, 16. JM, United Kingdom, 17. NPL, United Kingdom, 18. Uliv, United Kingdom		

Publishable Summary for 21GRD02 BIOSPHERE
Metrology for Earth Biosphere: Cosmic rays, ultraviolet radiation and fragility of ozone shield

Overview

One of the most significant – yet unexplored – ecological challenges facing EU member states and beyond is the impact on human and environmental health of the increasing atmospheric ionisation caused by extra-terrestrial radiation (cosmic rays and solar UV radiation) boosted by anthropogenic emissions. This project aims to develop the necessary tools, methodologies and measurement infrastructure needed to evaluate the mutual impact of cosmic rays and biologically active UV radiation on the Earth's biosphere, and to support EU policy makers with scientific assessments and information that have the potential to substantially improve policies on climate, health and anthropogenic emission activities.

Need

Cosmic rays, along with UV radiation and the Earth's natural radioactivity, are one of the main sources of atmospheric ionisation, contributing to the electrification of the lower atmosphere and, thus, to the climate system in general. Attempts to quantify the changes this radiation causes in climate processes (e.g., cloud formation and thunderstorms), however, are debated and remain poorly understood. Over millennia, living organisms have been continuously exposed to cosmic rays and solar UV radiation. Biological actions of many kinds have evolved to deal with such exposures and a balance between beneficial and harmful effects of these radiation fields has been established. In recent years, however, this balance has been disturbed due to anthropogenic (man-made) emissions and environmental pollution creating an urgent need to study how these combined radiation fields are shaping our natural habitat, affecting the evolution of the biosphere, and impacting on our health. To achieve this, a combination of observations is needed using modern satellite technologies and ground-based *in situ* and remote sensing in environmental biology, chemistry and also radiation protection, to start the evaluation of cosmic and solar radiation effects on the biosphere.

Ionisation of the biosphere by cosmic radiation is known to correlate significantly with disease prevalence in humans, infectious disease mortality, and overall mortality. This is in addition to the harmful effects caused by UV radiation alone, which increases the incidence of skin cancer by about 2 % for every one percent reduction in ozone. Genomic, epigenetic, transcriptomic, and metabolomic changes potentially responsible for cellular radio-sensitivity and possible long-term dysfunction remain, however, largely unknown. The lack of understanding of these effects is exacerbated further by ozone depletion-induced overexposure to UV radiation and its implications for cellular defence mechanisms. Therefore, monitoring, modelling, and correlating cosmic rays, terrestrial solar radiation, and ozone thickness is critical not only to understand the radiological sensitivity of cells, but also to make informed decisions regarding the global challenges facing our society.

Traceable metrological data on cosmic ray fluxes, solar UV spectra, and the total ozone column are key to assessing the role of cosmic rays as climate drivers but quantification of correlations between them is required to inform new approaches to chemistry-climate models that will help clarify current ambiguities in the scientific community related to climate variability. Cosmic rays entering the top of the Earth's atmosphere, or primary cosmic rays (PCR), interact with atmospheric constituents to produce secondary cosmic rays (SCR), which are measured by ground-based instruments. The generation of an improved understanding of the role of PCR and SCR in ozone depletion, would provide a better assessment of biological implications due to natural UV overexposure. Quantification of ionisation and the production rates of charged molecular fragments and other reactive species is needed to extend present-day models that are currently limited to ionisation and the nonspecific energy loss values required to produce an ion pair. The interaction cross sections for these

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

processes need to be examined and measured experimentally to improve the reliability of the ionisation data of natural atmospheric and anthropogenic gases relevant to ozone layer chemistry. Implementation of these cross sections into simulation codes for space radiation propagating through the atmosphere leads to refined radical, ion and slow electron production rates, which are needed to enable a more accurate estimation of the effectiveness of the cosmic ray model compared to the photochemical model in depleting the ozone layer. This is important for predicting future trends in ozone hole dynamics and for assessing the role of new chemicals in the ozone depletion.

Therefore, it is necessary to identify and quantify the relationship between cosmic radiation, ozone depletion and anthropogenic emission with the help of simultaneous modelling and traceable measurements of (i) ground-level muon and neutron fluxes, (ii) terrestrial solar UV-irradiance, and (iii) total ozone column (Objective 2). To achieve this, this project will characterise and calibrate novel SCR instrumentation – including an upgraded LIDAR system. Since generation and decay of SCR depend on air density, knowledge of atmospheric profile parameters such as temperature, density, and aerosols are needed to establish an accurate relationship between SCR and PCR fluxes (Objective 1). For the first time, this project will determine fundamental data on the interaction of low-energy cosmic-ray induced electrons with atmospheric gases of both natural and anthropogenic origin (Objective 3). This includes collision cross sections for the molecular processes such as dissociative electron attachment, molecular fragmentation and ionisation needed for the evaluation of mitigation strategies for the effects of anthropogenic emissions for the greater protection of human, animal and ecological health, and the development of policies that support these strategies. The impact of combined cosmic and UV irradiation on human health will be assessed by investigating structural and functional damages inflicted by such mixed radiation fields in human primary cells such as primary skin fibroblasts, blood monocytes and brain endothelial cells (Objective 4). Genomic, epigenetic, and transcriptomic changes that might be responsible for cell radiosensitivity and possible long-term dysfunction will be assessed, in this project, in connection with the fate of irradiated cells in terms of viability, morphology and functions.

Objectives

The overall aim of this project is to develop metrological methodologies to establish the correlations between primary and secondary cosmic rays (PCR and SCR), solar UV radiation and ozone layer thickness, and to assess their mutual impact on the Earth's biosphere.

The specific objectives of this project are:

1. To determine the dependence of SCR on PCR and atmospheric parameters (e.g., temperature, density, aerosol concentration), based on field measurements made using well characterised and traceable modified mobile SCR muon and neutron detectors, a novel semiconductor detector and adapted and/or existing LIDAR systems for vertical atmospheric profiling.
2. To identify and quantify the correlation between PCR and solar UV radiation on the ground including their dependence on anthropogenic gas emissions using simulations and traceable measurements of (i) ground-level muon and neutron fluxes, (ii) terrestrial solar UV-irradiance, and (iii) total ozone column.
3. To determine the molecular processes affecting ozone depletion and atmospheric dynamics, and to provide a complete database of collision cross-sections for natural atmospheric and anthropogenic gases. This is to be based on simulations and experimental validations that quantify molecular ionisation (absolute ionisation, excitation, dissociation cross section energies and projectile energy loss) and production rates of charged molecular fragments of both natural and anthropogenic atmospheric gases including CFCs and CH_2Cl_2 from interactions with low and medium energy (<10 eV - 2000 eV) electrons.
4. To assess the potential effect on human health from exposure at environmental levels to combined SCR and UV radiation fields using healthy human cell lines. This is to be based on simulating environmental level exposures under experimental conditions to establish correlations between radiation type and flux, and changes to cellular parameters (cell death, DNA damage and genomic instability, adhesion, and proliferation). In addition, to determine the expression profile of stress genes using established radiation effect models and systems biology approaches.
5. To facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain (NMIs and DIs, atmospheric monitoring networks), standards

developing organisations (e.g. IEC, ISO, CENELEC, CCRI (I) and EURAMET Technical Committee for Ionising Radiation (TC-IR)) and end users (e.g., health and environment regulatory bodies, research institutions focused on environment, climate, medicine and biology, and radiological protection, and instrument manufacturers).

Progress beyond the state of the art and results

Cosmic ray-induced low energy electrons and solar UV radiation are major drivers for atmospheric chemistry. For quantitative description of atmospheric ionisation, interactions with anthropogenic gases, collision and chemical processes involving ozone, climate-chemistry models require reliable cross-sections for the interactions of gases in the stratosphere with low energy electrons as well as for the production of reactive species by those interactions. This project will determine for the first time the medium to low-energy electrons cross sections for ionisation and fragmentation-ion production of atmospheric constituents such as N_2, O_2, NO, NO_2, selected chlorofluorocarbons (CFCs), halogenated molecules (such as HCl, HF, HBr, SF6), as well as aromatic and nitrogenated molecules (such as pyridines whose cations facilitate aerosol formation).

Determining the dependence of SCR on PCR and atmospheric parameters

The SCR flux measured at ground level is affected by the survival probability of the incoming parent PCR particles, the various atmospheric conditions such as air density and temperature, and the particle absorption rate down this path. Corrections which exploit the exponential dependence of pressure or temperature on altitude are currently used for these effects, but these do not consider the inhomogeneities of air density that affect the accuracy of the recorded SCR fluxes. This project will develop, for the first time, metrological methods to quantify the correlation between PCR and SCR using atmospheric profile parameters measured by LIDAR(s). These will include a novel mobile scintillator-based muon detector capable of measuring muon flux reaching the ground level with an energy distribution from a few hundred MeV to a few hundred GeV, a novel boron scintillator-based mobile neutron detector which can measure neutrons in a wide range of energies (from thermal up to several tens of MeV), and a spectral-tracking particle telescope assembled as stack array from 2 semiconductor pixel detectors (Timepix3) in miniaturised and portable architecture for high-angular resolution wide field-of-view mapping of SCR with resolving power of mixed-field components (muon, electron, proton, ion, gamma, X ray, neutron).

Identifying and quantifying the relationship between cosmic radiation, UV radiation and anthropogenic emission

Side-by-side measurement of the terrestrial solar UV spectrum, total atmospheric ozone, and SCR flux rate has never been attempted so far due to the lack of the proper measurement framework. This project will provide such measurements for the first time and will go beyond the state of the art not only by measuring these parameters simultaneously, but also by supporting the ground-based measurements with satellite measurements such as satellite observations of energetic electron, proton and Helium-ion fluxes. Simultaneous measurement of SCR fluxes, UV radiation spectrum and ozone column, enabling a quantification of the relationship between them, will be carried out at four European sites (Greece, Belgium, Czechia, and Germany). This will provide the necessary infrastructure for an accurate measurement of atmospheric profiling parameters and have different anthropogenic emission inventories to integrate the influence of anthropogenic emissions on ozone dynamics.

Molecular processes affecting ozone depletion and atmospheric dynamics

This project will produce for the first time a complete database of collision cross sections for natural atmospheric and anthropogenic gases relevant for ozone layer chemistry. The database will be in an open format and will also include the quantification of molecular ionisation and production rates of charged molecular fragments and other reactive species going beyond present-day models which restrict to ionisation and a nonspecific energy loss value per produced ion pair.

Effects of combined SCR and UV radiation fields on biological systems

Understanding the mutual impact of cosmic and ultraviolet radiation on human health is important not only for humans, but for all mammalian and plant species and the entire living ecosystem. This project will go beyond the state of the art by creating, for the first time, a database of results from irradiated and non-irradiated biological samples such as lung and primary skin fibroblasts, cerebral microvascular endothelial cells from the brain, and healthy blood monocytes. Through advanced bioinformatics and systems biology methodologies, a complex network of molecular changes related to cell death, DNA damage and genomic instability, adhesion and proliferation, and expression profile of stress genes will be established.

Outcomes and impact

Outcomes for industrial and other user communities

The project's data on the combined SCR and UV irradiation of human primary cell lines (such as primary skin fibroblasts, blood monocytes, brain cerebral microvascular endothelial cells) will be provided to enable key information on a plethora of biological effects such as DNA damage, genome instability, cell death, oxidative stress, subtle structural changes and transcriptomic changes. This information is crucial for assessing the impact of such radiation fields on human health. Therefore, European health groups and organisations such as ECCO (European Cancer Organisation), EORTC (European Organisation for Research and Treatment of Cancer), ESMO (European Society for Medical Oncology), and more globally World Health Organisation (WHO) will benefit from this project.

The cross-section data produced in this project will support worldwide monitoring programmes such as the Global Atmosphere Watch (GAW) of the World Meteorological Organisation (WMO) and the International Ozone commission (IO3C) of the International Association of Meteorology and Atmospheric Sciences (IAMAS). These data will also be a valuable input for the chemistry-climate models (CCM) such as, for example, SOCOL (SOlar Climate Ozone Links), MEZON (Model for the Evaluation of Ozone Trends), and CRAC:CRII designed to study the impact of different external factors such as galactic cosmic rays (GCR) and solar proton events (SPE) on the Earth climate system and the ozone layer.

Outcomes for the metrology and scientific communities

The new metrological method for determining the dependence of the SCR flux to the ground on PCR and atmospheric profile parameters will greatly improve the prediction accuracy of the SCR rate at ground stations as a function of pressure and temperature, which is particularly needed during intercomparisons of environmental monitors. This would also lead to better quantification of ground level enhancements (GLEs) and subsequent radiation dose assessments. The participants will also provide input to BIPM Consultative Committee for Photometry and Radiometry on matters related to photometry and ozone dynamics. The metrology infrastructure and methods developed in this project will help estimate the on-ground magnitude of cosmic events such as Solar Proton Events (SPE) and Gamma Ray Bursts (GRB) and will provide information for designing biomedical studies for assessing the impact of radiation exposure on human health, in relation to radiation dose and dose rates. In addition, quantifying the dependence of SCR on atmospheric profile parameters such as temperature would enable improvements to the tracking of short-term atmosphere dynamics such as Sudden Stratospheric Warmings and geoscience applications such as characterising the density structure of volcanoes. This would be of interest to organisations such as the European Geosciences Union (EGU) and the European Space Weather Community.

Traceable metrological data on cosmic ray fluxes, solar UV spectra, and the total ozone column generated by this project are key to assessing the role of cosmic rays as climate drivers. Quantifying the correlations between these three observables will contribute to new approaches to chemistry-climate models that will help clarify the ambiguities in the scientific community.

The new database of collision cross sections for natural atmospheric and anthropogenic gases will enable modellers, developers and end users to assess the role of low-energy cosmic electrons on the ozone depletion and atmospheric dynamics. The project's new database with results of irradiated and non-irradiated biological samples will enable modellers, developers and end users to assess the effects of combined SCR and UV radiation fields on human health.

Outcomes for relevant standards

The project will provide guidance for stakeholders and input to international standardisation bodies (ISO, IEC, CENELEC), for both ionising and non-ionising radiation protection via input to the following committees: ISO TC 85/SC 2/WG 2 (Radiological Protection, Reference radiation fields), IEC/TC45 (Nuclear Instrumentation, SC45B Radiation protection instruments, WG9 Detectors and systems), CENELEC/TC 45B (Radiation Protection Instrumentation). Thus, the project will support the harmonisation of procedures and methods for the measurement of cosmic rays and solar UV radiation in the environment and hence their inclusion into European and international standardisation.

Longer-term economic, social and environmental impacts

This project will provide data that will help assess the contribution of cosmic rays and UV radiation exposure in the risk for developing chronic diseases and cancer. The data and methods ensuing from the current project will be useful for ecological correlative studies, providing a first glimpse of some of the possible unexplored interactions between the environment and human health. Such findings will have significant economic implications, particularly in terms of public health, agricultural production and food security on a global scale. Policymakers and regulatory bodies will be able to make better informed decisions on climate and environmental policies by using an improved understanding of ozone depletion and its effects on the Earth's Biosphere.

List of publications

n/a

This list is also available here: https://www.euramet.org/repository/research-publications-repository-link/

Project start date and duration:		1 October 2022, 36 months
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Project website address: https://euramet-biosphere.eu		
Internal Beneficiaries: 1. PTB, Germany 2. BFKH, Hungary 3. CEA, France 4. CMI, Czechia 5. GUM, Poland 6. IMBiH, Bosnia and Herzegovina 7. TUBITAK, Türkiye	External Beneficiaries: 8. ADVACAM, Czechia 9. BIRA-IASB, Belgium 10. DTU, Denmark 11. DWD, Germany 12. IFIN-HH, Romania 13. IVB, Romania 14. LZH, Germany 15. MPG, Germany 16. NOVA, Portugal 17. NTUA, Greece 18. Raymetrics, Greece 19. UJF CAS, Czechia	Unfunded Beneficiaries: 20. CSIC, Spain 21. GGO, Germany 22. IRM, Belgium

Publishable Summary for 21GRD03 PaRaMetriC
Metrological framework for passive radiative cooling technologies

Overview

Cooling systems account for nearly 20 % of electricity consumption and 10 % of greenhouse gas emissions, globally. With demand for cooling expected to grow tenfold by 2050, and the increasing frequency of extreme heat waves, improving the efficiency of cooling systems plays a critical role in addressing the global climate challenge. Passive Radiative Cooling (PRC) materials that can dissipate heat as infrared radiation have recently emerged. This project aims to develop a comprehensive metrological framework, including standardised performance indicators (i.e. figures of merit) and testing protocols, to enable the comparable evaluation of their cooling performance on-site and determination of the potential energy savings that could derive from the deployment of such technologies.

Need

The annual cost of heat-related issues is estimated at about $2.4 trillion, with cooling systems costing an estimated $300 billion and producing 1 Gt of CO_2 per year. By 2050, the additional energy needs related to cooling are expected to surpass the total electricity use of China and India today, combined. This is often referred to as one of the most critical blind spots in today's energy debate, given that the rising demand for cooling will add an enormous strain on the electricity systems of many countries, driving up emissions and triggering a self-aggravating feedback loop.

PRC materials can dissipate heat through the infrared transparency window (8 μm – 13 μm) without using any electricity, using outer space as a cold and renewable thermal energy sink to reach sub-ambient temperatures even under direct sunlight owing to their tailored optical and infrared photonic properties.

Despite hundreds of promising PRC coatings and devices demonstrated in the literature in the past few years, reliable testing protocols to evaluate their cooling performance have not been established yet, which is a major obstacle hindering the further development and commercialisation of this new technology. Typical tests up to now are limited to measuring either a temperature drop or cooling power with a heater, using improvised testing rigs with inconsistent insulation and shielding properties, unspecified thermal loads and under different atmospheric conditions, altitudes, ambient temperatures, etc.

Defining standardised figures and testing protocols requires the development of a new conceptual framework and a highly multidisciplinary approach improving both the modelling and the characterisation of emissivity and reflectance properties of thin coatings over a broad wavelength range, the realisation of benchmark systems with known properties, the calibration of portable instruments for on-site monitoring, as well as models accounting for the impact of atmospheric and geoclimatic conditions on the expected cooling potential and the design of standardised testing apparatuses with known thermal loads and insulation.

Objectives

The overall goal of this project is to establish a metrological framework for comparable performance assessments of passive radiative cooling technologies. The specific objectives of the project are:

1. To develop the conceptual framework for comparable performance assessments of passive radiative cooling technologies. This will include the preparation of candidate benchmark PRC materials and

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preliminary characterisation of their spectral responses, with a view to selecting a subset. Additionally, to define one or more figures of merit to assess the performance of PRC materials.

2. To develop and validate numerical models to correlate the cooling performance of PRC materials with the thermal and optical properties of their components, and thus to establish their specifications and associated tolerances. This will include carrying out the thermal infrared spectral modelling of the radiative exchanges between PRC materials, the atmosphere and space at different zenith angles for calculations of the net cooling power of the materials. Additionally, to evaluate the potential impact of PRC materials on energy savings and heat-island effect for urban environments in different climatic regions of Europe.
3. To develop accurate and traceable approaches for determining the thermophysical properties and thermal conductivity of PRC materials, and for converting measured radiometric quantities into a usable form for heat balance calculations. The reflectance and emittance will cover a broad spectral range (0.25 µm – 50 µm) encompassing the solar spectrum and the infrared transparency window of the atmosphere (8 µm – 13 µm). The target uncertainties will be below 3 % for emissivity and absorptivity, 5 % for the total hemispherical emissivity and below 10 % for the thermal conductivity.
4. To develop setups and protocols for on-site testing of PRC materials, with a target uncertainty below 10 % for the figures of merit.
5. To facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain (testing laboratories), standards developing organisations (CEN/TC 89) and end users in the commercial and residential sectors.

Progress beyond the state of the art and results

Figures of merit tailored to passive radiative cooling materials and reproducible model systems

To date, figures of merit to evaluate the cooling performance of a PRC coating are either based on intrinsic material properties, the temperature difference between the substrate and ambient air, or the cooling power of the radiator at ambient temperature. All these quantities are severely affected by ambient, atmospheric and geoclimatic conditions, failing to predict cooling performances under different solar irradiance or relative humidity levels, or to differentiate between broadband and selective emitters. Other parameters typically used for traditional cool-roof applications, such as the Solar Reflectance Index, suffer from similar shortcomings as they were designed for a different class of materials. Within this project, tailored figures of merit will be established to predict how external parameters affect the cooling power of PRC materials. Similarly, the reproducible benchmarking of PRC materials is hindered by the lack of established model systems, with comparisons often made against generic white or black substrates. During this project, several candidate materials will be characterised in terms of their performance to identify stable and reproducible coatings with a measurable net cooling power.

Multi-scale modelling of PRC composite materials

Modelling of PRC materials is a complex task involving several disciplines, length scales and numerical tools, requiring research efforts beyond the reach of single institutes. Moreover, high-performing PRC materials are often hierarchical disordered materials. This is particularly challenging for numerical approaches which are often limited to 2D approximations. This project aims at overcoming this limitation by resorting to heterogeneous computing and multi-scale modelling techniques. Additionally, the project will model the transparency and emissivity of the atmosphere based on several parameters such as, for example, the vertical temperature distribution, cloud fraction or water vapour content, leading to more reliable heat balance calculations and enabling the estimation of the potential energy savings from widespread deployment of PRC materials.

Optical and thermal characterisation of thin, composite materials

Thermal characterisation of sub-mm composite coatings is particularly challenging for state-of-the-art methods used to measure thermal conductivity, such as the Guarded Hot Plate or Heat Flux Meter. More flexible, transient methods need to be examined and validated for this purpose. Similarly, routinely used methods to measure the emissivity of building materials rely on commercial instruments measuring directional emissivity values. However, heat balance calculations relevant to PRC materials require the total hemispherical emissivity, which must be either measured directly or extrapolated from directional measurements using validated methods. Similarly, the angular dependence of the emissivity of PRC devices needs to be evaluated to determine the best relative orientation between the radiating panels and the sky. The EMPIR project 16NRM06 EMIRIM, focused on the measurement of total hemispherical emissivity of the reflective foils used as the skin of thermal insulation products for buildings, demonstrated that the extrapolation of total hemispherical emissivity from near-normal emissivity is not well controlled in terms of uncertainty. Such uncertainty could be even less controlled for PRC materials due to their heavily “optically structured” coating, thus requiring additional adaptations to the reference setup developed during 16NRM06 EMIRIM.

Testing protocols to assess the performance and energy savings deriving from PRC materials

The cooling performance of PRC materials is typically measured using improvised testing rigs under shielding and thermal insulation conditions that are difficult to reproduce and not relevant for real applications, where realistic thermal loads and direct exposure to ambient conditions should be considered. Furthermore, testing of PRC materials should include intense heat conditions and monitoring campaigns spanning months rather than hours/days, which is rarely the case in the literature. In this project, realistic use conditions will be accounted for when designing the testing apparatus and protocol for the evaluation of the cooling performance of PRC materials, filling this critical gap in the current state of the art and allowing the evaluation of the (typically disregarded) uncertainty budget associated to the cooling performance of PRC materials.

Outcomes and impact

Outcomes for industrial and other user communities

This project will establish a shared framework for the performance assessment of passive radiative cooling technologies fostering the development of new energy-saving materials and providing a competitive advantage to EU companies in this emerging field. Companies in the building sector will be able to review their product portfolio in terms of the radiative cooling performance and to develop improved materials and coats based on well-defined figures of merit and standardised protocols for their evaluation. Similarly, industries in the HVAC sector will be able to quantify the expected performance boost and energy savings deriving from the synergic combination of active and passive cooling technologies. End users in both communities will further benefit from the guidelines developed within the project for the validation of emissivity measurements with portable instruments and from the identification of a benchmark material exhibiting near unity emissivity for the calibration of such devices. Expected benefits extend beyond the cooling of residential and commercial spaces, also including applications in the industrial sector such as in power plants or large-scale data centres, both of which have high cooling demands but also large roof areas which could be covered with PRC panels providing net cooling power via non-evaporative methods, thus reducing water withdrawals and thermal discharges in the environment. Notably, industrial processes represent an ideal application area for the large-scale deployment of PRC cooling appliances as in this case there is no need to avoid or reduce potential overcooling effects. The consortium will actively seek the engagement of stakeholders in industry, leveraging on the network of contacts of participants with trade and industrial associations, which will be targeted with dissemination activities.

Outcomes for the metrology and scientific communities

In the past few years, the scientific community has expressed the need to develop and define standardised testing conditions to assess the cooling performances of emerging PRC materials. Several critical points will be addressed within the scope of this project, including the need to account for different atmospheric conditions, different/extreme geoclimatic regions, and the lack of established figures of merit. By developing validated testing protocols and the expertise to evaluate PRC materials, the metrological community will be able to fulfil the needs of researchers in the scientific community seeking standardised testing and facilities to benchmark the performances of their proposed materials in an objective and reproducible way against well-characterised references. Additional outcomes of the project will address open and fundamental questions concerning this emerging technology. For instance, the role of spectrally selective emissivity in achieving sub-ambient cooling and its interaction with other external factors is still unclear. This is a key point to clarify to understand whether PRC materials can contribute not just to local cooling needs, by dumping heat to the atmosphere, but to terrestrial cooling as well, by effectively discharging heat to outer space. Finally, a relevant scientific and technological outcome of the project will be the identification of the main bottlenecks limiting the performance of PRC materials, which requires a multidisciplinary modelling effort beyond the capabilities of single institutes. The metrological insights obtained during the project will be shared as open access peer-reviewed publications, thus allowing the scientific community to better understand how to accurately evaluate the expected cooling power of proposed PRC materials.

Outcomes for relevant standards

The output of the project will contribute to the improvement of standardisation in the field of energy performance of building standards. The whole set of standards, starting from EN ISO 52000 “Energy performance of buildings - Overarching EPB assessment - Part 1: General framework and procedures” and those dealing with the performances of the building envelope developed under EC Mandate M/480 will be analysed and a list of possible adjustments, amendments, integrations will be proposed to the relevant standardisation bodies to foster the introduction of PRC technologies within the Energy Performance of Buildings Directive (EPBD) framework. Input to Technical Committees engaged in several fields such as energy performance of building, thermal insulation, thermal performance and energy efficiency will also be provided, including CEN/WS 107 on “Mitigation of Urban Heat Island effects with cool materials”, developed by CEN under AFNOR and ECRC leadership, whose CEN Workshop Agreement will be further analysed as pre-normative document aiming at the integration based on the emerging PRC technologies. Efficient dissemination and uptake of the project’s results will be ensured by the direct involvement of several consortium members in the relevant TCs.

Longer-term economic, social and environmental impacts

Due to the energy intensive nature of cooling, which is responsible for 20 % of electricity consumption and 10 % greenhouse gas emissions globally, any technology optimising its efficiency will necessarily have long-term economic, social and environmental impacts. Estimated energy savings in the US range between 20 % and 80 % of the current electricity needs for building cooling, depending on the climates, which is particularly attractive in the EU due to the higher average electricity costs compared to the US.

Regarding social and health aspects, heat-related stress is known to affect human well-being and mortality with an associated risk that escalates rapidly with temperature. Especially in urban environments, increasing the albedo of buildings and roofs with PRC coatings can help curb the heat-island effect. The length, frequency and intensity of heat extremes is constantly increasing, causing tens of thousands of premature deaths in Europe each year, especially in vulnerable population groups. The emergence of space-cooling as a basic need could exacerbate energy poverty, especially for low-income households, while the inherently passive, all-day, electricity-free nature of sub-ambient radiative cooling offers opportunities for off-grid access to cooling power, thermo-electric generation and daytime solar water harvesting and purification.

On the environmental side, in addition to the benefits deriving from reduced freshwater and electricity consumption, this project also aims at tackling less explored but equally relevant aspects related to the introduction of new materials. Especially in the case of PRC coatings, which come in a multitude of heterogeneous architectures, components and constituent materials, it will be important to perform a life-cycle assessment of the different alternatives, as well as to evaluate their sustainability and durability to weathering agents, which is especially relevant due to their inherently outdoor application.

List of publications

n/a

This list is also available here: https://www.euramet.org/repository/research-publications-repository-link/

Project start date and duration:	1 October 2022, 36 Months	
Coordinator: Lorenzo Patelli, INRIM Tel: +39 055 457 2477 E-mail: l.pattelli@inrim.it Project website address: https://parametric.inrim.it/		
Internal Beneficiaries: 1. INRIM, Italy 2. Aalto, Finland 3. CMI, Czechia 4. CSIC, Spain 5. DFM, Denmark 6. LNE, France 7. PTB, Germany 8. RISE, Sweden 9. TUBITAK, Türkiye	External Beneficiaries: 10. CNR, Italy 11. CP, Spain 12. CTI, Italy 13. FIW, Germany 14. NKUA, Greece 15. POLITO, Italy 16. ZAE Bayern, Germany	Unfunded Beneficiaries: 17. ALMECO, Italy

Publishable Summary for 21GRD04 isoMET
Metrology for European emissions verification on methane isotopes

Overview

Atmospheric observations provide a reality check on the true efficacy of climate change mitigation policy. Methane is a potent greenhouse gas (GHG) with multiple complex sources and stable isotope ratios provide a fingerprint needed to verify emissions by source type. This project seeks to improve 1) ambient air monitoring capabilities; 2) the quality of source signature information; and 3) the modelling information necessary to direct the measurement strategy and make top-down emissions estimates.

Need

Methane is a GHG with anthropogenic and natural sources. Its anthropogenic contribution to climate change is only second in importance after carbon dioxide (CO_2) in terms of its radiative forcing and current emission rates. It also contributes to air quality problems through its role in tropospheric ozone formation. Key source categories for anthropogenic CH_4 emissions in Europe estimated with 'bottom-up' methods suggest a breakdown as: Agricultural sector (~50 %), waste (~22 %), and energy (~15 %). These three sectors account for up to 95 % of global anthropogenic CH_4 emissions and are therefore the focus of mitigation action within the EU through the European Green Deal, and the EU Methane Strategy that describes stronger actions to address CH_4 emissions in each sector. Verifying the efficacy of mitigation policy related to each sector's influence on total CH_4 emissions is not yet possible, yet the measurement and modelling technologies exist. Metrology research is the missing link to bring isotope ratio measurements into operational use for top-down emissions estimation by source category. Integrated Carbon Observation System (ICOS) is the foremost GHG monitoring network for tracking Europe's GHG composition, however, currently formal protocols for measurements and calibration of deployed laser spectrometers do not exist, in turn limiting end-users' confidence to operate such instruments and collaborate as a network of sensors (objective 1). The source signature information needed to interpret atmospheric isotope ratio measurements is lacking. Defined measurement methods that are dependent on the source under study and a centralised system to accrue and disseminate the measurements are needed (objective 2). Further, highly promising new 'clumped' isotope measurements could provide additional observables yet metrology research in Europe in this area is yet to begin. For isotope ratio measurements to have impact on policy and for the measurement strategy to be based on evidence, atmospheric transport modelling activities also need to be stepped up. Understanding the gaps and requirements in measurement for emissions estimation requires a collaboration between metrologists and modellers (objective 3).

Objectives

The overall objective of the project is to develop and deliver an infrastructure for the use of CH_4 isotope ratios in improving emission estimate of CH_4 in Europe.

The specific objectives of the project are:

1. To develop a harmonised in situ CH_4 isotope dataset of ambient air in Europe to resolve compatibility issues of datasets when combining measurements of $\delta_{13}C(CH_4)$ and $\delta_2H(CH_4)$. This harmonisation includes a) improved methodologies and procedures for comparability of independent in situ analyses of ambient air CH_4 for $\delta_{13}C(CH_4)$ and $\delta_2H(CH_4)$ by Optical Isotopic Ratio Spectroscopy (OIRS) to the Vienna Pee Dee Belemnite (VPDB) and Vienna Standard Mean Ocean Water (VSMOW) scales, respectively, and b) Isotope Ratio Mass Spectrometry (IRMS) and OIRS methodologies validated through interlaboratory comparisons across participants.

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The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

European Partnership Co-funded by the European Union

2. To develop a sustainable metrological infrastructure for a dataset for $\delta_{13}C(CH_4)$ and $\delta_2H(CH_4)$-emissions source measurements in Europe and to evaluate the potential for source apportionment through clumped isotopes. This will include developing the analytical protocols for measurements of sources, especially those underrepresented in current databases, and the data analysis and uncertainty estimates for input of new and existing source signature data into inverse modelling for emissions estimation.
3. Use atmospheric chemistry transport modelling to inform objectives 1 and 2, creating estimates of the minimum measurement requirements for deployed instruments. The full dataset of measurements across Europe from objectives 1 and 2 will be used in atmospheric transport models and inverse statistical methods, to enable a first demonstration of estimates of emissions from the new datasets.
4. To facilitate – in cooperation with the EMN for Climate and Ocean Observation and the EMPIR JRP 20NET03 POLMO – the take up of the data and measurement infrastructure developed in the project by key stakeholders such as the global monitoring networks WMO GAW and ICOS and the inclusion in the ICOS and MEMENTO databases.

Progress beyond the state of the art and results

Developing a harmonised in situ CH_4 isotope dataset (objective 1)

Following the success of GHG mixing ratio determination using OIRS, the development of precise real time, in situ field measurements is at hand. The calibration procedures, reference materials and analysis protocols, however, are not sufficiently developed to allow efficient harmonisation of measurements to provide a compatible dataset needed for input in atmospheric transport models. For the first time the consortium will develop such a framework and allow isotope ratio measurements to be used as a complete dataset over a significant spatial and temporal range.

Developing metrological infrastructure for a dataset for $\delta_{13}C(CH_4)$ and $\delta_2H(CH_4)$-emissions source measurements (objective 2)

For scientific interpretation of ambient air measurements from objective 1, improvements in source signature information are needed. Several studies have looked at sources across Europe, however, the approaches often entail use of different sampling, measurements and data analysis techniques. Improvements are needed in standardisation of measurements, including full uncertainty analyses, and the methods to curate and disseminate results. Attempts have been made at the global level and this project will look to create a more detailed European domain-based database. As with analysis of $\delta_{13}C(CH_4)$ and $\delta_2H(CH_4)$, OIRS techniques offer another route towards more routine and robust measurements of the rarer isotopologues. This area of research is in its infancy, however, progress in the fundamental metrology behind spectroscopic measurement of these rare ratios will help accelerate advancement and lead to discovery of potentially powerful new observables for source identification.

Using atmospheric transport models to direct monitoring strategy and improvements (objective 3)

Uniquely the project will use state-of-the-art atmospheric chemistry transport modelling techniques to help understand the measurement requirements and plot the course of future expansion. Atmospheric modelling is a prerequisite to translating amount fraction and isotope ratio measurements into policy relevant information. Not all measurements are equal in value for use in a modelling framework. Likewise, the uncertainty requirements on measurements can be relaxed in certain instances (where a measurement site is particularly sensitive to emissions) or required to be improved (e.g. for clean air sites that are needed to constrain the amount of CH_4 already present in the atmosphere before additional regional influences). The consortium will use more than one model to quantify where model uncertainty is an important factor to consider in interpretation – the first such detailed study for CH_4 isotope ratios.

Outcomes and impact

Outcomes for industrial and other user communities

This project will lead to confident uptake of the new methods, from using the calibration and measurement protocols to inform how instruments are developed and calibrated by manufacturers, through to the confident use of atmospheric flux estimates by governments and other communities. In development of the protocols for pushing the limits of precision and accuracy of measurement, the project will define the limitation of current instrumentation, therefore finding the most efficient and practical lines for improvement by manufacturers.

Instrument manufacturers will also benefit from the supply of the next generation of accurate calibration standards for isotopic composition, which will enable their instruments to be traceable and provide valid data for atmospheric monitoring. The IPCC has set out the best practises for use of top-down emissions estimates to verify emissions estimates and their reporting to the United Nations Framework Convention on Climate Change (UNFCCC). For these aims governments need to use data established confidently in networks that are linked internationally. The work of this project will inform the practises of such networks based on metrological principles. Other organisations aiming to help governments and industry will be very interested in both the details of this project's work (they themselves make measurements) through to the longer-term outcomes - improved top-down emissions estimates will help direct their mitigation efforts and monitoring strategies (e.g. Environmental Defence Fund (EDF) and International Methane Emissions Observatory (IMEO)).

Outcomes for the metrology and scientific communities

The Consultative Committee for Amount of Substance: Metrology in Chemistry and Biology (CCQM) strategy document (2021-2030) is aligned to the aims of this project including for 2022-2023 'developing an extended global GHG measurement system' and beyond 2023 'interfacing with and providing technical solutions to global stakeholder communities'. The project will extend the remit of ICOS to measurement of isotope ratios of CH_4 and create the solutions required by the stakeholder community through its focus on using atmospheric transport modelling. The consortium will therefore be able to realise the aims of the CCQM strategy within the timeframe of this project and include the contribution to standards.

Through this effort other scientific groups will have the confidence to operate more instruments, thus bringing more measurements to a combined dataset, ultimately improving the quantity of high quality in situ observations which are critical for scientific research and for eventual routine top-down assessment of CH_4 emissions. There is also a wider isotope ratio measurement community looking to use OIRS techniques for measurement of GHGs and other species. Stable isotope ratios and radioactive isotope ratios across other GHGs (name CO_2 and N_2O) also hold significant value for understanding the carbon and nitrogen cycles and the sources of emissions. Many of the techniques and approaches that will be developed for CH_4 isotopes could be adapted across other measurement systems.

Outcomes for relevant standards

In terms of standardisation, the project activities are broad, ranging from the preparation of gas standards to the methods of emissions estimation. The ISO technical committees targeted will be ISO/TC 158 (Analysis of gases), ISO/TC 146 (Air quality) and ISO/TC 207 (Environmental management). The project participants that have connections via their institute or direct memberships of these committees will ensure that the knowledge developed within the project is fed into the committee meetings. The project will have a strong impact in the CCQM and also stakeholder-led standardisation activities (e.g. the reports from outputs of the WMO/IAEA Meeting on Carbon Dioxide, Other Greenhouse Gases, and Related Measurement Techniques (GGMT) or the ICOS Monitoring Station Assembly (MSA) Atmosphere Meeting).

Longer-term economic, social and environmental impacts

Economic

An increasingly rapid policy response will be vital to enhance responsiveness on the move towards net zero in under 30 years while ensuring any possible negative economic costs are minimised. The EU 2030 Climate Target Plan Impact Assessment suggests an accelerated effort to tackle CH_4 emissions: A requirement of 35 % to 37 % CH_4 emission reductions by 2030 compared to 2005 – a significant step up for effectiveness of policy action. With binding emission targets being set accounting for emission changes is now inherently linked with decision making by local, regional, and country level governments regarding the wider economy. Issues of trade-offs e.g. in policies that might limit CH_4 emissions but increase CO_2 emissions and perverse incentives (for example in the biogas industry) are further detailed economy-related reasons to improve the transparency behind emissions reported, including top-down verification. The EU aims to spend 30% of its overall budget for 2021-2027 on tackling climate change and its effects (www.consilium.europa.eu/en/infographics/recovery-plan-mff-2021-2027/). Targeting the right mitigation measures for investment will enhance the effectiveness from this budget and prevent unnecessary spending on mitigation measures that are ineffective. If emissions can be broken down by sector/industry it will lead to greater engagement with the relevant industries responsible for those emissions, making way for direct economic impact through improvements in GHG mitigation efficiency at the industry level. Air pollution can also considerably benefit from mitigation of CH_4

emissions (being a major cause of ground-level ozone pollution), affecting health, including both mortality and morbidity, and agricultural productivity. This has knock-on effects for the economy and the welfare costs from premature deaths and pain and suffering are quantitatively assessed.

Environmental

Methane makes up a significant part of the anthropogenic radiative forcing that is driving the global rise in temperature (now around ~1 °C above preindustrial). The IPCC have reported that limiting a temperature rise this century to 1.5 °C could avoid the most harmful effects of climate change, which include huge changes to the environment and loss of biodiversity in terrestrial ecosystems (Masson-Delmotte et al., 2018); above this threshold the chances of loss of unique and already threatened ecosystems become very likely. Other areas of the planet are already under significant strain from rising temperatures due to the rising total of global anthropogenic GHG emissions. Methane is an especially strong greenhouse gas with the effective radiative forcing in 2019 from 1750 at 0.54 W m_{-2}, second only to CO_2 at 2.16 W m_{-2} (IPCC, 2021). The global warming potential for every mass unit of emissions of CH_4 is 27-30 times greater relative to CO_2, making significant emission reduction of CH_4 vital for reaching climate targets. Europe therefore has a role to play in limiting these global environmental problems by leading the way in climate mitigation action. Objective measurement and understanding of these issues can help to make the right balance of decisions to protect the environment.

Social

Methane emissions mitigation policy will impact how we grow food through to how we heat our homes. Outcomes from projects like this to understand the primary sources of methane emissions will ultimately accelerate changes that need to be made in one sector over another. Climate change mitigation policy is also an opportunity to address societal equity, ensuring that emissions mitigation measures do not burden the most vulnerable through unfair policies. Direct GHG emissions mitigation measures will complement other developments for policies aimed at the agriculture sector and rural areas, in particular an expected societal shift to more balanced diets, with less red and processed meat, more fruits, vegetables and plant-based protein sources, in line with the EU Farm to Fork Strategy.

Future uses

Developing the protocols and methods for this new measurement network will allow CH_4 isotope ratios to be an integral part of established country-scale operational emissions verification systems that are now considered 'best practice' for reporting to the UNFCCC. The project provides a scientific platform to expansion of isotope ratio networks to higher resolution spatial coverage or different areas of the planet.

List of publications

n/a

This list is also available here: https://www.euramet.org/repository/research-publications-repository-link/

Project start date and duration:	1 October 2022, 36 months	
Coordinator: Volker Ebert, PTB Project website address: -	Tel: +49 (0)531-592-3401	E-mail: volker.ebert@ptb.de
Internal Beneficiaries: 1. PTB, Germany 2. TUBITAK, Türkiye 3. VTT, Finland	External Beneficiaries: 4. StockholmU, Sweden 5. UHEI, Germany 6. UU, Netherlands 7. UVSQ, France	Unfunded Beneficiaries:
Associated Partners: 8. Empa, Switzerland 9. NPL, United Kingdom 10. RHUL, United Kingdom 11. UoB, United Kingdom 12. UofG, United Kingdom		

Publishable Summary for 21GRD05 Met4H2
Metrology for the hydrogen supply chain

Overview

The urgent need to mitigate climate change and to limit greenhouse gas emissions is driving actions to reduce the use of fossil fuels. However, meeting current and future energy needs necessitates the increased use of alternative energy sources such as, hydrogen from renewable sources. To achieve this goal, the metrological infrastructure for hydrogen needs to address all parts of the supply chains. This project will provide novel and improved standards for the safe application of hydrogen flow measurement, hydrogen quality assessment and custody transfer. Together with outcomes from previous projects, an infrastructure will be established that provides measurement data that are fit for demonstrating compliance with regulations and contracts. This infrastructure will facilitate ramping up the use of hydrogen and society to adapt to using hydrogen instead of fossil fuels.

Need

The report from the Intergovernmental Panel for Climate Change of 2021 underlined once more the urgent need to reduce greenhouse gas emissions to mitigate climate change. The European Commission developed the European Green Deal to decarbonise energy use, shifting from fossil fuels to renewable fuels. One of the pillars is a phased approach to the introduction of hydrogen to replace fossil fuels in electrical power generation, transport, industry and the built environment. In addition, recent geopolitical developments on the edges of Europe have further highlighted the need for diverse, reliable and resilient, non-fossil fuel-based energy supplies in Europe. To apply hydrogen safely within the existing gas grid network and other infrastructure, traceable measurements for leak testing, material compatibility, sensors for monitoring processes and odorization are required to demonstrate compliance with legislation. Traceable flow measurement and hydrogen quality assessment are necessary for custody transfer and fair trade. Demonstrating compliance with hydrogen quality specifications, such as ISO 14687, and legal metrology requirements, such as International Organization of Legal Metrology (OIML) R140 and OIML R137, for metrological type approval and for assessing the performance of measuring systems, is therefore essential. Hydrogen sampling methods for applications below 20 MPa, such as gas grids, need to be developed and validated, to ensure metrological traceability and reliability of data obtained using those methods.

Metrological traceability and accuracy already developed need to be deployed to onsite measurement systems, so that robust and comparable results are obtained that support their use beyond monitoring processes. Finally, there is a need to improve and expand documentary standards for totalisation of quantity and energy used for custody transfer, such as OIML R140, ISO 15112 and EN 1776, to make them fit for purpose for use with hydrogen-enriched natural gas and hydrogen and to cover the totalisation of impurity content.

Objectives

The overall objective of the project is to further develop and integrate the metrology necessary to support the entire supply chain of hydrogen, from production to storage and end use. The project will disseminate metrological traceability to the field, so that measurement results become fit-for-purpose with respect to health, safety, environmental, and fiscal purposes.

The specific objectives of the project are:

1. To develop calibration and measurement methods to support reliable, traceable, and accurate measurements of hydrogen in production processes and end-user applications, in view of safety, process efficiency and environmental issues, such as for purity, leak detection, odorization, and

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METROLOGY PARTNERSHIP EURAMET

materials performance, ensuring that online measurement instruments and sensors are operating within their specifications (e.g., to ISO 14687, OIML R139, and OIML R140).

2. To develop measurement standards to enable calibration and validation of flow metering equipment under actual conditions (pressure, temperature), used to accurately quantify flow rates of hydrogen (including blended hydrogen) through the hydrogen supply chain, and to facilitate compliance with respect to, e.g., OIML R137, OIML R140, and the Measurement Instruments Directive.
3. To develop and improve measurement standards and methods to enable traceable validation and performance evaluation of gas quality measurement methods for hydrogen, to thus improve on the current lack of equivalence for impurities, e.g., oxygen, hydrogen sulphide, moisture content, and for reactive components such as hydrogen chloride and chlorine. To develop and improve analysers for critical impurities for online monitoring of changes in gas quality, through the supply chain and processing equipment, to ensure the gas quality meets the required specifications (ISO 14687).
4. To develop novel methods for the evaluation of measurement uncertainty along the supply chain as a whole, namely with regard to the measurement of total quantity, and energy and impurity content of hydrogen and hydrogen blends.
5. To facilitate, in cooperation with the European Metrology Network Energy Gases, the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain (accredited laboratories, instrumentation manufacturers for hydrogen), standards developing organisations (ISO, OIML) and end users (e.g., industry, consumers, power generation and transport).

Progress beyond the state of the art and results

The project will deliver novel standards and methods for leak flow measurement, material compatibility testing, and odorization of hydrogen-enriched natural gas (HENG) and hydrogen. These standards and methods build on previous projects, such as 20IND10 Decarb regarding leaks, and ENG01 GAS and ENG54 Biogas regarding odorization standards, which focused on other energy gases. To support calibration, validation and verification of sensors, rigs and methods will be developed, so that sensors can generate traceable results with a defined uncertainty. This work builds on the work in, e.g., 16ENG01 MetroHyVe and 19ENG04 MetroHyVe 2.

This project will collate and analyse the results from previous projects regarding flow metering (e.g., 16ENG01 MetroHyVe, 18NRM06 NEWGASMET, 19ENG03 MefHySto, 19ENG04 MetroHyVe 2, 20IND10 Decarb, 20IND11 MetHyInfra, and 20IND13 SAFEST) to combine these and improve their accessibility and therefore their uptake. Primary standards for flow metering developed in, e.g., 18NRM06 NEWGASMET will be improved and assessed for equivalence in support of calibration and measurement capabilities (CMCs) of European NMIs. For small-scale gas meters, novel calibration facilities will be developed for use with HENG and hydrogen. With these facilities, open access data will be generated showing how an impurity content of 2 % affects meter performance. Finally, for gas meters for flow rates above 0.2 kg/min, metrological traceability chains will be designed and matched with ongoing developments of calibration facilities to understand better the need for calibrations for these gas meters.

The framework for hydrogen quality assessment developed in, e.g., 16ENG01 MetroHyVe and 19ENG04 MetroHyVe 2 will be expanded to cover chlorine, one of the impurities listed in ISO 14687 for which accurate measurement standards and methods are lacking. Furthermore, sampling methods will be developed and validated for applications below 20 MPa, e.g., for electrolysers and gas grids, supplementing those from 16ENG01 MetroHyVe and 19ENG04 MetroHyVe 2 for hydrogen refuelling stations. The capabilities for analysing trace levels of sulphur will be improved and expanded, focussing on equivalence between facilities in measuring the total sulphur amount fraction around the specification of 4 nmol/mol. Improved spectroscopic methods will be developed for ammonia in hydrogen. Stability studies for moisture and hydrogen chloride in static standards will be performed to generate data for the provision of gas standards with defined stability. Measurement standards for water dew/frost point will be developed or adapted to work with HENG and hydrogen up to 6 MPa, a pressure relevant for transmission grids. Developments in, e.g., ENG01 GAS, ENG54 Biogas and 20IND06 PROMETH2O will be taken up to achieve this outcome. Finally, the metrological traceability chains to onsite measurements will be demonstrated and validated.

The models for calculating the total quantity and energy from, e.g., OIML R140 and EN 1776 will be improved to address correlations in the results used to calculate these totals, dynamic effects in gas grids due to varying flow rate and gas composition in order to avoid underrating the measurement uncertainty. A model for the calibration for the totalisation of impurity content (purity exposure) will be developed to facilitate calculation of this parameter, which is critical for appliances that are sensitive to the presence of a particular impurity.

Outcomes and impact

Outcomes for industrial and other user communities
This project will support the industry involved in the hydrogen supply chain from hydrogen production to transport and end use.

Novel measurement standards for hydrogen leak rate measurement will enable industry to have reliable devices to monitor the integrity of gas grids, thereby ensuring safety when feeding hydrogen into these grids. The methods and standards for material compatibility assessment will enable universities, research institutes and industry to assess materials for their suitability to be used with hydrogen, ensuring that potential hazardous situations are recognised at an early stage. The odorization standards will enable gas grid operators, for example, to confirm that the odorant level in HENG and hydrogen meets the specifications, thereby ensuring the safe distribution of these gases to the built environment. They also enable research institutes and other bodies to assess the olfactometric properties of these odorants with hydrogen-containing energy gases.

The rigs developed for the calibration and evaluation of sensors for hydrogen quality will enable users and producers of these sensors to have them assessed, so that these sensors have a known performance, and the results obtained are metrologically traceable. This traceability in turn enables users of the sensors to apply them beyond the monitoring of processes, thereby avoiding the need to measure again for, e.g., assessment of compliance with specifications.

The validated primary standards for flow metering of hydrogen-containing energy gases will enable custody transfer for these gases, in combination with the methods for sampling and hydrogen quality assessment, and the improved methods for totalisation and the associated measurement uncertainty evaluation.

The hydrogen quality measurements performed at two industrial sites, electrolyser plant and gas pipeline, will demonstrate to the industry how metrological traceability and accuracy can be delivered in real-life situations. These demonstrations and the good practice guidelines derived from them, will create a close link with the hydrogen production and transport sector as well as with the measurement system manufacturers and therefore, ensure a swift take up of project outcome.

Outcomes for the metrology and scientific communities
In order to facilitate the take up of hydrogen in Europe and worldwide, a well-established measurement infrastructure is a must. This project focuses on developing, optimising and comparing traceable measurement standards and methods, so that this infrastructure is created.

The novel flow measurement standards will enable NMIs, DIs and calibration laboratories to provide measurement services for the hydrogen supply chain and industry to have their instruments calibrated. These in turn enable research into the development of gas meters for HENG and hydrogen. The sampling methods, standards and methods for hydrogen quality assessment will enable services to be provided by the gas industry in the form of secondary and working gas standards and measurements and will provide research groups with the necessary tools to ensure their measurement results are metrologically traceable, so that conclusions from their work can directly be taken up by others.

The improved methods for hydrogen quality assessment will enable metrological traceability to be disseminated to laboratories, which in turn can seek accreditation based on ISO/IEC 17025 for their services related to ISO 14687, including sampling. Research groups will benefit from these capabilities in that they can assess improvements in processes along the supply chain with the necessary standards for calibration of their equipment.

Legal metrology organisations and their national bodies benefit from the work related to especially OIML R137 and OIML R140, as well as the calibration and measurement services enabling assessment of the performance of measurement equipment supporting conformity assessment and type approval.

Outcomes for relevant standards
The project will provide enhanced guidance for calculating the total quantity, energy and impurity exposure of supplied or received gas and good practices in taking into account the dynamics of the gas grid and gas properties in the uncertainty evaluation to OIML R140 and ISO 15112. The work on flow measurements will provide evidence as to whether OIML R140 can also be applied to metering and custody transfer of hydrogen and HENG. Material compatibility testing is covered in standards such as ISO 15105 and ISO 2782; this project

contributes approaches for increasing the sensitivity of the measurement and set-up adjustments allowing for extension of the parameter range in terms of the boundary conditions. The results in WP3 will demonstrate that the scope of ISO 21087 can extended to supply chains other than just PEM fuel cells. The materials compatibility overview for calibration gas mixtures in ISO 16664 can be updated based on the stability study data for static gas standards with, e.g., hydrogen chloride and moisture.

Longer-term economic, social and environmental impacts

As natural gas is the primary fuel source for heating in Europe, the market is approximately 550 billion cubic metres per year. The introduction of hydrogen in this part of the gas supply relieves the pressure on the electrical grids. This project will provide the tools to adapt the measurement infrastructure to distributing HENG in the first instance, and hydrogen at a later stage. Using HENG comes with relatively small changes for end users, and thus is a very economical measure to decarbonise the gas supply in the short term. It is also far less disruptive than requesting end-users to switch from gas to electricity for these purposes.

The outcomes support the safe application of hydrogen in gas transmission and distribution systems, as well as charging end-users and industry for their gas use in accordance with current requirements. Thereby it facilitates the transition from fossil fuels to net-zero carbon dioxide emission renewable fuels. Feeding in hydrogen enables end-users and industry to gradually adapt to this future, with as little disruption as necessary. In the coming years, feeding in green hydrogen in the natural gas grids leads to a reduction of carbon dioxide emissions, thereby contributing to meeting intermittent goals of the European

List of publications

n/a

This list is also available here: https://www.euramet.org/repository/research-publications-repository-link/

<table>
<tr><td colspan="2">Project start date and duration:</td><td>01 October 2022, 36 months</td></tr>
<tr><td colspan="3">Coordinator: Adriaan van der Veen, VSL Tel: +31 6 12021712 E-mail: avdveen@vsl.nl
Project website address: under construction</td></tr>
<tr><td>Internal Beneficiaries:
1. VSL, Netherlands
2. BAM, Germany
3. BEV-PTP, Austria
4. CEM, Spain
5. Cesame, France
6. CMI, Czechia
7. CNAM, France
8. DFM, Denmark
9. FORCE, Denmark
10. INRIM, Italy
11. JV, Norway
12. LNE, France
13. PTB, Germany
14. RISE, Sweden
15. VTT, Finland</td><td>External Beneficiaries:
16. DTU, Denmark
17. ENVIPARK, Italy
18. GERG, Belgium
19. Nippon Gases, Italy
20. NORCE, Norway
21. POLITO, Italy
22. UL, Slovenia
23. ZAE Bayern, Germany</td><td>Unfunded Beneficiaries:
24. SICK, Germany</td></tr>
<tr><td colspan="3">Associated Partners:
25. METAS, Switzerland,
26. NEL, United Kingdom,
27. NPL, United Kingdom</td></tr>
</table>

Publishable Summary for 21GRD06 MetCCUS
Metrology Support for Carbon Capture Utilisation and Storage

Overview

Europe must make reductions in CO_2 emissions in order to meet stringent reduction targets related to global warming. Carbon capture utilisation and storage (CCUS) can be used to remove the CO_2 produced by industrial processes for storage either underground or locked in an alternative material. It is versatile, in the sense that the CO_2 removal step can complement any process e.g. production of power, fuels, chemicals and heating. In order to facilitate efficient and safe usage of this technology across Europe and to support the CCUS industry, this project will address key measurement challenges related to flow metering, emissions monitoring, chemical metrology and the physical properties of CO_2.

Need

The European Union set a target to reduce greenhouse gas emissions by 55 % by 2030 and to become carbon neutral by 2050. To support meeting these ambitious targets the Green Deal was introduced which specifically states that “priority areas include clean hydrogen, fuel cells and other alternative fuels, energy storage, and carbon capture, storage and utilisation”. As of the end of 2020, several European countries including Czechia, Finland, France, Germany, Portugal, the Netherlands, Denmark and the UK had included CCUS as part of their national strategies. The European Commission has acknowledged the role that CCUS plays in meeting this target, but have also stated that “the environmental integrity of CCUS is their overriding concern”. Monitoring of carbon dioxide through flow metering within the delivery system and through leak monitoring outside the system is key to quantifying real amounts of carbon dioxide captured (Objective 1). Directive 2009/31/EC on the geological storage of carbon dioxide stated a requirement of a regulatory framework for monitoring CO_2 leakage which was established through the Emissions Trading System (Objective 2). Additionally, as highlighted by the European Metrology Network for Energy Gases in their annual Strategic Research Agenda and in an energy transition report on CCUS measurement challenges authored by NPL with contributions from NEL, new requirements for measurement solutions were identified for CO_2 quality assurance, physical properties and material testing, such as pipeline corrosion and capture solvent degradation (Objectives 3 and 4). The reports were written following direct consultation with over 300 stakeholders from European industry including the key players within the CCUS field. This will be the first metrology for CCUS project that will solve the key metrology challenges for CCUS identified by industry and it will provide the Primary Standards, methods, good practice guides and literature reviews that they require to successfully grow a CCUS industry in Europe.

Objectives

The overall aim of the project is to develop new metrology tools in the form of Primary Standards and methods, as well as the relevant best practice/guidance, necessary to support industry in carbon capture utilisation and storage. The specific objectives of the project are:

1. To develop a metrology infrastructure for monitoring the CO_2 gas-flow and CO_2 liquid-flow as required by the CCUS industry with target uncertainties of 1.5 % – 2.5 %, including development of primary facilities and transfer standards, by investigating existing flow facilities for the possible use with CO_2 and development and intercomparison of new facilities for both intermediate scale (typically below 50 m^3/h and low pressure) and large scale flow (Q_{max} = up to 400 m^3/h and higher pressure).

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EURAMET. Neither the European Union nor the granting authority can be held responsible for them.

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

European Partnership Co-funded by the European Union

2. To develop the metrological support to enable the measurement and reporting of emissions to air from different stages of the CCUS process; including novel methods to determine emissions to the atmosphere through carbon capture processes, infrastructure (leaks), or geological storage.
3. To develop new standards and measurement methods to support European industries with performing the gas composition measurements required for carbon dioxide within CCUS; including primary reference materials with low-level impurities in CO_2, sampling methods to determine the material compatibility of key impurities in CO_2, online gas analysers for monitoring impurities in CO_2 as well as to determine CO_2 quality.
4. To establish the metrological infrastructure to support the design, monitoring and maintenance of industrial infrastructures dedicated to carbon capture, transportation, utilisation, and storage; including development of a coherent empirical model for understanding the thermophysical properties of CO_2, and sensors and procedures to preserve the efficiency of the transportation and utilisation of CO_2.
5. To facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain (accredited laboratories, instrument manufacturers), standards developing organisations (ISO TC 265) and end users (CCUS industry).

Progress beyond the state of the art and results

The progress beyond the state of the art for the objectives and the planned results from this project are:

Metrology infrastructure for monitoring the CO_2 gas-flow and CO_2 liquid-flow (objective 1)

No independent, traceable, flow calibration facilities are available for calibrating flow meters with carbon dioxide across the full range of conditions which are likely to occur in capture, transport and storage. Carbon Capture and Storage (CCS) streams may be in gas, liquid, dense phase, or possibly supercritical state at metering locations. Investigation is required into the risk of operating near phase boundaries where phase change and two-phase flow could affect accuracy and the effects of impurities could shift the phase boundaries. New traceable flow calibration facilities and primary standards will be developed in this project to evaluate the performance of various flow meter types when used with gaseous and liquified carbon dioxide including an assessment of the lowest uncertainties. The project will also provide guidance on calibrating these meters with alternative fluids that are common in laboratories.

Metrological support for measuring and reporting of CO_2 emissions to air (objective 2)

Methods for accurately measuring emissions from post-capture flue gas (including amines present in capture solvents) have not been developed and validated. The project will develop a facility capable of simulating emissions from post-capture flue gas and new methods to monitor emissions (Proton Transfer Reaction Mass Spectrometry (PTR-MS), Cavity Ringdown Spectrometer (CRDS), Fourier-Transform Infrared (FTIR)).

Potential techniques for monitoring and quantifying carbon dioxide leaks from pipelines and storage sites (including sub-sea) are available (e.g. acoustic imaging, sonar bathymetry and tuneable diode lasers) but these techniques have not been validated as possible methods for quantifying leaks for sites. To ensure the performance of these instruments meets industry requirements, testing must include accuracy, selectivity (against air and other leaks), spatial resolution and repeatability. The project will develop capability to simulate precise CO_2 leaks from pipelines to test and validate commercial new leak monitors. Further, methods will be developed to monitor large scale CO_2 leaks from on-shore and sub-sea storage sites using state of the art gas detection techniques such as LIDAR and other spectroscopic methods.

Chemical metrology (objective 3)

For accurate composition measurements, offline analysis will be needed. Some reference mixtures have been prepared previously by research organisations (such as SINTEF); however these have been mainly high amount fraction inert gases in carbon dioxide to support fluid property measurements. The project will identify the key impurities in CO_2 that need to be measured by industry, and it will develop the analytical methods, Primary Reference Materials and good practice for sampling.

The solvents used in capture materials degrade over time; there is a need for a measurement method that can monitor solvent degradation and for the validation of the analytical techniques that can monitor for the release of additional impurities due to the breakdown. The project will develop a testing rig capable of subjecting capture solvents to high temperatures under controlled CO_2 atmospheres (containing varying levels of impurities). This facility will allow CO_2 capture cycling to monitor degradation and the presence of impurities from the material.

Understanding the physical properties of CO_2 to support CCUS industrial infrastructure (objective 4)

Knowledge of the thermophysical properties of carbon dioxide mixtures with a range of potential impurities, and within the operational conditions of CCS processes, presents some gaps between the experimental data and the requirements of the system design and operation. Even complex equations of state (Lee-Kesler, SAFT and GERG) do not provide accurate results for the pressure, volume and temperature (PVT) properties and the vapour-liquid equilibrium (VLE) for carbon dioxide mixtures. The development of a specific reference equation of state and mixing rules for CCS is essential and underway (e.g. Equations of State for Combustion Gases (EOS-CG)), for which the density, speed of sound and VLE data of the selected mixtures is needed. Although EMPIR JRP 20IND10 Decarb included a literature review of this data, no laboratory work was performed. One work package in this project will be dedicated to physical property measurements, which includes experimental work to provide traceability for a physical property (density, viscosity, heat capacities and speed of sound) at a specific gas composition (made traceable through the preparation of binary mixtures). Furthermore, activities will be focused on developing new equations of state models and uncertainty budgets.

Outcomes and impact

Outcomes for industrial and other user communities

Using the CO_2 primary standards, the leak monitoring methods and the reports/guides developed in this project, CCS operators will be able to perform flow metering and leak monitoring of CO_2 to accurately quantify amount of CO_2 capture, transported, stored and lost in their process. This is required to operate the facilities safely, but also to quantify CO_2 capture and losses when reporting.

Using the Primary Reference Materials, new gas analysis methods, a materials testing facility, physical property methods and other guidance developed in this project, CCS operators and CO_2 suppliers will be able to determine suitable conditions and materials (e.g. pipelines). In addition, they will be able to monitor these conditions through purity and physical property measurements to ensure safe and efficient operation.

Knowledge will be transferred from the project to users by sharing all reports and good practice guides on the project website as well as to stakeholders by sharing these documents and any other developments (methods and standards) through a LinkedIn profile page.

Outcomes for the metrology and scientific communities

NMIs and DIs will develop Primary Standards for flow metering, gas analysis, physical property measurement and leak detections specifically which can be used to develop new Calibration and Measurement Capability (CMCs) to support national traceability for these measurements in CCUS. Furthermore, these new capabilities can be utilised by other measurement or calibration laboratories to provide their own calibration services for the CCUS community.

Laboratories, research organisations and academia will be able to use the new capabilities developed by NMIs, DIs and the other research participants in this project in order to perform high quality research within the CCUS area. The measurements will be traceable to the SI and suitably accurate so that the results obtained will support the development of new CCUS technologies.

The project will perform fundamental scientific work in the development and uncertainty evaluation of equations of state for CCS conditions.

Outcomes for relevant standards

The consortium will promote the results of the project within the standardisation community and will provide input into the standardisation process (ISO, CEN). For ISO, the standards relevant to the project that are in preparation/revision are identified, and the work on these standards will be suggested to the appropriate working groups or committees. There are plans to establish a new European working group dedicated to CCUS within CEN over the next few years, and the work from this project will greatly support the development of new standards within this working group.

The deliverables of this project are expected to directly support development or revision of standards within ISO/TC 265. The following ISO standards and New Work Item Proposals from ISO/TC 265 include measurements that will be studied in this project, and can be improved through this project, during the next revision: ISO 27913:2016 - Carbon dioxide capture, transportation and geological storage - Pipeline transportation systems, ISO 27914:2017 - Carbon dioxide capture, transportation and geological storage - Geological storage, ISO/TR 27915:2017 - Carbon dioxide capture, transportation and geological storage - Quantification and verification, ISO/TR 27921:2020 - Carbon dioxide capture, transportation, and geological storage - Cross Cutting Issues - CO_2 stream composition, ISO/TR 27922:2021 - Carbon dioxide capture - Overview of carbon dioxide capture technologies in the cement industry, and NWIP (approved June 2021) - Performance Index and Standard Test Method of Absorbent Performance for CO_2 Capture.

Longer-term economic, social and environmental impacts

<u>Economic impact</u>

The work of this project will support the flow metering, emissions monitoring, purity analysis and physical property measurements performed directly by CCUS operators.

Flow metering of carbon dioxide is required for monitoring emissions for CCS processes according to the EU Emissions Trading System (ETS). Inaccuracies could lead to errors in the calculations, which could either lead to overcharging of carbon emission costs or fines for providing inaccurate information.

The work of this project will support the monitoring of leaks in pipelines. The early identification of leaks will reduce the risk of extensive damage/loss of CO_2.

Impurities in carbon dioxide if not monitored can provide problems to the CCUS operator through unintended toxic releases, and corrosion or damage to pipelines, equipment and storage sites. These incidents can be costly. Firstly, they will require the operator to stop operation, but there would also be considerable costs for maintenance, repair and equipment replacement.

The work of this project will support CCUS operators, particularly for reducing operational costs. Impure carbon dioxide in CCS processes (e.g. inert gases at volume percent level) can increase energy requirements (for compression) which would inherently increase the cost of operation.

An inaccurate equations of state model (or the lack of one) may lead to issues with meeting CCUS operator conditions by not being able to monitor real physical properties. This could lead to dangerous scenarios for operation such as over-pressurisation or even cases where pure hydrogen could bubble out from the CO_2 and come into contact with pipelines.

<u>Social impact</u>

Developing new capability to monitor for carbon dioxide leaks is imperative for ensuring health and safety in the gas industry and it will protect citizens.

A focus will be made to educate new players (e.g. laboratories and instrument manufacturers) entering the CCUS market on the importance of laboratory accreditation and showing competency through comparisons, either for purity analysis or for the performance of online analysers. This will be a principle aim of the project.

Several technical seminars will be hosted by the participants to disseminate the newly developed standards and methodologies to allow fast uptake by commercial laboratories and organisations.

Several countries across Europe are running their own independent projects implementing CCUS technologies; however, this project will be the first time relevant industrial stakeholders from across Europe will join together in a collaborative effort to progress this topic.

The project, through hosting a website, organising seminars, presenting at conferences and running a Stakeholder Advisory Board will inherently support better networking between gas distribution networks, and the relevant laboratories and instrument manufacturers.

<u>Environmental impact</u>

CCS contributes to reductions of carbon dioxide emissions which support countries to meet targets set by the Climate Change Act. The activities within this project will not only support CCS for decarbonising gas, but all CCS processes including those used in tandem with power production and the direct extraction of carbon dioxide from the air. Many of the measurement requirements specified in this project originate from mandatory legislation, such as the EU ETS or national legislation (that may reference International Standards). Where legislation has not yet been developed, this project will support its development by ensuring the relevant measurement capability is already available.

The direct environmental impact from the metrological infrastructure, methods and guides generated from this project is as follows:

- The entire project is focused on supporting the success of European companies in implementing CCUS technologies; doing so will support the significant decrease in CO_2 emissions from industrial and energy processes or by direct air capture.

- Companies will have the ability to accurately measure carbon dioxide in CCS processes to track their carbon dioxide emissions in accordance with the EU ETS.

List of publications
n/a

This list is also available here: https://www.euramet.org/repository/research-publications-repository-link/

Project start date and duration:	1 October 2022, 36 months	
Coordinator: Iris de Krom, VSL Project website address: tbc	Tel: +31152691754	E-mail: idekrom@vsl.nl
Internal Beneficiaries: 1. VSL, Netherlands 2. CMI, Czechia 3. DFM, Denmark 4. FORCE, Denmark 5. INRIM, Italy 6. IPQ, Portugal 7. JV, Norway 8. PTB, Germany 9. RISE, Sweden 10. VTT, Finland	External Beneficiaries: 11. Air Liquide FuE, Germany 12. DNV, Netherlands 13. DTU, Denmark 14. GERG, Belgium 15. NOVA, Portugal 16. RUB, Germany 17. SINTEF ER, Norway 18. UNITO, Italy 19. UVa, Spain	Unfunded Beneficiaries:
Associated Partners: 20. NEL, United Kingdom 21. NPL, United Kingdom		

Publishable Summary for 21GRD07 PlasticTrace Metrological traceability of measurement data from nano- to small-microplastics for a greener environment and food safety

Overview

PlasticTrace aims to address the urgent need for development and harmonisation of methods for the chemical identification, physical characterisation and quantification of released small micro/nanoplastics (SMPs/NPs) in drinking water, food and environmental matrices, as required by the EU's Circular Economy Action Plan (CEAP). In this context, hyphenated and complementary analytical approaches will be developed, optimised, compared and harmonised, leading to the establishment of metrological traceability of measurements through robust validation studies. Novel and environmentally relevant SMP/NP reference materials will be developed within the project. International cooperation with key stakeholders globally will be considered as the basis for a European Metrology network.

Need

Plastic pollution is recognised as a severe anthropogenic issue globally, where complex physico-chemical transformation processes (such as aging, degradation and fragmentation) producing MPs and, subsequently, NPs. These processes occur during production, consumer use, waste processing, as well as through environmental process after vehicles/industrial emissions. Several studies have reported the occurrence, analytical methods and toxicity of larger MPs in the environment and food matrices. However, MPs (< 100 µm SMPs) and NPs (< 0.1 µm) in natural systems have been overlooked, primarily due to significant methodological challenges associated with their micro- and nano-specific properties.

In this respect, the European Commission (EC) commissioned a study focused on the potential ecotoxicological impacts of smaller plastic particles (SMPs/NPs), encouraging research aimed at a more accurate characterisation of both materials and exposure conditions. The need for efficient and reliable measurement infrastructure is required in support of (i) European Chemicals Agency (ECHA)'s proposed restriction targeting intentionally added MPs in consumer products, (ii) the Marine Strategy Framework Directive (MSFD) which requires specific thresholds for litter types after harmonisation of the methodology, (iii) the new Drinking Water Directive (DWD) that mentions MPs explicitly, and (iv) the new Circular Economy Action Plan (CEAP) adopted in March 2020. In particular, the CEAP promotes circular economy processes, encourages sustainable consumption, and aims to ensure that waste is prevented. However, to support the CEAP and reduce plastic contamination, methods for SMP/NP identification in food and environmental matrices are needed. These methods need to be metrologically validated using appropriate reference materials, so that Europe can establish harmonised and traceable measurements of SMPs and NPs.

End users of the procedures to be developed include public organisations / non-governmental organisations (NGOs) dealing with environmental and food monitoring, regulatory bodies responsible for the control of environmental pollution and food safety, as well as industries potentially responsible (directly or indirectly) for MP emissions and disposal into the environment or the human food chain.

Objectives

The overall aim of this project is to develop international metrological capacity that enables the traceable measurement and characterisation of SMPs and NPs in environmental and food samples and the production of suitable reference materials, according to the metrological requirements.

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EURAMET. Neither the European Union nor the granting authority can be held responsible for them.

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

The specific objectives are:

1. **To develop pristine SI-traceable reference materials for SMPs (0.1 µm - 100 µm) and NPs (< 0.1 µm),** representative of partially degraded/naturally aged samples in complex food and environmental matrices. Realistic polydisperse size distributions and irregular shapes will be investigated.
2. **To develop accurate and efficient sample preparation methods for the measurement of SMPs and NPs in complex food and environmental matrices** (drinking and surface water, sewage sludge and milk). Such methods will include (i) enrichment prior to analysis, (ii) selective removal of natural background organic/inorganic matter, (iii) size fractionation/isolation, and (iv) homogenisation and partition steps. The sample preparation methods will be optimised to demonstrate a negligible effect on the particle characteristics and polymer compositions of samples
3. **To develop accurate and robust methods** for the (i) characterisation of chemical identity of the SMPs/NPs polymer type; (ii) physical particle characterisation and quantification, size distribution and particle morphologies; and (iii) quantification of the mass fraction in complex matrices.
4. **To demonstrate the validity and applicability of the methods and reference materials developed in Objectives 1-3 via an inter-laboratory comparison**. As part of the comparison, best practice guidance on the traceable measurement and characterisation of SMPs and NPs in food and environmental matrices will be developed.
5. **To facilitate the take up of the technology and measurement infrastructure** developed in in the project by the measurement supply chain, appropriate EURAMET's European Metrology Networks, relevant associations outside of Europe (e.g. National Nanotechnology Initiative USA), standards developing organisations (e.g. ISO TC 229, ISO TC 61, CEN TC 249 and those associated with the Urban Waste Water Treatment Directive (91/271/EU), the Marine Strategy Framework Directive (2008/56/EC) and the Drinking Water Directive (EU) 2020/2184) and end users (e.g. food and drink producers, environmental monitoring programmes and health experts).

Progress beyond the state of the art and results

Development of SI-traceable reference materials for SMPs (0.1 µm - 100 µm) and NPs (< 0.1 µm)

SMP/NP reference materials representative of partially degraded/naturally aged samples are currently not available and will be developed and provided by PlasticTrace. Candidate SMP/NP RMs representative of real plastic particles found in food and the environment will be developed in accordance with their relevant types, shapes, sizes and ageing status. Particle sizes are produced according to the possibilities of production and the toxicological relevance with two primary categories: (i) 100 - 10 µm and (ii) < 10 µm. To increase environmental relevance, some of the RMs will be aged. All prepared SMP/NP RMs will be tested for homogeneity and stability control (at least 3-month) according to ISO GUIDE 35:2017(E).

Development of accurate and efficient sample preparation methods for the measurement of SMPs and NPs in complex food and environmental matrices

The identification and the analysis of SMPs/NPs in complex media is very challenging due to the inability to readily distinguish SMPs/NPs from other types of particles in the same size range (dissolved and particulate organic matter) and due to the need for pre-concentrating samples to meet the detection limits for their identification. The existing procedures for sample preparation are often critical in terms of the stability of very small and aged particles, as well as very time consuming. PlasticTrace will cover the application and harmonise these procedures, including the application of state of the art digestion protocols for complex organic media, the selection of specific enrichment procedures suitable for each analytical approach, the development of filters in the sub-micron/nanometre range for SMPs/NPs filtration, and the application of different types of innovative fractionation steps for size separation.

Development of accurate and robust methods for the characterisation of SMPs/NPs

Given the challenge of characterising SMPs/NPs in complex matrices, PlasticTrace will primarily focus on the development and harmonisation of routine/established analytical methods for the measurement of SMPs (100-10 µm) and on the development of innovative hyphenated, complementary and correlative analytical approaches for the measurement of SMPs/NPs (<10 µm) in complex samples.

In particular, the following beyond state measurement capabilities will be developed and optimised:

(i) Light scattering methods for the characterisation of size distribution and particle number with hyphenated approaches based on fractionation techniques;
(ii) Innovative micro-spectroscopy methods for fast automation and data processing for large scale plastic particle monitoring and a new online hyphenated prototype based on fractionation-sizing-quantification and chemical characterisation;
(iii) Mass spectrometry-based methods for the characterisation of mass concentration, number and chemical identification with hyphenated approaches based on fractionation techniques;
(iv) High-resolution, correlative and automated microscopy methods for the characterisation of size distribution, shape and chemical identification performed on fractionated or filtered samples.

Validity and applicability of the developed methods and reference materials

To establish a reference value for critical MP/NP measurands (size, particle number concentration, particle mass fraction), at least two selected and more representative pristine SMPs with different polymeric composition and one selected NPs sample material prepared in this project, whose homogeneity and stability has been thoroughly evaluated in accordance with ISO GUIDE 35:2017(E), will be characterised via ILC. This will be considered a feasibility study driving to the certification process of the reference materials. Moreover, another ILC test will be organised with the involvement of the consortium and a wide external laboratory community in close cooperation with regulatory bodies. This will address the characterisation of a selected food and/or environmental sample matrix spiked with SMPs and NPs, in order to support the validation and harmonisation of the developed methods, as well as to provide reliable quantitative data that contribute directly to the development and implementation of future management strategies.

Outcomes and impact

The project will impact many different sectors including plastics industries, national / international food and environmental agencies, globally leading instrument producers, commercial and accredited laboratories, and leading food producers. It will also improve the reliability and accuracy of SMPs/NPs characterisation in food and environmental media.

Outcomes for industrial and other user communities

The project will provide application-oriented analysis tools, as well as an infrastructure for SMPs/NPs measurement across various fields. The establishment of a traceable measurement chain, with the provision of new reference materials and associated methods, will improve the reliability and accuracy of SMPs/NPs characterisation, and thus supporting utilisation of the results by end users (accredited commercial laboratories, national environmental institutes and monitoring agencies). Together with tools for quality control and proficiency testing, the traceability will guarantee standardisation and comparability of the results, currently lacking for SMPs and especially NPs. The outcome of the project will enable comparable and traceable monitoring to support decision-making and effective assessment of mitigation measures implemented by the EU's Plastic Strategy.

The research results from PlasticTrace will benefit the plastics and food industries, international/national food and environmental monitoring agencies, instrument producers, institutional and commercial laboratories, due to the production of certified reference materials for SMPs/NPs, the publication of metrological traceable analytical methods for SMPs/NPs in (drinking) water and food samples, and the development of new innovative and cost-effective technologies to measure SMPs/NPs. The project outcomes will directly benefit industry and monitoring agencies, through the involvement (as project participants, collaborators and stakeholders) of key actors, from SMEs (Postnova, SmartMembranes), to globally leading instrument producers (ThermoScientific, HF and Agilent), commercial laboratories (EUROFINS), leading food producers (Nestlé Waters, Barilla and Parmalat) and national / international environmental agencies (Norwegian Environment Agency, AMAP, UNESCO).

Outcomes for the metrology and scientific communities

PlasticTrace will provide validated SI-traceable measurement capabilities for the integral quantification of SMPs/NPs derived from the most common polymers, which is currently not available. It will also provide efficient sample preparation SOPs (Standard Operation Procedures) for relevant complex environmental and food samples, which will support both the measurement infrastructure (aimed at routine laboratories) and the academic scientific community. New technological developments in innovative hyphenated, complementary and correlative analytical approaches and their standardisation represent major outcomes for PlasticTrace, to be quickly adopted into common use by metrological, research and scientific communities. These new and innovative methods and technologies not only have a significant potential for high-impact publications in high ranking scientific journals in both the environmental, food and metrological fields, but also direct implementation of the standardised methods to measure SMPs/NPs within ongoing and future scientific and research projects. Metrological outcomes related to food and nutrition will be communicated to METROFOOD-RI, the European Metrological Network for Safe and Sustainable Food, the European Metrological Network for Pollution Monitoring, and the NORMAN network WG micro and nano plastics, assuring a solid anchoring in the European research community for a rapid uptake of the new developed methodologies and their harmonisation. To further promote the use of the developed SMPs/NPs reference materials and the associated analytical validated tools, the consortium will target interactions with the European Commission’s General Directorate for Health, Consumers & Reference Materials, the Consumer Products Safety Unit within the Joint Research Centre (JRC) and the European Research Executive Agency (REA). This will also ensure a solid connection and uptake at the international level due to the close connection with several international experts from China, Australia, USA, South Africa, Korea, Japan and Brazil, who have expressed their interest to be part of the PlasticTrace Stakeholder Advisory Board.

Outcomes for relevant standards

Several project participants are represented internationally in several ISO/CEN committees and working groups in VAMAS and BIPM, as well as national standardisation organisations (DIN, AFNOR, SFS, Standard Norway). This will guarantee the implementation of the project results in standardised methods both at a national and international level. In turn, this will build capacity for European environmental, food and drinking water monitoring programmes on SMPs/NPs. In line with the EU strategy and action plans, several EU directives are currently being revised or updated to include SMPs/NPs. This includes (i) the Urban Waste Water Treatment Directive (UWWTD), in which the MPs are currently not included and which is under revision in 2022, (ii) the Sewage Sludge Directive (SSD) which has signalled similar needs, (iii) the Environmental Quality Standards Directive (EQSD) where inclusion of MPs is currently being discussed, and (iv) the Marine Strategy Framework Directive (MSFD) which is currently discussing threshold values that need to be measured and controlled. Concerning food, no regulation on SMP/NPs is currently being considered due to the lack of harmonised analytical methods, but the European Commission sees a critical need in this field. In addition, the recast of the Drinking Water Directive (DWD) will adopt a methodology for measuring MPs in drinking water by adopting a legal binding delegated act(s) by January 2024. The results of PlasticTrace represent a crucial contribution towards achieving the objectives of these standards and directives on the restriction and especially control of SMP/NPs.

Longer-term economic, social and environmental impacts

PlasticTrace will address major societal needs defined in the Priority Themes of the EU Framework Programme for Research and Innovation 2021–2027, particularly in Horizon Europe Cluster 6, and by the CEAP, which highlights the severe impact of chemical pollutants and MPs on the health of water bodies and the need to develop harmonised measurement methods for unintentionally released of SMPs/NPs to close existing gaps in the scientific knowledge related to the risk occurrence of SMPs/NPs in the environment, drinking water and foods. Achieving reliable SMPs/NPs analytical determination is a prerequisite for addressing these major knowledge gaps, for providing a framework for science-based risk assessment and for consequent adoption of measures tackling plastic particle distribution and accumulation in the environment and food with potential long-range public health, economic and social impacts.

In order to monitor mitigation measures and emission control, efficient metrological traceability methods and technologies for SMPs/NPs are needed to support the EU's Green Deal, including the EU's Plastic Strategy and the Zero Pollution Action Plan for air, water and soil. Without the availability of traceable and quality assured analytical methods and reference materials, the goals of several EU directives on waste water treatment, sewage sludge, environment quality, marine framework and drinking water (UWWTD, SSD, EQSD, MFSD, and DWD) to reduce SMP/NP emissions to the environment cannot be achieved. By delivering cutting-edge outputs, including innovative measuring technologies combined with traceable QA/QC tools and environmentally relevant polymer reference materials, PlasticTrace will contribute directly to the EU Plastic Strategy objective to reduce the impact of SMPs/NPs to the environment.

Moreover, the development of novel analytical methodologies for the identification and quantification of SMPs/NPs in food matrices will facilitate the generation of critical exposure, ingestion and uptake data, thereby laying the basis for dietary exposure assessment. PlasticTrace has the ambition to provide the analytical tools necessary to facilitate a solid evidence-base for any regulatory action at national, EU and international level aimed at increasing the sustainability of the plastic industry and addressing the challenges posed by plastics throughout their entire life-cycle. The standardisation of methods will help to facilitate the assessment of the relevance, origin and fate of SMPs/NPs at European and international level and thus contribute to the creation of efficient strategies to reduce plastic inputs into the environment and food chain. This will also be in support of EFSA evaluation for risk assessment and toxicity of plastic materials along the food chain. In the long term, PlasticTrace is expected to directly contribute to new regulations for nanoplastics.

List of publications

n/a

This list is also available here: https://www.euramet.org/repository/research-publications-repository-link/

Project start date and duration:	01 October 2022, 36months	
Coordinator: Andrea Mario Giovannozzi, INRIM Tel: +39 011 3919330 E-mail: a.giovannozzi@inrim.it Project website address: -		
Internal Beneficiaries: 1. INRIM, Italy 2. BAM, Germany 3. DFM, Denmark 4. IHi, Portugal 5. IPQ, Portugal 6. LNE, France 7. NIVA, Norway 8. SMD, Belgium 9. SYKE, Finland 10. UBA, Germany	External Beneficiaries: 11. FC.ID, Portugal 12. FhG, Germany 13. Hereon, Germany 14. Postnova, Germany 15. Sciensano, Belgium 16. SINTEF, Norway 17. UDC, Spain 18. UNIPR, Italy 19. UNITO, Italy	Unfunded Beneficiaries: 20. HF, France 21. Nestlé Waters, France 22. SmartMembranes, Germany
Associated Partners: 23. LGC, United Kingdom		

Publishable Summary for 21GRD08 SoMMet
Metrology for multi-scale monitoring of soil moisture

Overview

Water and soil are vital resources that are seriously affected by climate change and degradation. Water at the land surface, primarily in the form of soil moisture, is a key resource influencing agriculture, forestry, groundwater recharge, weather, climate, and greenhouse gas emissions. Several soil moisture observation systems exist on multiple scales, but they need to be harmonised. The overall objective of this project is to develop novel metrological tools and establish a metrological foundation for soil moisture measurements on multiple lateral scales, ranging from decimetre to kilometre, ensuring the traceability and harmonisation of the various soil moisture measurement methods.

Need

Soil moisture is one of the Essential Climate Variables (ECVs) as defined by the Global Climate Observing System (GCOS) of the World Meteorological Organisation (WMO). Soil moisture influences the land-atmosphere interactions on both weather and climate timescales. Long-term carbon storage and release in soil is strongly influenced by soil moisture - only a healthy and adequately moist soil can act as carbon sink in the strategies for greenhouse gases (GHG) reduction and adaptation to climate change impacts. Soils are a cross-cutting theme within the European Green Deal (EGD), communicated by the European Commission (EC) in ‘EC COM/2019/640 final’, as the sectors of water management, agriculture, forestry, and biodiversity are inherently interdependent. Soil quality and soil moisture play a key role in the future EGD policies, namely in the future Common Agricultural Policies unified under the Farm to Fork Strategy (‘EC COM/2020/381 final’), policies for environmental protection (Biodiversity Strategy for 2030, ‘EC COM/2020/380 final’) and the climate change action (The European Climate Law, ‘EC COM/2020/80 final’).

Soil moisture measurements at point scales, performed by practical users in agriculture and hydrology (e.g., farmers, agronomists) or by scientists dealing with soil moisture as an ECV, are not immediately representative of the soil moisture at the larger scales that are relevant for practical applications. Point scale measurements use physical tactile sensors which are invasive and subject to local issues. To overcome this, complex sampling designs and interpolation methods can be implemented, however uncertainties need to be improved and practical calibration guidelines developed. Remote observation of the Earth can be used for real-time and continuous assessment of soil moisture on the kilometre-scale however intermediate scale soil moisture methods such as cosmic-ray neutron sensing (CRNS) are needed so that gap from point scale to remote sensing can be bridged. The necessary hardware and data processing tools need to be harmonised and reliable calibration, validation and characterisation methods developed. Several comparison campaigns of soil moisture measurement methods at different spatial and temporal scales have been performed however many research areas (e.g., for the remote sensing of surface temperature for meteorology and climatology) have recognised the need for the integration of observations at different spatial scales based on different methods. There is a need for new on-field comparison campaigns to provide researchers with datasets using traceable methods which can be used to review the existing approaches and develop novel methods to overcome the limitations and different estimates of the soil moisture measurand derived from existing methods. In addition, there is also a need to set out appropriate validation practices for the deep-sensing CRNS method, including fusion of supporting soil data, moisture profiles, and vegetation information, and to harmonise the different methods across scales, in a holistic and yet metrologically traceable approach. Furthermore, there is a need for ‘the next logical step’, i.e., for performing the data fusion of the multi-scale soil moisture measurements to generate high-quality, temporally, and spatially consistent soil moisture information, useful

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for land surface sciences and applications, such as climate observations, weather forecasting, hydrology, and agriculture.

Objectives

The overall aim of this project is to develop novel and traceable methods and establish a metrological infrastructure for soil moisture measurements covering lateral scales ranging from the decimetre to kilometre.

The specific objectives of the project are:

1. To develop metrological framework, including primary and secondary transfer standards, to ensure SI-traceable point-scale soil moisture measurements with uncertainties of 5 % under laboratory conditions. To develop metrological framework for validation of existing cosmic-ray neutron sensing (CRNS) devices, currently available in the market, under laboratory conditions.
2. To develop new validation practices for cosmic-ray neutron sensing (CRNS) methodology for use in outdoor conditions. This includes the application and validation of neutron transport models used to interpret CRNS detector signals specific to the soil moisture measurand, and the standardisation of the CRNS on-field calibration procedure for soil moisture assessment on lateral scales ranging from 10^2 m to 10^3 m and to depths of up to 1 metre.
3. To investigate the constraints and accuracy of soil moisture measurement methodologies using intercomparison campaigns on local and remote sensing. In addition, to develop procedures, summarized in good practice guides, to overcome (i) temporal and spatial differences regarding the sensing domains of soil moisture measurement methods and (ii) the influence of other state variables such as air humidity and soil temperature affecting the measurements.
4. To develop a multi-scale metrological system and metrologically traceable methods for soil moisture monitoring, covering lateral scales ranging from 10^{-1} m to 10^3 m and to depths of up to 1 metre and temporal scales ranging from hours to days, to assess the soil moisture with traceable relative uncertainty of 20 % or better. This includes the development of a cross-disciplinary harmonisation system on the medium sub-kilometre-scale and the establishment of (i) metrological traceability of soil moisture measurements using point-scale sensors (from Objective 1) and satellite measurement techniques and (ii) fit for purpose modelling. In addition, to develop techniques to support the harmonisation of soil moisture assessment.
5. To cooperate with user communities to define design criteria for emerging and future hydrological and meteorological/climatological soil moisture networks using the combination of point-, intermediate- and large-scale methods. To cooperate with the European Metrology Network for Climate and Ocean Observation (EMN COO) and relevant international organisations (e.g., WMO) to facilitate the dissemination of the project outputs.

Progress beyond the state of the art and results

Several soil moisture observation systems have been developed, ranging from invasive point-scale soil moisture sensors to large-scale remote sensing products. In addition, more recently, a non-invasive intermediate scale soil moisture method, cosmic-ray neutron sensing (CRNS) has found widespread use. Despite several initiatives, no harmonisation approaches under metrology standards are available. This project will address this gap by developing the metrological tools needed for traceable and validated soil moisture measurements. For the first time, metrological tools for all three domains/scales will be considered in a holistic approach, to harmonise soil moisture monitoring across scales.

Metrologically traceable methods for multi-scale soil moisture measurements: New traceable methods for the measurement of soil moisture in outdoor conditions on lateral scales in the range of 10^{-1} m to 10^3 m with relative combined uncertainty of 20 % will be developed. To achieve this, new standards and methods for the traceability of the point-scale soil moisture measurements under laboratory conditions will be developed. The measurement supply chain will be extended to outdoor conditions by transfer standards and an improved on-field sampling method developed.

New traceability scheme and validation practices for CRNS method: A traceability scheme for CRNS methodology will be developed. The neutron response functions of the CRNS devices will be validated using calculations and neutron reference fields. This will allow for an effective validation of current and upcoming

CRNS device designs. The combination of metrology for neutron radiation, temperature, and humidity will allow, for the first time, a traceable benchmarking of CRNS devices under outdoor conditions, leading to new validation practices. There will be improved understanding of the CRNS footprint, of systematic effects, and of the uncertainty of the soil moisture retrieval.

*New on-field comparison campaigns on local and remote sensing***:** New soil moisture data will be systematically collected at established experimental field sites, operated by participants and selected according to their relevance for the calibration and validation practices of soil moisture retrieval by CRNS and remote sensing. This data will be a clear improvement over previous historical data sets as they will be based on newly characterised devices of point-scale and CRNS methods, and the measurements will be designed for the purpose of harmonisation. The data will be used to investigate the limitations and accuracy of the individual methods. New approaches and methods will be developed to overcome the temporal and spatial differences regarding the sensing domains of the individual methods.

Cross-disciplinary harmonisation system for soil moisture monitoring: Based on the newly collected data sets, and on the historical time series, novel procedures for harmonising soil moisture assessments on different temporal scales and on lateral scales ranging from point scale to kilometre scale will be developed. New recommendations for the calibration and validation practices of the soil moisture retrieval by remote sensing, as well as new methodologies for data fusion, will be developed.

Outcomes and impact

Outcomes for industrial and other user communities

The calibration procedure developed in this project will allow manufacturers of hydro-meteorological equipment (used in the meteorological, hydrological, agricultural, environmental and related fields) to certify the performance of their instruments based on standard procedures. This would enable them to respond to the needs of national meteorological services for maintenance-reduced instrumentation and fully automated weather stations. The growth of the global automated weather station market is likely to result in significant financial benefits.

Manufacturers of laboratory equipment for instrument calibration will also benefit from the calibration procedure and metrological framework developed within this project, since they will be able to provide compliant calibration devices for soil moisture instruments. This will enable them to market standardised and interoperable equipment and services that will underpin the harmonisation efforts in application areas such as weather monitoring and forecasting, and precision farming.

The development of the traceability scheme and validation practices for the CRNS method as part of this project, as well as the recommendations on networks design and validation practices, will support the existing and upcoming CRNS networks in Europe and worldwide. This positive effect will be in form of SI-traceable CRNS devices, more reliable and interoperable data sets from CRNS networks, harmonised data for further use in hydrology, meteorology, and agriculture. The improvements in the metrological basis of the CRNS method are also important for further joint initiatives such as Joint FAO and IAEA Programmes.

Organisations providing advice to policy makers (such as the European Union of Water Management Associations (EUWMA), the European Environment Agency (EEA)) will benefit from the calibration procedure and harmonisation of various soil moisture measurements developed in the project, as they will have access to local hydrological conditions that are interoperable and comparable on the European scale. This will provide them with improved soil and environmental scenario analysis for not only current purposes but also future planning of the managements of water and soil resources, e.g., in agricultural policies.

This project will directly liaise with industrial stakeholders via the formation of a Stakeholder Committee. This group will include representatives from agro-meteorological services, national meteorological services, WMO members of expert teams, regional instrument centres, manufacturers centres, and will help the project's results to directly impact such representatives.

In addition, this project will also produce and publish 3 good practice guides for end-users:

- Good practice guide for calibration practices for CRNS soil moisture data retrieval in outdoor field conditions covering on lateral scales ranging from 10^2 m to 10^3 m and to depths of up to 1 metre
- Good practice guide for harmonising soil moisture measurement methods to overcome temporal and spatial differences (lateral scales ranging from point scale to km scale) and the influence of other state variables such as air humidity and soil temperature affecting the measurements

- Good practice guide for interdisciplinary data fusion of soil moisture measurements on multiple scales

Outcomes for the metrology and scientific communities

SI-traceable metrology for water content in materials has been partly established over the last decade. However, at present, no countries have BIPM Calibration and Measurement Capabilities (CMCs) for moisture measurement, and SI-traceable measurements of soil moisture on primary level have, to our knowledge, not been reported. One important outcome of this project is to establish primary-level soil moisture measurements with developed uncertainty budgets. TUBITAK will establish a new calibration service for soil moisture measurements. DTI will integrate the results of the project in its existing services related to field trials and plant technology (https://www.dti.dk/specialists/agrotech/36805). DTI will also offer new consultancy and laboratory services to the scientific community on the traceability of soil moisture measurement using point scale sensors. In general, the established metrological foundation for soil moisture measurement should allow traceable calibration and validation of secondary measurement standards such as those based on traditional loss-on-drying and of transfer standards.

For soil moisture measurement there are currently unresolved issues with appropriate transfer standards and sampling methods. This project will address these issues and the transfer of the metrological chain of traceability to outdoor conditions, using new transfer standards based on visible and near-infrared spectral reflectance measurements for on-site calibrations. This improved metrological basis will be used for improving the CRNS methodology and should have direct impact on networks in Europe (e.g., TERENO, COSMOS-UK, eLTER) and worldwide (COSMOS, CosmOz, COSMOS-India). Harmonised multi-scale soil moisture data, with reliable uncertainties, will improve hydrological modelling, climate and weather forecasting by ensuring better comparability between data sets obtained with different methods.

The project will also host two one-day stakeholder events to disseminate results of the project and promote the uptake of the technology and measurement infrastructure developed. The first workshop will train participants from the stakeholder community, specifically those from hydro-meteo agencies, agrometeorological consortia, and manufacturers. The second one-day “Soil Moisture Workshop” will present and discuss the project results, including the project’s three good practice guides, to stakeholders, including WMO representatives, national meteorological and agro-meteorological representatives.

Finally, the project will provide output to the metrology and scientific communities via input to the EMN COO by interacting closely with the EMN COO network members. The consortium will also liaise with the EMN’s associated projects dealing with establishing the metrology for ECVs observation.

Outcomes for relevant standards

Currently, most of the guidance for soil moisture measurements in the field is contained in good practice guidelines (e.g., IAEA technical documents on field estimation of soil water content and on CRNS, Committee on Earth Observation Satellites (CEOS) good practice protocol for remote sensing, and methods for soil analysis by the American Society of Agronomy), and there is a lack of relevant validation and standardisation. Standardised procedures based on suitable calibration devices would benefit manufacturers and users of soil moisture instruments. Indeed, their use is currently limited due to insufficient standardised calibration procedures and the lack of both metrological comparison and harmonisation among different sensor typologies and gravimetric/volumetric manual soil moisture measurements.

This project will support standardisation work for soil moisture measurements by providing a technical report to CEN TC444 Environmental Characterisation WG5 Physical tests for consideration and adoption as well as to ISO TC-190 Soil quality WG1 Soil and Climate Change SC3 Chemical and physical characterisation for update of an existing standard. The project will also provide input to WMO Standing Committee on Measurements, Instrumentation and Traceability (WMO SC-MINT), WMO Commission for Observation, Infrastructure and Information Systems (INFCOMM), WMO Commission for Instruments and Methods of Observation (CIMO) expert team on Operational Metrology, WMO Global Climate Observing System (GCOS) Surface Reference Network, WMO SC-MINT expert team on Measurement Uncertainty (ET-MU), EURAMET Technical Committee for Thermometry (TC-T) and BIPM Consultative Committee for Thermometry Working Group for Humidity (CCT-WG-Hu).

Members of the consortia sit in and chair relevant WMO expert teams and a goal of the project is also to provide input to guidance material such as updates to the WMO ‘Guide to Meteorological Instruments and Methods of Observation’ (WMO Guide No. 8).

Longer-term economic, social and environmental impacts

A wider impact of the project results is expected on companies operating in the fields of hydro-meteorological warnings, water resources management, flood control, agriculture and hydro-power plants. These companies generally provide services based on the monitoring of hydro-meteorological variables and the processing of the related measurements to support the final users' decisions about the configuration of industrial systems, even in real time. The use of calibrated soil moisture type instruments, in conjunction with the other meteorological observables, would improve the management capabilities of the users since decisions would be based on traceable measurements, and enable more comparable data in space and time. With more reliable data it would therefore be possible to promptly inform the weather services, local agro-meteorology consortia and users, about the risk of drought and flood. The accuracy of such information is vital for the issuing of effective and timely warnings. This main economic impact would therefore be two-fold; an increase in trustworthy and timelier irrigation plans, with direct benefits on agricultural and farming production (such as an increase in crop yields) and reduction of water waste for irrigation and hence increased water availability. A reduction in maintenance costs for hydro-meteorological agencies and agro-meteorology consortia and users is foreseen. This project has the potential to increase the demand for such systems, possibly lowering their commercial costs.

Based on a general lack of traceability and data quality in historical observation, the Global Climate Observing System (GCOS) is preparing the creation of the GCOS Surface Reference Network (GSRN). Among the ECVs prescribed by GSRN, soil moisture is one of the fundamental observed quantities for a reference site. The non-contact systems (CRNS) developed in the project will offer more reliable data and are nearly immune to maintenance and mechanical drifts and shocks, thus becoming a more robust candidate for long-term data series recording. In addition, this project is expected to have a substantial impact in climate science through the GCOS and other similar initiatives.

The involvement of the consortium in BIPM and the WMO, at the operational level and in the supporting research, guarantees fast and efficient communication and feedback. Coordinating the efforts and avoiding duplication of work or contrasting conclusions, will increase the chances of successfully transferring the results into standardisation documents soon after the conclusion of the project. Improvements in traceability and better measurement facilities for soil moisture measurements, with lower and metrologically reliable uncertainty, will have direct impacts on the global environment which serves a healthy food system for people in the European Green Deal framework. Therefore, the project has an indirect impact on the health and quality of life of human society. As mentioned earlier, more reliable and traceable soil moisture observations are also the basis for supporting decision making in many water-related sectors, from irrigation management and planning to flood forecasting and early warnings.

List of publications

n/a

This list is also available here: https://www.euramet.org/repository/research-publications-repository-link/

Project start date and duration:	October 2022, 36 months	
Coordinator: Miroslav Zboril, PTB Project website address: -	Tel: +49 531 592 6536	E-mail: miroslav.zboril@ptb.de
Internal Beneficiaries: 1. PTB, Germany 2. CIEMAT, Spain 3. CMI, Czech Republic 4. DTI, Denmark 5. INRIM, Italy 6. IRSN, France 7. JV, Norway 8. SMU, Slovakia 9. TUBITAK, Türkiye	External Beneficiaries: 10. CNR, Italy 11. CTU, Czech Republic 12. IAPAN, Poland 13. PoliMi, Italy 14. UFZ, Germany 15. UHEI, Germany 16. UNIBO, Italy 17. UP DE, Germany	Unfunded Beneficiaries:
Associated Partners: 18. UKCEH, United Kingdom		

Publishable Summary for 21GRD09 MetroPOEM
Metrology for the harmonisation of measurements of environmental pollutants in Europe

Overview

European Green Deal's ambition for zero pollution requires the development of highly sensitive techniques to detect ultra-low amounts of pollutants and to determine their isotope ratios. Mass spectrometry is a key method for determination of non-radioactive polluting elements and is of increasing importance for long-lived radionuclides. This project will bridge the gap between both methods and will establish new tools for tracing pollutants. Measurement uncertainties and detection limits will be significantly reduced using newly developed reference materials and SI-traceable measurement procedures with an immediate impact for tracking pollution sources by commonly available mass spectrometers.

Need

This project supports the strategies described by the upcoming European Metrology Network (EMN) on Pollution Monitoring (POLMO) and the established EMN on Radiation Protection (supporting the Basic Safety Standards directive). According to their strategies, there is a strong need to improve data quality for monitoring and reporting pollution in the air, water, and soil. In addition, the lack of suitable traceability chains and appropriate quality control compromises the comparability and robustness of measurements.

To detect radioactive isotopes and stable polluting elements in the environment, fast, sensitive and inexpensive analytical procedures are needed. Mass spectrometry techniques have a great potential to address this requirement. Despite the increasing application of single collector ICP-MS (Inductively Coupled Plasma Mass Spectrometry), this potential cannot be fully realised unless techniques can be validated with traceable multi-element reference materials. However, multi-element certified reference materials are usually not available and even single-element certified reference materials are limited to very few elements. Nevertheless, these reference materials are urgently needed to calibrate mass spectrometric measurements, due to mass bias effects occurring during the measurements in mass spectrometers.

The orientation document, issued by EURAMET´s Ionising Radiation Technical Committee and the EMN on Radiation Protection, clearly described a metrological need for "*traceability of radionuclide concentration measurements in the environment*". This topic refers to the classification of the Green Deal as "*a zero-pollution ambition for a toxic-free environment'*". There is a need to increase the use of modern mass spectrometric techniques for measurements of both radioactive and non-radioactive pollutants in monitoring labs and beyond. However, this will require increased access to certified reference materials traceable to the SI.

Objectives

The overall aim of the project is to bridge the gap between radiometric techniques and mass spectrometry for the characterisation and detection of polluting long lived radionuclides and stable elements and element tracers by comparing and linking both techniques, thus significantly improving measurement uncertainties and detection limits.

The specific objectives of the project are:

1. To establish and compare the selectivity and detection limits of different types of mass spectrometers (e.g., AMS, HR-ICP-MS, ICP-MS/MS, ICP-QMS, MC-ICP-MS, SIMS, SNMS, TIMS) for selected radioactive pollutants (e.g., U, Np, Pu, Am) using isotope reference materials

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and/or activity standards. This includes assessing relative instrument performance with respect to current measurement challenges and establishing detection limits in relation to regulatory waste criteria levels or environmental regulations.

2. To develop measurement methods for isotope ratios that are traceable to the SI by using multi-collector ICP-MS and apply these methods on more commonly available techniques (ICP-MS/MS, ICP-QMS) by providing suitable operating procedures focussing on stable polluting elements (e.g., Li, B, Cr, Cd, Ni, Sb, Pb, U). To produce recommendations for sample processing, treatment, uncertainty budgets, and if feasible, the quantification of the so-called mass bias.
3. To develop two radioactive reference materials with the sample matrix containing radioactive pollutants (e.g., U, Np, Pu, Am) for use in an inter-laboratory comparison employing techniques used in objective 1, which will demonstrate the variations in parameters including detection limits, sample preparation requirements, sample introduction methods, total procedural time, and uncertainty budgets.
4. To implement and validate the methods for isotope ratio measurements established in objective 2 by the development of one aqueous certified reference material (CRM) that is certified for the same stable polluting elements with lowest possible uncertainties using multi-collector instruments, in order to facilitate the calibration of single collector ICP-MS, instrument validation, as well as quality control.
5. To facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain (e.g., accredited laboratories), standards developing organisations and international organisations (JRC, CIPM CCs [CCQM-IRWG, CCQM-IAWG, CCRI], IAEA, ICRM) and end users (e.g., environmental monitoring agencies).

Progress beyond the state of the art and results

Measured selectivity and detection limits of different types of mass spectrometers for selected radioactive pollutants using single and mixed activity standard solutions

Non-radiometric techniques show great potential for the measurement of radioactive pollutants. However, the traceability and validation of the methods are missing. The project will go beyond the state of the art by establishing the capabilities of different mass spectrometry designs, such as:

- Accelerator Mass Spectrometry/Spectrometer (AMS),
- High Resolution Inductively Coupled Plasma Mass Spectrometry/Spectrometer (HR-ICP-MS),
- Inductively Coupled Plasma Tandem Mass Spectrometry/Spectrometer (ICP-MS/MS),
- Inductively Coupled Plasma Quadrupole Mass Spectrometry/Spectrometer (ICP-QMS),
- Multi-Collector Inductively Coupled Plasma Mass Spectrometry/Spectrometer (MC-ICP--MS),
- Secondary-Ion Mass Spectrometry/Spectrometer (SIMS),
- Secondary Neutral Mass Spectrometry/Spectrometer (SNMS) and
- Thermal Ionisation Mass Spectrometry/Spectrometer (TIMS).

This will be achieved by using single and mixed activity standard solutions of actinides (^{237}Np, ^{234,235,236,238}U, ^{239,240}Pu, ^{241}Am), accessible by mass spectrometry, at activities relevant to regulatory limits. The focus will be on relative instrument performance concerning current measurement challenges. It aims to establish detection limits at levels below current environmental regulations, reduce isobaric interferences, and compare decay counting techniques. The range of radionuclides chosen is well suited for comparison. This is based on the half-lives (<500 years to >4×10^9 years), the presence of multiple spectral interferences that must be overcome to ensure accurate measurement, and the precise isotopic ratio measurements (^{239}Pu/^{240}Pu, ^{236}U/^{238}U) for source identification.

SI-traceable measurement methods for isotope ratios of stable polluting elements

SI-traceable isotope ratios for Li, Pb, and U as pilot elements with relative measurement uncertainties (u_{rel}, of <0.01 %) will be realised. The process is based on the *ab initio* calibration for SI-traceable isotope ratios without any *a priori* assumptions, introduced for Mg as a three-isotope system in 2016. This approach will be expanded to other multi-isotope systems and will set the basis for the certification of the first iRM (e.g., Li) with SI-traceable isotope ratios and u_{rel} ≤0.01 %. For many stable elements, enriched isotopes are not available, or the required uncertainty level does not justify the costs and efforts of applying a gravimetric isotope mixture approach to obtain SI-traceable isotope ratios. For quantitative elemental analysis, and for general isotope ratio applications, less expensive and laborious approaches based on inter-element normalisation will be developed.

Inter-laboratory comparison with two new reference materials containing radioactive pollutants

Existing radioactive Reference Materials (RM) and Certified Reference Materials (CRM) adapted to mass spectrometry measurements on environmental samples are limited and often lack relevant parameters, including isotopic ratios. The project will go beyond the state-of-the-art by developing two RMs – liquid and solid – containing the radioactive pollutants U, Np, Pu, Am for use in an inter-laboratory comparison. The project will employ techniques used for the measurement of the activity standards solutions. This will demonstrate the variations in parameters such as detection limits, sample preparation requirements, sample introduction methods, total procedural time, and uncertainty budgets. Eventually, this approach will help characterise the matrix related mass bias. Reference Materials, produced in this project, will be used in future QC measurements.

Aqueous certified reference material with stable polluting elements (and traces of radioactive pollutants) for the calibration of single-collector ICP-MS

One certified seawater reference material with clearly defined concentrations at natural levels will be developed for use in the validation of analytical procedures, supporting proficiency testing and quality control in future monitoring campaigns.

Outcomes and impact

Outcomes for industrial and other user communities

This project will enable and harmonise measurement methods for the detection and characterisation, of both radioactive isotopes and stable polluting elements, in support of the EU Green Deal's aim toward a zero pollution, toxic-free environment. The measurement of the species in this project (Li, B, Cr, Ni, Cd, Sb, Pb, U, Np, Pu and Am) will benefit the users of such data, such as monitoring organisations and the owners of potentially polluting facilities. This project, by providing information to the ICP-MS (of whatever type) measurement community, will allow them to select the most appropriate technology (from AMS, HR-ICP-MS, ICP-MS/MS, ICP-QMS, MC-ICP-MS to single collector ICP-MS) to meet their needs. As a result, users seeking to invest in one of the available ICP-MS based modalities will be able to make informed decisions. The Europe-wide collaboration developed in the project will provide the foundation for future inter-laboratory comparison exercises for the determination of species of interest in a variety of environmental matrices where ICP-MS based techniques offer significant advantages over decay counting. The new RMs developed in this project will address the ongoing need to produce suitable and relevant (in terms of matrices and analytes) RMs that can validate state-of-the-art measurement capabilities.

Outcomes for the metrology and scientific communities

The scientific outcome of the proposed research will deliver validated and traceable analytical approaches for the analysis of the concentration of pollutants, as well as determining the source and monitoring any contamination of pollutants through isotope ratio measurements. This will close existing metrological gaps and will lead to a harmonisation of the different methods currently applied for the analysis of isotope ratios to support the investigation of natural environmental processes and anthropogenic impacts.

Combining the expertise in isotope ratio measurements of the Comité Consultatif pour la Quantité de Matière: métrologie en chimie et biologie (CCQM) and radioactivity measurement by the Comité Consultatif des Rayonnements Ionisants (CCRI) will provide new and innovative tools for advancing the application of mass spectrometry for contributing to improved half-life determinations.

Outcomes for relevant standards

This project will deliver an improved system of metrology and will establish an infrastructure that directly supports the application of the following EU regulations or EU directives:

- Council Directive 2013/51/Euratom (22 October 2013): requirements for protecting the health of the general public concerning radioactive substances in water intended for human consumption.
- Council Directive 2013/59/Euratom (5 December 2013): basic safety standards for protection against the dangers arising from exposure to ionising radiation; Chapter VIII – Public Exposures.
- Treaty establishing the European Atomic Energy Community, Chapter III – Health Protection, Article 35: Each Member State shall set up the facilities necessary for the permanent control of the level of radioactivity in the atmosphere, water and soil and for controlling compliance with basic standards. The Commission shall have the right of access to such control facilities; it may examine their operation and efficiency.
- EU Regulation 995/2010: the origin of legal timber by, for example, determining the Sr isotope composition.
- EU Regulation 2729/2000, 2220/2004, 2030/2006, 555/2008 and 1169/2011: the provenance of food.
- Directive 2009/29/EC, decision No 406/2009/EC, directive 2009/31/EC: Climate research (δ11B), greenhouse gases (pathways of δ13C), carbon storage (possibly applicable for the geological assessment of Sr and Nd).

By implementing new traceability chains, different methods will be combined in the field of pollution monitoring, which will then lower the detection limits. This will result in better protection of the environment, provide new tools for complex studies in climate observation, support validated data collection of the European Research Centres and enhance the implementation of the ALARA goal expressed in the radiation protection regulation of the EC.

Longer-term economic, social and environmental impacts

The integration of highly specialised MS techniques, such as Accelerator Mass Spectrometry/Spectrometer (AMS) and Secondary-Ion Mass Spectrometry/Spectrometer (SIMS), into the project, considerably widens the horizon for environmental monitoring or forensic studies and harmonises these detection methods with more commonly applied ICP-MS methods. The outcomes of the project will contribute to meeting the challenge of achieving highly sensitive and cost-effective pollution control. Using ICP-MS techniques in routine pollution monitoring allows the rapid determination of multiple elemental pollutants (both radioactive and stable) within a single sample. This ability, linked to the automated high sample throughput of ICP-MS systems, allows the capture of more and better sample information from single measurements. These factors will help to make a rapid and detailed mapping of pollutants, within defined areas, relatively straightforward. As a result, remediation strategies can be closely targeted and operated with good resolution. The cost of these activities will be reduced without losing effectiveness.

The development of validated and traceable methods will improve societal confidence in the measurement and quantification of pollutants across many sectors, such as manufacturing, industrial decommissioning and the long-term decommissioning and remediation of aged and disused nuclear sites. Accurate waste classification engenders public confidence and ensures inventories are correct for future infrastructure planning, such as the scale and design of pollutant remediation programmes.

The outputs from the project may be employed in several diverse fields including routine real-time monitoring, emergency response, geological dating and climate change studies through isotopic ratio measurements, and in other activities, such as nuclear forensics, decommissioning non-nuclear industries (such as the oil industry in the North Sea) and radiopharmaceutical facilities, where use is made of long-lived radioactive precursors. The collaboration between European laboratories established in this project is expected to continue beyond the end of the project.

List of publications

n/a

This list is also available here: https://www.euramet.org/repository/research-publications-repository-link/

Project start date and duration:	1 October 2022, 36 months	
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Project website address: https://www.npl.co.uk/euramet/metropoem		
Internal Beneficiaries: 1. PTB, Germany 2. BAM, Germany 3. CEA, France 4. CMI, Czechia 5. JSI, Slovenia 6. LNE, France 7. STUK, Finland 8. TUBITAK, Türkiye	External Beneficiaries: 9. AU, Denmark 10. DTU, Denmark 11. Hereon, Germany 12. HZDR, Germany 13. IFE, Norway 14. IFIN-HH, Romania 15. LUH, Germany 16. MUL, Austria 17. NMBU, Norway 18. UH, Finland 19. VINS, Serbia	Unfunded Beneficiaries:
Associated Partners: 20. ETHZ, Switzerland, 21. LGC, United Kingdom, 22. NPL, United Kingdom		

Publishable Summary for 21GRD10 quantiAGREMI
On farm quantification of ammonia and greenhouse gas emissions from livestock production

Overview

Many current food production practices still result in air, water and soil pollution, contributing to biodiversity loss, climate change and poor air quality. Increasing global food demand drives ruminant livestock numbers, rapid land use change and nitrogen (N) fertilizer use, accelerating greenhouse gas (GHG) emissions. The aim of this research is to provide a SI-traceable field measurement infrastructure for accurate determination of animal houses emissions as well as nitrogen footprints. Mitigation measures can therefore be assessed to reduce emissions and improve inventories.

Need

The EU agricultural sector contributes to 93% of ammonia (NH_3) and 48% of methane (CH_4) emissions in Europe and dominates Europe's anthropogenic N_2O emissions (72%). While NH_3 is an important contributor to particulate matter, with adverse health effects estimated to cause 4.2 million premature deaths worldwide per year (2016), CH_4 and N_2O are potent GHG. The Farm to Fork strategy is a central part of the European Green Deal for a climate neutral Union in 2050. The strategy aims to reduce the GHG emissions from agriculture and food value chain to 55% compared to 1990 levels by 2030. Additionally, innovative CH_4 mitigation strategies are required to be explored under the "EU strategy to reduce CH_4 emissions". It is essential to develop a coordinated European metrology infrastructure to improve and reduce the uncertainty of emission data GHG and reactive N from agriculture, in order to understand the processes governing emissions, assess the efficiency and reliability of developed reduction strategies and to provide reliable evidence for policy makers who set emission targets. In addition, there is a requirement from the United Nations Framework Convention on Climate Change (UNFCCC) and the United Nations Food and Agriculture Organization (FAO) to reduce the environmental and climate footprint from agriculture.

Objectives

The overall objective of the project is to enable a more reliable quantification of livestock emissions and allow policy makers assessing and establishing efficient mitigations strategies.

The specific objectives of the project are:

1. To develop, building upon existing techniques, traceable techniques for quantifying NH_3 and CH_4 emissions from selected livestock housings with a target uncertainty of 10% (CH_4) and 20% (NH_3) for mechanically ventilated and 30% (CH_4) and 40% (NH_3) for naturally ventilated housing. In addition, to define target applications (e.g. animal category, housing systems) according to stakeholder needs.
2. To develop and characterise CO_2, NH_3 and CH_4 emission monitoring techniques, considering atmospheric conditions, for enhanced spatial and temporal coverage.
3. To identify, using emissions data from objective 2, key-indicators (e.g. milk urea content and manure storage) and to improve emission models (e.g. based on feeding, climate conditions) for increasing the representativeness of the emission estimations and determine their uncertainty. In addition, to

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METROLOGY PARTNERSHIP EURAMET

develop farm-monitoring systems for evaluating the efficiency of reduction measures and provide management tools to farmers for ensuring reduction performance.

4. To reduce the uncertainty associated with up-scaling GHG emissions and nitrogen loss from soils by improving model parameterisation (e.g. relative contributions of nitrification and denitrification to N_2O emission) using field-deployable spectroscopic techniques to determine N_2O isotopic species for different production pathways. In addition, to improve methods for quantifying NH_3 deposition from livestock housing and tracing nitrogen isotopes (e.g.^{15}N) in managed soils.

5. To facilitate the dissemination and uptake of the technology and measurement infrastructure developed in the project by (i) contributing to emissions inventory reports under the UNFCCC, (ii) providing guidelines to the measurement supply chain (researchers, commercial measuring institutes), expert groups (VERA, COST Action LivAGE) and standardisation developing organisations (CEN TC264) on techniques/modelling approaches to facilitate the establishment of decision matrices and the promotion of mitigation measures by policy makers, and (iii) providing farmers access to reliable methods for identifying efficient mitigation strategies and provide quantitative GHG emissions at farm level.

Progress beyond the state of the art and results

Development of techniques for the quantification of NH_3 and CH_4 emissions from selected livestock housings with a target uncertainty of 10% (CH_4) to 20% (NH_3) for mechanically ventilated and 30 % (CH_4) to 40 % (NH_3) for naturally ventilated housing and for target applications such as animal category and housing systems. Development and characterisation of CO_2, NH_3 and CH_4 emission monitoring techniques, considering atmospheric conditions, for enhanced spatial and temporal coverage.

Objectives 1 and 2 will contribute to a more reliable quantification of GHG and NH_3 emissions from agriculture by improving existing and developing new measurement methods, characterising metrologically the emission measurements and providing complete uncertainty budgets. This will enable SI-traceable emission estimations. SI-traceable estimations and their uncertainty will contribute to the accuracy improvement of the inventories, thereby ensuring a better implementation check of the National Emission Ceilings Directive (NEC 2001/81/EC) and the UNECE 1999 Gothenburg Protocol (revised in 2012), which set national emission reduction commitments. For this purpose, the results of EMPIR JRP ENV55 MetNH3 will be used. That project aimed to achieve metrological traceability for ammonia measurements in ambient conditions by developing improved reference gas mixtures (RGMs) by static and dynamic gravimetric generation methods of NH_3 amount fractions, as well as by developing laser-based optical transfer standards. The transfer from high-accuracy standards to field applicable methods was also established by employment of characterised exposure chambers and field sites for validation and comparison experiments. Based on the existing mobile reference gas generator ReGaS (developed and validated in EMPIR JRP ENV55 MetNH3), a setup will be developed to produce wet RGMs for the calibration of devices used in livestock housings.

Identification of key-indicators (e.g. milk urea content and manure storage) and improvement of emission models (e.g. based on feeding, climate conditions) for increasing the representativeness of the emission estimations and their uncertainty evaluation. Development of farm-monitoring systems for the evaluation of the reduction measures efficiency in order to provide management tools to farmers for ensuring reduction performance.

Objective 3 will allow step-by-step validation measurements in the laboratory and under real housing conditions to identify suitable sensors and to evaluate them with regard to their suitability and field of application (animal category, housing system, manure storage). There is now no clear solution for farmers and policy makers to measure GHG and reactive N emissions, and thus to develop a mitigation policy. This project will allow the sensors implementation, while a survey policy at the European scale will be developed.

Reduction of the uncertainty associated with up-scaling GHG emissions and nitrogen loss from soils, by improving model parameterisation (e.g. relative contributions of nitrification and denitrification to N_2O emission) and with the use of field-deployable spectroscopic techniques for defining the N_2O isotopic species for different production pathways. Improvement of methods for NH_3 deposition quantification from livestock housing and tracing nitrogen isotopes (e.g.^{15}N) in managed soils.

Objective 4 will reduce the uncertainty of N_2O inventories from agricultural soils and improve the quantification of NH_3 footprint around livestock buildings through i) evaluating the methodologies used to study the fate of

NH_3 released from animal housings and ii) the study of the capability of current field N_2O emission measurements to attribute N_2O emitted from soils to the different microbial N production processes. N_2O emissions from soils have constant emission factors applied, irrespective of soil properties and meteorology, which leads to large uncertainties. In addition, human activities profoundly influence the N-cycle by converting more N into reactive N forms than all of Earth's terrestrial processes combined. Thereby, nitrogen cycles exceed their safe operating space in Europe, by a factor of 3.3 resulting in diffuse N pollution of terrestrial and aquatic ecosystems. The results will be used to determine bias and reduce uncertainty arising from near-field N deposition and parametrisation of different N_2O production processes in biogeochemical models.

Outcomes and impact

The project results will create impact by providing policy-makers with the tools required to develop efficient mitigation measures for emissions. Improved SI-traceable estimations of NH_3 and GHG emissions from agriculture, with a defined uncertainty available will create further impact not only on the scientific community, by enhancing emission data comparability across monitoring studies, but also support national agencies, by improving emission inventories for air pollutants and greenhouse gases

Outcomes for industrial and other user communities

Research outputs, such as improved accuracy of emissions, enhanced spatial and temporal measurements, and reduced model input uncertainties, will be beneficial to farmers, industry, agricultural agencies and national authorities. It will allow users to evaluate, with a higher level of confidence, the measures proposed for reducing emissions (e.g. set of measures for reducing NH_3 included in Directive 2016/2284/EU) and therefore to select and implement the strategies with the highest effectiveness, whilst considering the benefit-to-cost ratio. The impact of this work will reach beyond Europe as the work and the results will be communicated to international agencies such as the WMO and the FAO on how to reduce the environmental and climate footprint of the food system and lead to a global transition towards competitive sustainability from farm to fork.

Outcomes for the metrology and scientific communities

The project aims to characterise metrologically state-of-the-art techniques for estimating emissions from livestock (objective 1), such as natural and artificial tracer gas methods. This characterisation, along with the resulting method comparison, will create impact on the scientific community by offering tools to perform accurate decision matrix analysis of appropriate techniques and/or potential reference. Furthermore, the validation of measurement techniques to estimate the N footprint surrounding livestock buildings including NH_3 deposition, N_2O soil emission fluxes and isotope signatures, will generate data that will improve process descriptions and reduce biogeochemical model uncertainties. These will result in methodologies which will provide a better understanding on nitrogen conversions and fluxes between compartments. Furthermore, this project will enable a European fit-for-purpose metrological infrastructure (partly developed during the EMRP projects ENV55 MetNH3, ENV52 HIGHGAS, IND63 MetAMC and the EMPIR project 16ENV06 SIRS) for direct field applications, and in particular for trace level gases of NH_3 and GHG. It will also enhance the collaboration between different fields/laboratories thus fostering cross-disciplinary tasks and applications (e.g. gas measurement, wind measurement, modelling approach).

Outcomes for relevant standards

This project supports international standardisation technical committees and directive such as CEN/TC264/WG11 and *ad hoc group Stationary Source Emissions — Methods for the Quantification of Diffuse Emissions*, ISO/TC146 (*air quality – ambient air and emissions from stationary sources*) and the Directive 2008/50/EC for air quality. The consortium will disseminate its findings through new or revised guidelines and recommendations with their active participation in several working groups (e.g. CEN/TC264/WG12, ISO/TC158, new WMO-GAW measurement guidelines). Furthermore, the work will especially support the Directive 2008/50/EC for air quality as well as regulation (EC) No 842/2006 by increasing the confidence in the emission/immission measurements and by enabling improved evaluation tools for implemented emission reduction measures.

Longer-term economic, social and environmental impacts

Effective measures and strategies will in turn result in lower socio-economic costs associated with environmental and health issues. For example, avoiding premature deaths associated with NH_3 emissions will translate into benefits > 14800 M€/year in Europe. In the case of measures for reducing NH_3 emissions, the estimated implementation costs range between 80 and 3780 M€. In particular, the project will have a direct impact on the work carried out by expert groups such as VERA (Verification of Environmental Technologies for Agricultural Production), GRA (Global Research Alliance) and the COST LivAGE Action (European Cooperation in Science and Technology - Ammonia and Greenhouse Gases Emissions from Animal Production Buildings). The outputs will facilitate their tasks on harmonisation of measurements and modelling aspects to reduce emissions from livestock buildings, which will additionally support the strategy adopted under the "EU Methane Strategy" and "Farm-to-Fork" as part of the European Green Deal.

List of publications
n/a

This list is also available here: https://www.euramet.org/repository/research-publications-repository-link/

<table>
<tr><td colspan="2">Project start date and duration:</td><td>01 November 2022, 36 months</td></tr>
<tr><td colspan="3">Coordinator: Axel Fouqueau, LNE Tel: +33 140433852 E-mail: axel.fouqueau@lne.fr
Project website address: -</td></tr>
<tr><td>Internal Beneficiaries:
1. LNE, France
2. CMI, Czechia
3. PTB, Germany
4. TUBITAK, Türkiye
5. VSL, Netherlands
6. VTT, Finland</td><td>External Beneficiaries:
7. GASERA, Finland
8. IMTelecom, France
9. INRAE, France
10. KIT, Germany
11. LUKE, Finland
12. Senseair, Sweden
13. TI, Germany
14. TNO, Netherlands
15. WR, Netherlands</td><td>Unfunded Beneficiaries:
16. Vaisala, Finland</td></tr>
<tr><td colspan="3">Associated Partners:
17. Empa, Switzerland
18. LGC, United Kingdom
19. METAS, Switzerland
20. UKCEH, United Kingdom
21. WBF-Agroscope, Switzerland</td></tr>
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Publishable Summary for 21NRM01 HiDyn
Support for the standardisation of luminance distribution measurements for assessing glare and obtrusive light using high-dynamic-range imaging systems

Overview

Luminance distribution measurements with high dynamic range (HDR) are required for various applications (e.g. measurement of new LED- or laser-based car headlights, obtrusive light and glare evaluation of indoor and outdoor scenes) where high contrast levels exist simultaneously in one image. Imaging luminance measurement devices (ILMD) and red-green-blue (RGB)-based cameras are often used for such assessments. HDR measurements are then achieved by post-processing image sequences, but standardisation and uncertainty statements are usually absent, which makes it impossible to fully explore the potential and limits of these systems. This project aims to develop procedures for using HDR imaging measurement systems in luminance distribution measurements and glare assessment, standardise the determination of the instrument performance, including associated uncertainties, and select an HDR algorithm adequate for SI-traceable measurements. This is expected to support relevant legislations on glare and obtrusive light mitigation with traceable and trustable field based HDR luminance measurements, contribute to a proper assessment of lighting installations regarding safety and discomfort from glare and obtrusive light sources, and increase working place ergonomics as well as safety levels in roads suffering from glare from lighting installations and environmental impact of obtrusive light.

Need

The complexity of the human visual system allows adaptation to extremely dark and bright lighting conditions. Due to its very large dynamic range for lightness perception (11 orders of magnitude of luminance), humans can safely and comfortably navigate the world, and perform tasks involving vision in lighting environments with very high luminance contrast. However, some lighting environments can be disturbing for some tasks and may pose issues regarding safety. Therefore, it is necessary to study these environments and adapt them to more adequate lighting. In particular, unsuitable distribution or extreme luminance contrast can produce glare, a vision condition in which there is discomfort or a reduction in the ability to see details or objects, and spill light with certain attributes, which can be obtrusive and give rise to annoyance, discomfort, distraction or a reduction in ability to see essential information such as a traffic signal. The evaluation of glare or obtrusive light, and other visual aspects important for safety and comfort, rely on experiments presenting a high luminance contrast. The characterisation of such scenes requires measuring instruments specifically designed for these conditions. In the recent years, an increasing number of research fields and industry applications have been using HDR imaging technologies. However, there is currently no metrological certainty obtained with measurements performed using commercial HDR imaging measurement systems, and glare and obtrusive light evaluations using such systems are not SI-traceable, which can lead to major shortcomings in safety and comfort for many visual activities. Additionally, as expressed in the 2019 revision of the EU's Green Public Procurement Criteria for Road Lighting and Traffic Signals, obtrusive light is an important issue for wildlife (high insect mortality, disruption of the migration of birds) and human quality of life (sleep pattern disruption), as well as for astronomical observations.

CIE recognised the need for further work on this field and submitted two documents to EURAMET identifying a lack of traceable SI calibration, poor long-term stability, and inadequate relative spectral responsivity, as well as the need for the calibration and characterisation of HDR-cameras used for luminance distribution measurements.

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European Partnership Co-funded by the European Union

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

METROLOGY PARTNERSHIP EURAMET

The measurement of luminance distribution covers such a broad range of topics, that the diversity of stakeholders' sectors requiring reliable guidance for traceable HDR imaging luminance measurements is immense: (e.g. CIE, CEN, national metrological institutes (NMIs), designated institutes (DIs), ILMD manufacturers, scientific community, end-users of HDR imaging systems dealing with quantitative glare and obtrusive light evaluation and all the communities impacted by obtrusive light, glare and high-contrast luminance scenes).

It is necessary to make references available to characterise HDR imaging measurement systems, and to establish instruments' requirements to guarantee traceable HDR luminance measurements as well as to demonstrate the comparability of the results. The latter includes the characterisation of the stray light produced inside the camera. It is necessary to improve the estimation of the uncertainty by the proper evaluation of these sources of error. Existing HDR algorithms must be evaluated from a metrological point of view, in order to provide a recommendation, if not of a single HDR algorithm, at least of the requirements they need to fulfil for traceable luminance measurements and assessments of glare and obtrusive light. Finally, guidelines on the determination of uncertainty budgets for HDR luminance imaging measurements, as well as glare evaluation, are required to support European stakeholders and feed the work of standardisation bodies (e.g., CIE and CEN).

Objectives

The overall goal of this project is to enable the traceability and characterisation of HDR imaging luminance systems, and to support the standardisation of luminance distribution measurement methods, which are required for glare, light pollution, and other lighting assessments. This will involve developing HDR luminance standards required for the characterisation of HDR imaging measurement systems and developing metrics and guidelines for the determination of the associated uncertainties.

The specific objectives of the project are:

1. To develop luminance reference standards (i.e. sources) with high dynamic contrast pattern (covering at least 6 orders of magnitude) in order to characterise the dynamic range and spectral mismatch for different types of commercial instruments that are available for luminance distribution measurements (e.g. ILMD, RGB matrix sensor cameras). This should be based on the recommendations stated in CIE 232:2019 and CIE 244:2021 and allow the reliable assessment of glare and obtrusive light.
2. To model and verify HDR luminance measurements (including non-linearity, internal stray-light, and lens flare), with the objective of reproducibly determining the input data required for the models (average luminance, luminous surfaces, if required contrasts in the glare source, peripheral angle). To define the requirements for traceable instrumentation and to demonstrate the inter-comparability of HDR luminance measurements (in general and between different camera technologies), including the effect of its uncertainty on glare assessment.
3. To develop an algorithm for (i) generating an HDR-luminance image from a sequence of multiple raw images and (ii) enabling traceability of relative images scaled to one or a few traceable spot measurements of the scene.
4. To develop guidance on the determination of uncertainty budgets for HDR luminance imaging measurements of single pixels and integral values (e.g. evaluation region, illuminance) as well as glare evaluation, according to existing standards EN 17037:2019, EN 13201-2:2015 and EN 12464-1:2011. This should include a report on the relevance of existing quality indices and test methods regarding HDR imaging luminance systems.
5. To contribute to the standards development work of CIE TC 2-86, CIE TC 2-95, CIE TC 3-57, CIE TC 4-58, TC 8-18, CEN/TC 169, and the resumption and continuation of the work of CIE TC 2-59 and CIE TC 4-33 (both inactive), to ensure that the outputs of the project are aligned with their needs, communicated quickly to those developing the standards and to those who will use them (e.g. manufacturers of RGB sensors and cameras), and in a form that can be incorporated into the standards at the earliest opportunity.

Progress beyond the state of the art and results

This project builds on and will progress beyond different projects. In the EMPIR project 19NRM02 RevStdLED, the traceability of luminance imaging measurement devices is addressed. The general model of evaluation and uncertainty budget for luminance measurements will be picked up in this project as a foundation. However, RevStdLED aims to reduce its complexity for selected individual applications relevant to test laboratories, and namely does not consider RGB matrix cameras nor HDR imaging systems for which the uncertainty contributions will have different significances.

In the EMPIR project 18SIB03 BxDiff, HDR imaging systems are used for studying the relation of reflectance measurements at different scales, on texturized, structured and translucent materials. However, BxDiff does not address the standardisation of an HDR algorithm nor the development of a reference source with luminance contrast.

In the EMPIR project 20NRM01 MetTLM, the research regarding imaging devices focusses on spatial resolved temporal light modulation (TLM) measurement modes of luminaires and extended scenes, and vivid examples demonstrating its feasibility using ILMDs and RGB matrix cameras. In this context, high contrast luminance scenes or sources will be included in the targeted measurements. This project will gain from the experience gained in MetTLM and will collaborate on the HDR measurement of TLM sources.

High contrast reference luminance standard source of at least 6 orders of magnitude

In this project, a type of high contrast reference standard source of at least 6 orders of magnitude will be developed, which will include several luminance levels, simultaneously presenting about 0.1 cd/m² to about 100 kcd/m² or more, and a light trap of <0.01 cd/m². The luminance of the sources will be determined with an expanded uncertainty no larger than 1 % for the brightest source and no larger than 2 % for the dimmest one. This type of standard source will cover the needs for testing and characterisation of measurement systems with narrow and wide measurement fields via a modular design concept. It will be designed and developed to meet the requirements of luminance dynamic range for applications and measurement needs of the relevant standards and documents, like CIE 232:2019, CIE 150:2017.

Validation of HDR luminance measurements

Characterisation procedures using the reference luminance standard source and beyond will be developed. They will allow the validation of the assessment of glare and obtrusive light, and the metrological demonstration of the comparability of evaluations by different HDR imaging technologies. At least three types of HDR imaging measurement systems will be tested (ILMD, commercial DSLR, camera based on an RGB matrix sensor). The comparability of measurements by these device types will be investigated though laboratory and field tests using the characterised systems.

Harmonised HDR algorithm for traceable HDR luminance measurements

This project will go beyond the state of the art by developing a dedicated HDR algorithm which will include functionalities that are missing from existing algorithms (e.g. estimating the uncertainty by considering also contributions from external standards which are beyond intrinsic information, like pixel signal noise, and by minimising uncertainty based on such traceable information) and will serve the metrological needs of HDR imaging measurements, including the propagation of uncertainties. It will be implemented in source code that will be distributed under an open-source license.

Uncertainty estimation of HDR luminance measurements, propagation to glare and obtrusive light assessment, and relevance of existing quality indices

This project will develop a model and a good practice guide for the uncertainty propagation of luminance measurements and of glare and obtrusive light evaluation using HDR imaging systems. It will be developed using data from the characterisation of the investigated HDR imaging technologies and demonstrated with the newly developed reference standard source, and field measurements. The part of the model regarding the uncertainty propagation in glare and obtrusive light assessment will be validated using dedicated measurements in well documented lighting installations. The model will be directly implemented with the algorithm developed for HDR processing.

Outcomes and impact

Outcomes for industrial and other user communities

HDR imaging measurement systems have been used in industry for more than 30 years for production monitoring and for the generation of ray data from luminance images. Due to the missing traceability, they were only used to analyse relative changes between consecutive HDR measurements made under the same conditions. Traceability would make HDR measurements from different measurement systems and varying conditions comparable. Different end-users e.g. manufacturers of luminaires and ILMD manufacturers would benefit from this traceability by a more flexible application of HDR measurement systems. Authorities currently do not assess photometric glare neither from roadlights nor from workplace lighting during daylight nor from façade shading systems, although citizens often complain about inappropriate installations which produce discomfort to pedestrians and disturbing glare within properties and dwellings. On-site glare and obtrusive light evaluation cannot be accomplished by relative measurement and without standard procedures and affordable measurement devices. With the results of the project, it will be possible for the first time to ensure the reproducibility and comparability of these kind of measurements, even for non-standardised measurement geometries on site. To promote the uptake of the project outputs, the consortium will organise workshops for industrial stakeholders and end-users and promote these online, at standardisation meetings and via the stakeholder committee.

Outcomes for the metrology and scientific communities

This project will provide tools, in the form of guidelines, open design guides and open-source software, which are all necessary for the realisation of traceable measurements and for a proper assessment of uncertainty in the process of capturing, processing and combining a sequence of low dynamic range (LDR) images to an HDR luminance image, and of assessing glare and obtrusive light. These results will help NMIs to offer new characterisation services for HDR imaging luminance measurement systems and to develop activities for in-situ measurements of scenes requiring a glare or obtrusive light evaluation.
The project will also, for the first time, provide a metrological basis for scientific results to be comparable and reliable, in the field of glare assessment, where there is a lack of metrological considerations. Thanks to the procedures and recommendations developed for measuring high luminance contrasts, scientists will have the tools to improve device characterisation and to validate the traceability of their measurements. To support the adoption of these new tools, this project will provide hands-on training in the correct handling of HDR imaging luminance meters. To promote the uptake of the project outputs, the consortium will organise a workshop for the research community and promote this online, at standardisation meetings and via the stakeholder committee.

Outcomes for relevant standards

This project will provide input to upcoming standardisation. This will be achieved by participation and contribution to several technical committees of the CIE (e.g. CIE TC 2-62, TC 2-86, TC 2-95, TC 3-57, TC 4-58, TC 8 18, JTC 12). This will indirectly influence standards developed by other standardisation bodies, such as the International Organization for Standardization (ISO), the Comité Européen de Normalisation (CEN) and the International Electrotechnical Commission (IEC). The results of this normative research project will provide the necessary conditions for the application of the latest CIE reports e.g. CIE 244:2021. Research on glare and human vision strongly depends on the setup and characterisation of test scenes with extremely high and very low luminance levels at the same time. These scenes can only be measured and quantified via imaging systems that offer HDR functionality, yet not standardised nor metrologically validated. The known deviations are too large at the moment and critically not covered by corresponding uncertainty contributions. Only a correct classification and limit definition of different camera systems based on an associated uncertainty assessment will close this serious gap. With the results of the project, it will be possible to reproducibly test the existing glare assessment models for the first time, and make recommendations for their application. This is an elementary step towards effectively combating discomfort glare. Several current TCs of CIE will benefit from the results of this project, in particular those related to the work involving applications of ILMDs. For this reason, CIE was selected as the Chief Stakeholder. In addition, new TCs are expected to be proposed to exploit the scientific results of this project. For instance, the closed TC 4-33 (discomfort glare in road lighting) will be re-established in case the measurement procedure for average luminance and luminous area of a glare source is to be standardised. To promote the uptake of the project outputs by the standardisation community, the consortium will organise a dedicated CIE workshop under the CIE quadrennial event in 2023.

Longer-term economic, social and environmental impacts

Light pollution, obtrusive light and light emission are currently gaining enormous societal and political importance. The massive replacement of traditional lamps by LED-based light sources with much higher luminous efficacy often encounters rebound effects and, in the scope of obtrusive light, even backfires due to the enormous luminance of these new light sources. The massive insect mortality, the constantly increasing number of people suffering from low sleep quality, the climate protection-driven necessity to use light only where it is really needed - and to use high luminance points in connection with this - make a clear photometric characterisation of the outdoor lighting installations regarding their obtrusiveness and glare indispensable. However, this will only be possible when a measurement technology exists for such situations to be evaluated on site. Traditional spot luminance meters are completely unsuitable for today's LED luminaires to fulfil this task since they cannot sample the complex angular distribution, plurality, and the temporal and spatial character of the outdoor light scenes. The uptake of the results of this project will enable for the first time a metrologically-based field assessment of glare, which in the longer term will make possible to mitigate the future risks of inadequate evaluations of glary and obtrusive situations, and therefore will have a major impact mainly on public safety but also concerning environmental protection, biodiversity and visual comfort.

List of publications
n/a

This list is also available here: https://www.euramet.org/repository/research-publications-repository-link/

<table>
<tr><td colspan="2">Project start date and duration:</td><td colspan="2">01 October 2022, 36 months</td></tr>
<tr><td colspan="4">Coordinator: Johannes Ledig, PTB Tel: +49-531-5924120 E-mail: johannes.ledig@ptb.de
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<tr><td colspan="2">Chief Stakeholder Organisation:
International Commission on Illumination (CIE)</td><td colspan="2">Chief Stakeholder Contact: Kathryn Nield</td></tr>
<tr><td>Internal Beneficiaries:
1. PTB, Germany
2. Aalto, Finland
3. CMI, Czechia
4. CNAM, France
5. CSIC, Spain</td><td colspan="2">External Beneficiaries:
6. ICCS, Greece
7. TUB, Germany</td><td>Unfunded Beneficiaries:</td></tr>
<tr><td colspan="4">Associated Partners: 8. EPFL, Switzerland, 9. METAS, Switzerland</td></tr>
</table>

Publishable Summary for 21NRM02 Digital-IT
Metrology for digital substation instrumentation

Overview

Due to the wider use of decentralised renewable energy resources, future electrical power grids require real-time control and monitoring to ensure their stability under more challenging conditions. Digital substation solutions according to IEC 61850 and IEC 61869 are increasingly replacing analogue instrumentation which are approaching the end of their useful lifespan. To support the European electrical power industry, this project will provide the currently missing solutions for the calibration and timing of new types of digital substation instrumentation, e.g. sampled value (SV) enabled equipment such as stand-alone merging units (SAMUs), digital instrument transformers and instrument transformer measuring bridges. The project will also support IEC TC 38 'Instrument Transformers' in their work on the revision of the related standards, with the goal of proposing solutions for more precise measurements of digital substation instrumentation.

Need

The decarbonisation of energy systems has resulted in significant changes in electrical power grids, due to the wide-scale connection of decentralised renewable energy resources. Future electrical power grids need real-time capable control and monitoring systems to ensure stability under increasingly complex conditions, as well as metering systems, to ensure fair trading of electrical energy.

New standards in the IEC 61869 series (on instrument transformers) have helped to address the digital communication of new electronic instrument transformers, as well as SAMUs (which are digitisers for analogue instrument transformers). The IEC 61850 standard series (on communication protocols for intelligent electronic devices at electrical substations) is also under revision and adding new definitions for routable SV data in order to establish a truly real time wide area measurement system. These new standards have helped to boost the transition from traditional analogue instrumentation towards new digital substation instrumentation technology, both on transmission and on distribution level. However, to be able to fully support this change, standardisation bodies need to further develop their standards to include the metrological aspects of digital substation instrumentation.

Currently, there is a lack of calibration methods and metrological infrastructure for new digital substation instrumentation e.g. SV enabled equipment. Therefore, new metrology-level facilities are needed to be able to test and to validate the performance of such intelligent electronic devices (IEDs). Further to this, solutions for higher sampling rates and PTP timing required by the new standards (for digital substation instrumentation) need to be developed.

The importance of this topic and its needs have been highlighted in the European Network of Transmission System Operators for Electricity's (ENTSO-E) new "*Research, Development & Innovation Roadmap 2020 – 2030*", where digitalisation is one of the four structural trends identified as affecting the European power system of which '*digitally-enabled substations of the future*' are a critical part. In addition, IEC TC 38 has recognised digital substations as one of the emerging trends related standardisation in their Strategic Business Plan. Finally, EURAMET's European Metrology Network for Smart Electricity Grids (EMN SEG) has identified digital substations as one of the key priorities in their strategic research agenda.

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EURAMET. Neither the European Union nor the granting authority can be held responsible for them.

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

European Partnership Co-funded by the European Union

METROLOGY PARTNERSHIP EURAMET

Objectives

The overall goal of this project is to develop the metrology infrastructure for the traceable measurement and calibration of digital substation instrumentation (i.e. SV enabled equipment such as SAMUs, digital instrument transformers and instrument transformer measuring bridges).

The specific objectives of the project are:

1. To **develop and calibrate reference systems (hardware) for calibration of SV enabled equipment**, covering the new requirements of recently released IEC standards. To develop new hardware for traceable measurement of new data rates up to 96000 samples per second (SPS), for the related measurement bandwidth up to c. 40 kHz.
2. To **develop software for controlling the setups and handling of SV data streams** and develop new data processing and uncertainty estimation approaches for new data rates up to 96000 SPS.
3. To **develop communication and timing networks**, in participating laboratories, by creating ethernet networks that will transmit SV data and Precision Time Protocol (PTP)-based timing between commercial devices. To **establish a traceable link between PTP timing and 1PPS (One Pulse Per Second) reference pulse** with a target uncertainty of 100 ns.
4. To provide the data, methods, guidelines and recommendations, which are necessary for the calibration of SV enabled equipment, to IEC TC 38. To integrate the plans for future research activities on the European Metrology Network for Smart Electricity Grids (EMN SEG).
5. To contribute to the standards development work of the technical committee IEC TC 38. Outputs will be in a form that can be incorporated into future standards at the earliest opportunity and will be communicated through a variety of media to the standards community and to end users (equipment manufacturers, transmission system operators (TSO), distribution system operators (DSO), and customers).

Progress beyond the state of the art and results

Primary reference systems for calibration of SV enabled equipment

Steps towards developing the capability to calibrate SV enabled equipment were taken in the preceding 17IND06 FutureGrid II project. Basic calibrations of SV based equipment are now possible by some National Metrology Institutes (NMIs) using their SAMUs, however they are only for basic measurements like Root Mean Square (RMS) voltage and RMS current. In addition, traceable measurement services are limited mainly to low sampling rates (4 kSPS) using the 1PPS timing protocol.

This project will extend traceable calibration services to both higher sampling rates (14.4 kSPS and 96 kSPS) and to equipment working on the PTP timing protocol, as required by the new standards. Calibration services will also be developed and implemented at metrology beneficiaries that have so far been unable to calibrate digital instrument transformers or SAMUs.

Control and analysis software solutions for handling of SV streams

Algorithms for calculating parameters – e.g. RMS value, ratio error or phase displacement – are typically implemented as proprietary solutions in digital substation instrumentation and related test sets. However, their calibration methods have to rely on available SV data streams and separate reference algorithms, which are (i) currently unavailable and not standardised for all parameters under non-synchronous conditions or (ii) are not validated for new data sampling rates up to 96 kSPS.

This project will go beyond the state of the art by developing new data processing schemes and algorithms to accurately characterise the amplitudes, phases, and relevant power quality (PQ) related parameters with complete system-wide uncertainty estimation, thus providing a solid basis for traceable calibrations. All of the project's developed software will be collected and documented in a reference software package that can be used to support a comparison of developed data processing schemes and algorithms. This should enable NMIs and calibration laboratories to better meet end user needs in their transition to digital substations. The comparison results can also be used by standardisation bodies to recommend best validated data processing schemes and algorithms for their intended use.

Timing networks and calibration method for 1PPS to/from PTP time protocol conversion

Recently, some NMIs (including project beneficiaries VSL and VTT) have developed calibration setups, where the device under calibration uses 1PPS as a timing source and the phase encoded into its SV stream can be compared to the 1PPS pulse front. These reference calibration systems rely on determining the latency of the reference device front-end electronics and compensating for it to produce a 1PPS aligned SV data stream. Similar, commercial devices are required to do the same, as per IEC 61869-9 (Digital interface for instrument transformers) Annex 9B. Several methods for determining the required compensation parameters, and a robust implementation of reference and commercial systems already exist.

The 1PPS timing has been replaced by PTP timing protocol in the new versions of related standards. Therefore, this project will go beyond the current state of the art by developing best practices for the calibration of PTP slave device timing and for verifying leap second insertion in the timing networks. As the PTP timing quality will ultimately depend on all networking components relaying timing packets, the project's focus will not only be on slave devices, but also on master clocks and network switches.

Outcomes and impact

The outcomes of this project will benefit the electrical power industry including digital substation instrument manufacturers and grid operators. The project will also contribute to standards especially those associated with IEC TC 38.

Outcomes for industrial and other user communities

This project will improve, and extend, the current electrical power and energy metrology infrastructure to cover digital substation instrumentation in order to support the development and improvement of electrical distribution and transmission grids. Industrial end-users and stakeholders such as TSOs, DSOs and digital substation instrumentation manufacturers will benefit from project outcomes, such as (i) enhanced measurement capabilities for the dynamic characterisation of instrument transformers for PQ measurements, (ii) a metrological infrastructure for the calibration of SAMUs, (iii) reliable time synchronisation (e.g. transmission of SV data and PTP-based timing) between commercial devices, and (iv) new test systems for measuring SV-enabled instruments based on IEC 61850-9-2 (Communication networks and systems for power utility automation - 9-2: Specific communication service mapping (SCSM) - Sampled values over ISO/IEC 8802-3), such as energy meters and digital Phasor Measurement Units (PMU).

This project will directly liaise with industrial stakeholders via the formation of a stakeholder committee. This group will include representatives from TSOs and DSOs, test and calibration service providers, digital substation instrument manufacturers and standardisation organizations, and will help the project's results to directly impact such representatives.

In addition, this project will also produce and publish 2 good practice guides for end-users (such as digital substation instrument manufacturers, TSOs, DSOs):

- Good practice guide on the calibration of commercial SV enabled instrumentation with sampling rates up to 96 kSPS
- Good practice guide for the calibration of substation instrumentation using PTP timing, including a traceable link between PTP timing and 1PPS reference pulse with a target uncertainty of 100 ns.

Outcomes for the metrology and scientific communities

The project will develop new and demanding measuring techniques including several important additions and extensions to CMC statements. The power systems scientific community will benefit from these new or enhanced measurement capabilities in areas where scientific information has been scant or lacking. Major scientific impact will be provided via the publication of the key project results in peer review journals and via presentations at key conferences. The project will also host two workshops which are targeted to standardisation bodies (IEC, CENELEC) as well as industrial stakeholders (e.g. digital substation instrument manufacturers and TSOs), to foster uptake in these communities. The first workshop will summarise the progress during the first half of the project and will be used to gain feedback from stakeholders in order to guide the work on the second half of the project. The second workshop will present the final results from the project and will highlight the 2 good practise guides developed.

Close cooperation between the project's different types of beneficiaries i.e. from research institutes, digital substation instrument manufacturers and NMIs will also support the dissemination and uptake of its outcomes. The project outcomes will also be shared with the NMI community through the EURAMET Technical Committee for electricity and magnetism (TC-EM), in particular the EURAMET TC-EM “Power and Energy” subcommittee.

Finally, the project will provide output to the metrology and scientific communities, via the plans for future research activities in the EMN SEG strategic research agenda. The beneficiaries VSL, RISE and VTT will also contribute to via their participation in the associated 18NET03 SEG-Net project.

Outcomes for relevant standards

This project will generate important results on the development of a metrology infrastructure for the traceable measurement and calibration of digital substation instrumentation that will be very valuable to standardisation work within IEC TC 38, CENELEC TC 38, IEC TC 13, IEC TC 57, IEC TC 77A WG1, WG2 and WG9, IEC TC 38 WG37 and JWG 55, IEC TC 42, CIPM CCEM, EURAMET TC-EM and CIGRE JWG B5/D2.67. Liaison will be accomplished by members of the project, who are active within the respective committees. The beneficiaries who are members of corresponding technical committees will inform them about the results of this project and will endeavour to ensure they are incorporated in any updates to the standards or guidelines-

Longer-term economic, social and environmental impacts

This project supports the long-term transition of the European power grid from analogue to digital control. The use of next-generation instrument transformers and PMU equipped substations is the prerequisite for successful integration of wide-scale connection of decentralised renewable energy sources in the High Voltage (HV) distribution and transmission grid. These next generation digital substations will also help to ensure the stability of the European power grid. European power grids are under increasingly complex and challenging conditions due to the societal desire for the large-scale introduction of renewable energy sources. By supporting the stability of the grid, more electricity supplied by renewable energy sources can enter into Europe's energy supplies, meaning that less conventional carbon-rich electricity generation (i.e. coal), is required and less CO_2 emitted.

Reliable electrical delivery is also one of the key needs in modern society e.g. even our water supply depends on the supply of electricity. This means that when black-outs and brown-outs occur, they result in major costs and disruptions to society. HV transmission grids are crucial for the electricity grid infrastructure; however, the current electricity grid infrastructure is aging. The ageing of the first generation of instrumentation is already stressing the network and impacting the reliability of our daily electricity supply. This project will help support the reliability of Europe's electricity supply by through the implementation of new digital substation instrumentation and HV transmission grids.

The project's outcomes will also support the long-term competitiveness of the European electrical industry, in particular digital substation instrumentation manufacturers, by providing them with the metrology tools to unambiguously prove the quality of their equipment. High quality equipment is one of the prime selling points for European industry and should provide a decisive competitive advantage with respect to other lower-cost but lower-quality equipment.

List of publications

n/a

This list is also available here: https://www.euramet.org/repository/research-publications-repository-link/

Project start date and duration:	1 September 2022, 36 months	
Coordinator: Jari Hällström, VTT Project website address: -	Tel: +358 50 382 2127	E-mail: jari.hallstrom@vtt.fi
Chief Stakeholder Organisation: IEC TC 38	Chief Stakeholder Contact: Volker Leitloff	
Internal Beneficiaries: 1. VTT, Finland 2. CMI, Czechia 3. GUM, Poland 4. JV, Norway 5. Metrosert, Estonia 6. RISE, Sweden 7. SIQ, Slovenia 8. VSL, Netherlands	External Beneficiaries: 9. CIRCE, Spain 10. LeftRight, Slovenia 11. Lukasiewicz-ITR, Poland	Unfunded Beneficiaries: 12. OMICRON, Austria 13. Statnett, Norway

Publishable Summary for 21NRM03 MEWS
Metrology for emerging wireless standards

Overview

Complex wireless technologies underpin the Internet of Things (IoT) and fifth and sixth generation (5G and 6G) mobile networks. These 'new radio' technologies require improved underpinning normative wireless standards for their radio signals, systems, and the transmission environments used, and for the radio frequency exposures created. Current telecommunications sector challenges include a lack of accurate, fast, low-cost, and traceable methods for manufacturers to demonstrate that 5G/6G product verifications match customer specifications. This project will develop the practical and efficient measurement methods required to enable normative standards for wireless channels up to sub-THz, and for radio frequency exposure assessment to better match rapidly emerging radio technologies for 5G/6G products and system over-the-air testing.

Need

The digital economy and high bandwidth mobile communications are essential tools for wealth creation in Europe and will enable an estimated USD12.3 trillion of global economic output by 2035. As digital connectivity becomes more and more ubiquitous, and offers higher capacity, it will become the new 'lifeblood' of the digital economy and connected society with over 8.9 billion mobile subscriptions envisaged by 2025. Emerging wireless technologies with Gbps connectivity has the potential to improve communications for 100 million students, more than 70 million workers, almost 2 million doctors and more than 2.5 million patients in hospitals within the EU alone by 2025. For this to happen a robust measurement infrastructure for emerging wireless technologies needs to be developed and then incorporated into relevant normative standards, e.g. CENELEC, IEC, ETSI, and IEEE, so that telecommunications manufacturers can have confidence that ICT products meet customer specifications.

The European Digital Agenda is driving the exploitation of Information and Communication Technologies (ICTs) by fostering innovations and economic growth, with a crucial role being played by the European telecommunications industry in the development of emerging wireless technologies for IoT and 5G/6G mobile networks. The rollout of these networks and large-scale deployments of cellular IoT will lead to fundamental changes to our society, impacting not only consumer service, but also industries embarking on digital transformations. Metrology has a pivotal role to ensure product quality and end-user confidence, and ultimately to improve the competitiveness of European Industry.

With the increasing adoption of complex new radio signals and large-scale multi-antenna technologies at different radio frequency (RF) bands in emerging wireless systems, manufacturer product verifications have become very time consuming and involve complicated procedures and equipment, leading to high testing costs. International standards bodies (e.g. ETSI, 3GPP), the telecommunication industries and research communities are now actively seeking improved process control on New Radio Over the Air (NR OTA) methods (*Objective 1*). Also, sub-THz wireless radio propagation channel characterisation (*Objective 2*) is currently an active topic being studied by ITU and IEEE standard development organisations, but there is a need for real-world empirical measurement data to support this R&D advancement toward 6G definitions and new product development. Furthermore, there is no reliable method to measure the RF exposure of 5G new radio systems. Importantly, CENELEC, IEC and IEEE international standards are actively seeking improved process control for addressing the product testing time-burden issue when using current RF exposure assessment methods (*Objective 3*). Hence, there is an immediate need for NMI-level metrology research to improve measurement capabilities and to provide underpinning metrology to input to the relevant standards to support the

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The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

competitiveness of European industry. The work proposed in this project aligns with broader European visions, as outlined in the European Commission Strategy – e.g. “Digital Single Market”.

It is recognised that no single NMI has, or will have, the capability to deliver all the work in this project. Our strategy, therefore, is to bring together the EU’s leading NMIs and academics in this area to build capability across all the participants that fully aligns with stakeholder and standardisation measurement needs. This approach aligns with the European Partnership on Metrology’s goal of promoting collaborative research in the most demanding fields of industrial metrology by exceeding the current state of the art.

Objectives

The overall objective of the project is to develop practical and efficient traceable measurement and characterisation methods for use in the emerging wireless standards being developed by ETSI, CENELEC, ITU, 3GPP, IEC, IEEE and other related groups. The specific objectives of the project are:

1. To develop traceable cost-effective NR over-the-air measurements to 30 GHz for: (i) new radio over-the-air system performance evaluation of sub-6 GHz and mm-wave MIMO systems with consideration where feasible of RTS, MPAC and RC+CE based methods taking into account ETSI TR 38.827 requirements; (ii) new radio over-the-air RF parametric conformance measurements of sub-6 GHz MIMO and mm-wave massive-MIMO systems using selected power-related parameters (e.g. TRP, EIRP) with uncertainty evaluations with consideration where feasible of DFF, IFF, NF-FF, mid-field and RC methods taking into account ETSI TR 38.810 and TS 38.141-2 requirements. In addition, to evaluate the methods via international comparison exercises.
2. To characterise the complex real-world sub-THz wide-bandwidth radio propagation channel suitable for the planning of short/medium-range wireless communication and active services operating up to 750 GHz for practical realisation for 5G/6G communications by: (i) the development, and verification of three traceable channel sounding testbeds (operating up to 330 GHz, 550 GHz and 750 GHz respectively), (ii) the performance comparison of these testbeds with the results added to an open access database and (iii) the validation of the test beds via channel modelling, and potentially using novel approaches based on band stitching techniques and optical cable solutions.
3. To develop and evaluate measurement protocols to quantify RF exposure levels from 5G base stations based on measuring PD exposure and from 5G mobile phones in terms of SAR and Absorbed Power Density measurements, including traceability. This will include (i) developing a measurement methodology for measuring PD exposure levels of 5G new radio base stations for incorporation into Good Practice Guidance and for submission to, e.g. IEC 62232, and IEC 62669 for their consideration as an input to Technical Specifications and (ii) developing a standardised measurement procedure for the quantification of RF exposure in terms of SAR and Absorbed Power Density measurements of 5G new radio mobile phones suitable for submission to international standardisation bodies, e.g. CENELEC CLC/TC 106X, IEC TC106 MT3 and JWG12 for their consideration as an input to standards.
4. To contribute to the standards development work of the technical committees of the relevant standards developing organisations, e.g. CENELEC CLC/TC 106X, IEEE 802.15 SC THz, 3GPP and ETSI ISG mWT and to ensure that the outputs of the project are aligned with their measurement needs, communicate quickly to those developing the standards and to those who will use them (e.g. the telecommunications industry), and in a form that can be incorporated into the standards at the earliest opportunity.

Progress beyond the state of the art and results

Efficient over-the-air testing, and RF exposure measurements of 5G new radio systems with many advanced features, is needed to efficiently and cost effectively assess complex new radio system performance and product conformance to specifications. Also, new knowledge of wide bandwidth sub-THz radio propagation channel measurements for R&D advancement towards 6G definitions and new product development is needed. This project will address these by building on previous projects that included some preliminary 4G over the air studies at sub-6 GHz and 5G new radio signals at 30 GHz, respectively.

Traceable cost-effective NR over-the-air measurements to 30 GHz (Objective 1)

3GPP and ETSI have been working on the performance metrics, measurement methodologies, and validation procedure for the MIMO over the air evaluation of 5G new radio user equipment and base stations. For 5G new radio (NR) performance testing, only the multi-probe anechoic chamber (MPAC) and radiated two-stage (RTS) methods have been considered. In addition, for 5G new radio RF parametric conformance measurements, consideration is only given to direct far-field (DFF), indirect far-field (IFF) and near-field to far-field transformation (NF-FF) techniques. This project will develop a more efficient and cost-effective over-the-air radiated testing metrology for RF conformance metrics and end-to-end performance metrics for new radio systems at both sub-6 GHz and mm-wave bands (up to 30 GHz). By developing: validated RTS and RC+CE methods based on new calibration algorithms for new radio systems equipped with high-order MIMO in the sub-6 GHz band and 2×2 MIMO in the mm-wave band; the test zone channel validation algorithms required for mm-wave MPAC solutions; measurement methodologies and algorithms for RF radiation pattern measurement; corrections for the measurement deviations found in practical test environments based on effective calibration algorithms for retrieving the desired measurement results that meet 3GPP measurement requirements and mid-field solutions based on reduced size test systems.

Traceable sub-THz wide-bandwidth radio propagation channel measurements to 750 GHz for 6G (Objective 2)

The current state of the art for THz channel sounding is up to 330 GHz and it is limited to measurement scenarios with a very short measurement range i.e. to 1 m. There is still a lack of measurement-based knowledge of the characteristics of many typical real-world deployment scenarios e.g. indoor/outdoor at different sub-THz and mm-wave frequencies. This project will extend the state of the art by putting in place THz channel sounding up to 750 GHz for both indoor and outdoor environments. This will enable users in the wireless communication industry to characterise propagation channels at these very high frequencies. Recommendations on THz and mm-wave measurements will be made to relevant standardisation bodies and industry groups (e.g. IEEE 802.15 SC THz and ETSI ISG mWT). Novel approaches using band stitching techniques for wideband channel sounding, and optical cable solutions for measurement range extension, will also be explored as well as sub-THz channel modelling and validation.

Strategies to quantify RF exposure levels from 5G base stations based on measuring PD exposure and from 5G mobile phones in terms of SAR and Absorbed Power Density measurements (Objective 3)

The International Commission on Non-Ionizing Radiation Protection (ICNIRP) produced new guidelines in 2020. According to these guidelines, the physical quantity of interest for near field exposure radiation above 6 GHz is now the Absorbed Power Density in W/m^2, whereas for radiation below 6 GHz it remains the Specific Absorption Rate (SAR) in W/kg. Similarly, the physical quantity of interest for far field exposure radiation above 2 GHz is now the incident power density in W/m^2 whereas for far field exposure radiation below 2 GHz it is the incident E-field in V/m or the incident H-field in A/m. The procedure to determine the power density in a way that it is traceable to the SI system of units has yet to be developed. The conversion of E-field to power density requires an assumption of the proportionality of the H-field to the E-Field, which is only valid for pure plane waves as in far field. This conversion is therefore not applicable for near field radiation. The current state of the art for new radio RF exposure measurement is up to sub-6 GHz (under the EMPIR SIP 18SIP02 5GRFEX that includes an experiment-based RF exposure study of the stochastic nature of massive MIMO system at sub-6 GHz). This project will extend the state of the art by putting in place traceability for RF exposure measurements up to 26 GHz for 5G base stations, and for Absorbed Power Density (APD) measurements up to 40 GHz for 5G mobile phones. One of the novelties of 5G base stations compared to 4G is the highly dynamic behaviour of adaptive beams. Actual measurement methods for 2G, 3G and 4G are not able to predict correctly in this situation.

Outcomes and impact

Outcomes for industrial and other user communities

This project will enable efficient, accurate and traceable measurements covering all aspects from the new radio signals, systems, antennas, propagation environments and public exposure at a wide range of frequencies up to sub-THz. This will have direct outcomes on wireless communications and electronics industries by ensuring product quality and end-user confidence. Notable examples include virtual and augmented reality, autonomous driving, remote surgery, artificial intelligence, smart manufacturing, unmanned aerial vehicles (UAV), IoT and vehicle-to-everything.

The establishment of measurement traceability and the improvement of measurement accuracy will enable manufacturers to provide confidence in their specifications. This plays a key role in the customer/supplier relationships, for which products need to be demonstrated as 'meeting specification', regardless of who is carrying out the test or when/where the test is being performed. The outcomes of this project will allow emerging wireless product manufacturers to specify their products more precisely, leading to systems with better performance. This in turn will boost the product yields for the manufacturers and potentially reduce prices for customers as well as enhancing user experiences.

This project will achieve new measurement capabilities by extending the current capabilities of the participating NMIs, to 750 GHz for radio propagation, to 30 GHz for new radio over-the-air measurements and to 40 GHz for new radio RF exposure measurements. This will lead to greatly improved access to, and dissemination of, measurement traceability for European NMIs, accredited testing and calibration laboratories and the manufacturers of test instrumentation. This will be beneficial for all end-users, including customers and suppliers of emerging wireless devices and systems.

Outcomes for the metrology and scientific communities

This project involves five European NMIs with world-leading capabilities, along with five world-leading academic, and seven key industrial unfunded beneficiaries, who bring in their specific knowledge, and measurement instrumentation to these emerging technologies. Together these provide a strong coherent consortium that will enhance the quality of the research outputs and this will maximise the overall outcomes from the project. The outcome will be to propose changes to NMI calibration and measurement capabilities to provide the underpinning metrology that supports the European emerging wireless technology research effort and to keep the focus within Europe. During the lifetime of this project, preparatory tasks will be undertaken to subsequently establish a coordinated network of NMIs that will provide comprehensive measurement capability based on the scientific activities in this project, and, in other earlier and current European projects (specifically, previous EMRP).

Outcomes for relevant standards

The NMI-level metrology research performed in this project, will provide the underpinning metrology as input to the relevant standards in this area in order to support the competitiveness of European industry. The project outcomes will enable standard bodies to implement practical and the efficient measurement methods required to enable normative standards to better match rapidly emerging radio technologies, which was not previously possible. This project will make substantial contributions to the following international standards and related documents:

(i) International standards developed by ETSI/3GPP: TS 38.141-2, TS 38.151, TS 38.161, TS 38.521-1, TS 521-2, TS 521-4

(ii) International standards developed by IEEE: IEEE 802.15.3d, IEEE 1720

(iii) International standards developed by IEC: IEC TC106 MT3 and JWG12

(iv) International standards developed by CENELEC: CLC/TC 106X

(v) International standards developed by ITU: ITU-R IMT-2020, ITU-R SM.2352, ITU-T SG5

This project will also have indirect outcomes on the European standards being developed by the European Telecommunications Standards Institute (ETSI) through 3GPP. These include 3GPP TR 38.827, 3GPP TR 38.810, 3GPP TR 37.842, 3GPP TS 38.101-1, 3GPP TS 38.101-2, 3GPP TS 38.101-4, 3GPP TS 38.104, 3GPP TS 38.141-2, ETSI EN 302 686 and ETSI EN 302 550. Progress and output from this project will be disseminated to the above standards bodies and committees, via representatives in the consortium who are involved in these standards bodies.

Longer-term economic, social and environmental impacts

<u>Economic:</u> The digital economy, and high bandwidth mobile communication, are essential tools for wealth creation in Europe. Digitisation of products and services has a significant economic impact, with more than 110 B€ extra revenue added to industry per year in Europe. To date, over 80 % of Europeans have a mobile phone and 50 % a smartphone. 315 million Europeans use the internet every day. These figures are constantly growing and have been illustrated by a demand-led compound data growth rate of 40 % per year. The measurement science generated by this project will pave the way for the development of emerging applications using the future generation wireless network including virtual and augmented reality, autonomous driving, remote surgery, smart manufacturing, UAV, IoT, Vehicle-to-Everything and security imaging. This will enable European businesses to move into these areas with confidence and it will ensure a strong competitive advantage over organisations outside the European region, and it will attract business from global markets.

Health and Social Care: The impact of emerging wireless technologies will extend well beyond telecommunications, and it is increasingly underpinning all aspects of health and social care activities. This will lead to fundamental changes to our society, impacting not only consumer service, but also industries embarking on digital transformations. It is envisaged to provide a universal communication environment that enables us to address the wider societal challenges, such as transport, automotive, safety, employment, health, environment, energy, manufacturing and food production. Furthermore, rigorous scientific evidence on RF exposure issues will enable effective wireless system deployment to be supported that balances user experience and public safety.

Environment: Space radiometers play a key role in Earth monitoring, which provides information about global climate change and weather forecasting. This project will facilitate more accurate and traceable measurements at millimetre-wave and terahertz frequencies, yielding radiometers with better performance. The energy efficiency of systems will also be improved as a result of more accurate measurements. The average electromagnetic radiation intensity has been steadily increasing, fuelled by the evolution of wireless communications for applications like IoT, 5G and beyond. To reduce the impact of electromagnetic fields on the environment, it is therefore important to decrease the transmitted power of wireless communication systems and to measure power density as precise as possible, which this project will underpin.

List of publications
n/a

This list is also available here: https://www.euramet.org/repository/research-publications-repository-link/

Project start date and duration:	1 October 2022, 36 months	
Coordinator: Djamel Allal, LNE Tel: +33 1 30 69 21 50 E-mail: Djamel.Allal@lne.fr Project website address:		
Chief Stakeholder Organisation: CENELEC	Chief Stakeholder Contact: Matthias Meier	
Internal Beneficiaries: 1. LNE, France 2. CMI, Czechia 3. RISE, Sweden	External Beneficiaries: 4. AAU, Denmark 5. IMTelecom, France	Unfunded Beneficiaries: 6. Anritsu AU, Austria 7. Keysight BE, Belgium 8. MVG, Italy 9. NNF, France 10.ZTE AB, Sweden
Associated Partners: 11. BJTU, China 12. CAICT, China 13. METAS, Switzerland 14. NPL, United Kingdom 15. QMUL, United Kingdom 16. SPEAG, Switzerland 17. SURREY, United Kingdom		

Publishable Summary for 21NRM04 BiometCAP
Protocol for SI-traceable validation of methods for biomethane conformity assessment

Overview

The conformity assessment of biomethane requires further standardisation in order to support Europe's green energy future. The overall EU target for Renewable Energy Sources consumption by 2030 has been raised to 32 % in the RED II directive [Directive (EU) 2018/2001, 2018]. This project will deliver accessible traceability to the stakeholder community by developing efficient and cost-effective methods for the preparation of traceable gas transfer standards for the performance evaluation of biomethane monitoring systems. Using these, a robust performance assessment protocol will be developed and validated in order to benchmark and characterise analytical systems (e.g. gas analysers). The outputs, including trial applications, will be directly fed into standardisation development. This project will bridge the gap between previously developed primary standards and the industry's need for accessible, traceable performance evaluation against a validated protocol.

Need

Biomethane is already used widely within Europe as a means to sustainably displace fossil fuels. Its usage is projected to increase significantly (doubling by 2030 from the current 26 Terawatt-hour (TWh) produced in Europe) [EBA "European Biogas Association Statistical Report: 2019 European Overview", 2020] as a result of European green energy targets [European Commission, A European Green Deal, 2019]. Biomethane quality monitoring is essential to prevent damage to the existing natural gas infrastructure and to end user appliances that can be caused by harmful impurities in biomethane. In addition, these impurities need to be kept below limit thresholds (as specified in EN 16723 for gas grids [EN 16723 1 Natural gas and biomethane for use in transport and biomethane for injection in the natural gas network Part 1: Specifications for biomethane for injection in the natural gas network, 2016] and vehicles [EN 16723 2 Natural gas and biomethane for use in transport and biomethane for injection in the natural gas network Part 2: Automotive fuel specifications, 2017]).

Reliable and traceable purity measurements can only be obtained with equipment of known performance, from which the sensitivity, selectivity, precision and bias have been traceably evaluated (as required under e.g. ISO/IEC 17025 §7.2 [ISO/IEC 17025, Testing and Calibration Laboratories, 2017]) (Objective 3). Instrument manufacturers and end users require a standardised protocol (Objective 2) in order to meaningfully demonstrate instrument performance in both laboratory and field settings. Despite similar approaches existing for other green fuels, e.g. hydrogen in the form of ISO 21087 [ISO 21087 Gas analysis — Analytical methods for hydrogen fuel — Proton exchange membrane (PEM) fuel cell applications for road vehicles, 2019], a suitable biomethane evaluation protocol does not yet exist.

An additional challenge is bias prevention, as existing measurement methods (e.g. as developed in EMPIR JRP 16ENG05 Biomethane) have not been traceably tested for cross-interference bias caused by gas matrix and impurity variation. This type of selectivity evaluation is essential to prevent bias in reported results, to prevent interruptions in the supply of biomethane into the European gas infrastructure (caused by over-reporting), and to prevent damage to infrastructure (caused by under-reporting).

To deliver this on a practical level, cost effective transfer standards need to be developed to disseminate traceability from the primary standards in an accessible format for the biomethane industry, which includes many small-scale producers (Objective 1). These transfer standards need to be fit-for-purpose in terms of measurement uncertainty (≤10 %) and shelf life (≥12 months). Improving accessibility to gas standards and a

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European Partnership Co-funded by the European Union

METROLOGY PARTNERSHIP EURAMET

validated protocol for their application will allow for a safe and effective expansion of the biomethane industry within Europe.

Objectives

The overall objective of this project is to support the development of standardisation and to provide the traceability, reliability and characterisation necessary for the conformity assessment of biomethane.

The specific objectives of the project are:

1. To develop and validate methods for the static and dynamic preparation of gas transfer standards containing different groups of impurities. These should be suitable for use in the SI-traceable validation and performance evaluation of current and future analytical instruments and methods that are used in the conformity assessment of biomethane in accordance with EN 16723. In addition, this should include determining the key metrological parameters of each method. Uncertainties of 1 % - 10 % are targeted for EN 16723 limit values.
2. To develop a comprehensive protocol for the validation and performance evaluation of the analytical instruments and methods that are used in the conformity assessment of biomethane (applicable to both current and future methods). The validated and implemented methods should be able to generate reproducible and SI-traceable measurement results and a NWIP and draft ISO text should be submitted to ISO.
3. To use the protocol, developed in objective 2, to evaluate the performance of commercially available industrial gas analysers, based on e.g. spectroscopy or gas chromatography, which are used for laboratory and field-based biomethane (test) measurements. The protocol should also be used to evaluate all relevant measurement methods. A review will be undertaken to evaluate its effectiveness and reproducibility across a wide variety of methods and compounds.
4. To maintain constant contact with the EMN for Energy Gases and collaborate with the technical committee ISO/TC193/SC1/WG25 "Biomethane" and the users of the standards they develop to ensure that the outputs of the project are aligned with their needs and are incorporated into future standards at the earliest opportunity and that user training and knowledge transfer is maximised throughout the project. This will include, in particular, the protocol developed in objective 2.

Progress beyond the state of the art and results

To develop and validate methods for the static and dynamic preparation of gas transfer standards containing different groups of impurities. These should be suitable for use in the SI-traceable validation and performance evaluation of current and future analytical instruments and methods that are used in the conformity assessment of biomethane in accordance with EN 16723. In addition, this should include determining the key metrological parameters of each method. Uncertainties of 1 % - 10 % are targeted for EN 16723 limit values. (Objective 1)

This project will develop novel, cost effective solutions in the form of multi-component gas standards and improved dynamic methods for the preparation of gas transfer standards, with a focus on the impurities and limit levels specified in EN 16723. This cost-effective approach will allow laboratories to perform verification, validation and quality control as required by, e.g. ISO/IEC 17025, with reduced and affordable costs, thus increasing access to traceability for the industry. These standards will also resolve the issue of some standards not being available for field use on biomethane sites due to their complexity, non-portability and cost.

Novel cost-effective standards will also be developed for the evaluation of the effects of the variable biomethane gas matrix and cross-interferences caused by impurities simultaneously present in biomethane. This project is the first research project addressing this issue in full and the project's output will help to secure the reliability of the analytical measurements of the impurities in biomethane, avoiding biases that are commonplace (e.g. terpenes/siloxane interferences via certain GC methods and methane interference with certain spectroscopic methods).

To develop a comprehensive protocol for the validation and performance evaluation of the analytical instruments and methods that are used in the conformity assessment of biomethane (applicable to both current and future methods). The validated and implemented methods should be able to generate reproducible and SI-traceable measurement results and a NWIP and draft ISO text should be submitted to ISO. (Objective 2)

Currently, gas analysers for biogas and biomethane applications cannot be reliably evaluated for performance. ISO 10723 [ISO 10723, Natural gas — Performance evaluation for analytical systems, 2012] describes the performance evaluation for analytical systems for natural gas composition, and ISO 21087 is in place for hydrogen applications, however methods and protocols for biogas and biomethane applications still need to be developed. This project will develop a robust protocol for the sampling, analysis and performance evaluation of analytical instruments (gas analysers) and methods that are used for biomethane conformity assessment. The protocol will be designed to be suitable for current and future measurement techniques.

To use the protocol, developed in objective 2, to evaluate the performance of commercially available industrial gas analysers, based on e.g. spectroscopy or gas chromatography, which are used for laboratory and field-based biomethane (test) measurements. The protocol should also be used to evaluate all relevant measurement methods. A review will be undertaken to evaluate its effectiveness and reproducibility across a wide variety of methods and compounds. (Objective 3)

The performance assessment protocol will be validated using lab-based analysers, and traceably validated methods that were previously developed as part of targeted research (e.g. EMRP JRP ENG54 Biogas, EMPIR JRP 16ENG05 Biomethane). The application of the performance assessment protocol will then be expanded to industrial analysers and a review will be undertaken of the results of its application, comparing the variables of location, analyte and technique in order to produce a good practice guide for the repeatable and accurate implementation of the performance assessment protocol. Such a comparison has not been undertaken for the biomethane industry and the results will provide a valuable route for more solutions to enter the market and for stakeholder knowledge to be enhanced.

Outcomes and impact

Outcomes for industrial and other user communities

By gaining an insight into the user communities measurement needs, the project's outcomes will enable fit-for-purpose biomethane conformity assessment measurement services to be provided to industries, testing laboratories, research organisations and other end-users. Such services will include: a) calibration gas mixtures b) calibration and measurement facilities and services c) performance evaluation of gas analysers; d) direct characterisation of biomethane quality in the field; e) proficiency testing; f) consultancy and g) training. Use of the good practice guide produced by the project will allow end users to have an accessible format to refer to for use with biomethane conformity testing, thus allowing the project's outcomes to be shared. Accreditation can be sought against e.g. ISO 17025.

Instrument (e.g. gas analysers) and sensor manufacturers will receive access to a performance assessment protocol which they can use to benchmark their products and use during the product development process as a means of quality control. Their customers will be able to utilise the performance assessment protocol for their own quality control checks when e.g. developing and characterising methods.

Biomethane producers will be able to use the performance assessment protocol in combination with transfer standards and training material outputs to repeatably and accurately quantify analyser performance, which will reduce the opportunity for measurement bias and improve the efficiency of biomethane production. This will ensure that they meet the quality assurance requirements of e.g. national regulations.

As outlined above, it is anticipated that a major outcome of this project will be the widespread uptake and use of the biomethane performance assessment protocol for biomethane conformity assessment throughout Europe and globally. Another outcome will be the increase in new industrial products and services for biomethane quality monitoring using the new solutions developed in this project (e.g. traceably validated industrial biomethane measurement systems as validated within this project).

Outcomes for the metrology and scientific communities

Laboratories, research organisations and academia will be able to use the state-of-the-art gas transfer standards and the performance assessment protocol developed within this project to perform further research within the biomethane purity area to support the development of new biomethane measurement technologies. Using the outcomes from this project, their performance will be able to be traceably quantified to the SI.

Metrology institutes will have new capability in the form of gas transfer standards and a performance assessment protocol by which to evaluate further techniques and methods they wish to develop within the biomethane area for research and delivery of measurement services to industry. This knowledge will be transferred from the experienced to the less experienced metrology institutes.

Outcomes for relevant standards

The project's outputs will provide direct input to ISO/TC193/SC1/WG25 "Biomethane" by providing them with a validated protocol for the sampling, analysis and performance evaluation of gas analysers. The results of the performance evaluation of the industrial gas analysers will give a realistic overview of (industrial) measurement capabilities, which will allow standards to be tailored to the real needs of industry and it will promote their widespread uptake. The protocol and method developed for the performance evaluation of gas analysers will be submitted to ISO/TC193/SC1/WG25 for consideration as a new ISO standard (in the form of a New Work Item Proposal (NWIP) and draft ISO standard text). The results obtained from the project will also be disseminated to CEN to enable it to update EN 16723 under its mandate M/475.

The project will also provide input to the activities of other committees, such as ISO/TC158, CEN/TC408, BIPM CCQM Gas Analysis Working Group (GAWG), EURAMET/Metchem SC-GAS, and national working groups and mirror committees.

Longer-term economic, social and environmental impacts

In the longer term, the project's outputs will enable fit-for-purpose services to be provided to industries, testing laboratories, research organisations and other end-users. End users will be able to verify the performance of their measurement equipment with a validated protocol using the developed gas transfer standards. The need for fewer gas transfer standards will significantly lower the cost of biomethane conformity assessment, making biomethane production cost-effective for small producers. These service receivers will be able to undertake e.g. SI-traceable calibrations of equipment and the calibration of gas mixtures, to improve the quality of their measurement results, and they will be able to use traceable and cost-effective gas transfer standards for measuring impurities in biogas and biomethane.

The accurate measurement of trace-level toxic impurities in biomethane will, in the longer term, ensure that regulations limiting the contents of these compounds to safe (non-toxic) levels can be enforced robustly.

This project will accelerate the increased use of biomethane and upgraded biogas and it will enrich the European natural gas supply chains. Therefore, it will also help to reduce Europe's dependence on natural gas imports and it will promote the realisation of the EU target on Renewable Energy.

Increased use of biomethane will help reduce emissions of greenhouse gases and reliance on fossil fuels, as biomethane is produced from renewable sources, such as organic waste, landfills, pulp sludge or manure. Its use in road vehicles will significantly limit harmful emissions. This project will assist the EU in moving towards solving the major global problem of decarbonisation.

List of publications

n/a

This list is also available here: https://www.euramet.org/repository/research-publications-repository-link/

Project start date and duration:		1 October 2022, 36 months
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Chief Stakeholder Organisation: Institute for Energy Technology (IFE)		Chief Stakeholder Contact: Fred Martin Kaaby
Internal Beneficiaries: 1. RISE, Sweden 2. BFKH, Hungary 3. CMI, Czechia 4. IMBiH, Bosnia and Herzegovina 5. PTB, Germany 6. TUBITAK, Türkiye 7. VSL, Netherlands 8. VTT, Finland	External Beneficiaries: 9. DTU, Denmark 10. GERG, Belgium 11. TFS, Germany	Unfunded Beneficiaries:
Associated Partners: 12. NPL, United Kingdom		

Publishable Summary for 21NRM05 STASIS
Standardisation for safe implant scanning in MRI

Overview

Magnetic resonance imaging (MRI) is the gold standard for medical diagnostics with more than 40 million MRI scans performed in the European Union (EU) every year. Whereas this number is further increasing, scanning of patients with implants still poses a safety hazard. Even though international standards exist to address these risks, improvements are urgently needed and called for by implant manufacturers, Magnetic Resonance (MR) manufacturers and convenors of MR safety standards. This project aims at updating and improving the relevant standards providing clinicians with more confidence when scanning their patients, and implant and MRI systems manufacturers with novel methods to implement safety strategies for safe implant scanning.

Need

Medical implants are a 3 billion € market in the EU, with approximately 50 million citizens carrying one or more. Implants can be generally categorised into active implantable medical devices (AIMDs) or passive implants. Active implants (e.g, neurostimulators, cardiac pacemakers, implanted infusion pumps or internal defibrillators) require power to operate and have embedded electronic circuits that fulfill a specific function. Passive implants (e.g. hip or knee prostheses, stents, aneurysm clips or screws) do not require an external power source.

Due to comorbidity effects, 60- to 80-year-old have the highest probability of both needing an implant and an MRI. With an aging population, these numbers are likely to further increase. Metallic implants in a patient's body are a safety hazard in MRI, since interaction of the conductive device with the MR scanner's strong electromagnetic fields can result in dangerous tissue heating. Demonstrating compliance with MRI safety, in particular with respect to heating effects, is a challenging process with high product liability risks for implant manufacturers.

At present, regulators assess MRI compliance based on i) *in silico* test results, ii) knowledge of the expected electromagnetic fields in the patient body, and iii) history of the MR safety of similar products in service. But this is not based on quantified *in vivo* data, and it does not establish the risk to the patients. As a consequence, device manufacturers are unable to readily determine whether their device will be compliant prior to submission to the regulator. Therefore, future 'smart' implant technologies for medical and non-medical use are needed. 'Smart' AIMDs equipped with simple, small, and cost-effective sensors, could communicate with a parallel transmission (pTx) capable MRI scanner. It has been demonstrated that pTx is capable of steering radiofrequency (RF) electric fields away from the implant, thus substantially reducing hazardous tissue heating, still maintaining the imaging quality at a level comparable to the implant-free case. Additionally, because the EU's Medical Device Regulation (MDR) demands that medical implants and MRI scanners adhere to harmonised standards, improvements to such devices will only have a tangible impact once incorporated into standards.

Heating of bulky metallic passive implants due to MRI switched gradient fields demonstrated, in some cases, to exceed RF induced heating posing an often-unrecognised hazard for implant carriers. Some normative documents, e.g. ASTM F2182 ignore this effect completely, while others, e.g. ISO/TS 10974 are limited in scope just to those implant categories where that effect is least relevant. Therefore, a dedicated methodology must be developed to address this issue.

At an international stakeholder workshop organised by the predecessor EMPIR project 17IND01 MIMAS, convenors and chief representatives for the three most relevant standards on implant safety in MRI (ASTM

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The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

F2182, ISO/TS 10974, and IEC 60601-2-33) expressed the need for further work on a metrologically sound assessment of all uncertainties and risks associated with implant safety in MRI; development and documentation of standardisation-compatible test procedures; open-source hardware, design concepts and ideally prototypes of suitable testing hardware; as well as guidelines for *in vitro* testing of gradient-induced heating of medical implants.

Objectives

The overall objective of the project is to support standardisation for safety assessment of medical implants in MRI scanners. Medical implants can refer to passive implants (e.g., orthopaedic prostheses) or active implants (e.g., cardiac pacemakers or deep brain stimulators). Specific objectives are:

1. To develop, evaluate and explore the uncertainty (maximum tip E-field, SAR or temperature) of an implant safety concept in MRI comprised of sensor-equipped smart medical implants (e.g., pacemakers or neurostimulators) and pTx capable MRI scanners to assess and mitigate *in situ* RF induced implant heating. In addition, to formulate technical specifications for sensor-equipped smart medical implants and a communication interface between such implants and an MRI scanner.
2. To develop open-source reference hardware and traceable measurement procedures that allow testing of implants (mainly active) under pTx MR conditions. In addition, to develop, design and build a preliminary version of an open-source reference system of a pTx body coil and RF transmission hardware, suitable for offline implant testing by manufacturers and test houses.
3. To develop standardised measurement procedures for the interaction of bulky passive metallic implants with RF fields and alternating gradient coil magnetic fields in the kHz range. In addition, to provide guidelines and technical specifications for comprehensive *in vitro* testing of gradient-induced heating of such implants.
4. To contribute to the standards development work of ISO 10974, ASTM F2182 and IEC 60601-2-33 to ensure that project outputs are aligned with the needs of these bodies, communicated quickly to those developing the standards and to those who will use them (MRI and implant manufacturers, test houses) and in a form that can be incorporated into the standards at the earliest opportunity.

Progress beyond the state of the art and results

From an MR safety perspective, RF induced heating on AIMDs is mostly restricted to the problem of tip heating of an elongated lead connected to an electronic casing. Safety assessment is currently performed based on ISO 10974, which is limited to 1.5 T and applies a four-tiered approach, where the tiers represent different levels of complexity and accuracy. The highest level (Tier-4) with the lowest safety margins is based on extensive simulations and so far is only conceptual with low practical value. The complexity stems from unpredictable complex lead trajectories and from changes between different RF field exposures on the implant that are influenced by patient anatomy, patient position and RF field distribution produced by an RF coil. An improved approach to MR safety, that derives in-situ patient-specific information on an RF heating threat, requires sensors embedded in an AIMD. In EMPIR project 17IND01 MIMAS, it was demonstrated that this is potentially feasible by using small and affordable RMS sensors, which can be used to detect and mitigate an RF heating threat on-the-fly, maintaining the image quality. In this project, those preliminary results will be translated into a novel safety concept of smart medical implants that communicate with an MR scanner to detect and mitigate an RF heating threat. Metrologically sound calibration procedures for sensor equipped implants and a communication workflow will be elaborated. A virtual test environment to determine safety relevant parameters will be developed alongside open-source reference hardware (generic wireless implant, implant leads, calibration setup, pTx RF coil and RF transmission chain) for implant safety testing.

While RF induced heating of passive implants is substantially covered by current standards (ASTM F2182 and ISO 10974), gradient-coil induced heating is an underestimated risk. This was demonstrated in EMPIR project 17IND01 MIMAS and needs to be reflected into standardisation documents. In this project, simple safety testing procedures following a Tier 1 and Tier 2 approach will be developed aiming at extending the metrics adopted in ISO/TS 10974. Furthermore, investigations will study the conditions under which RF and gradient-coil heating can be considered totally independent or where a superposition is found to be significant and needs to be considered in safety testing of implants. As a result of this project, a standard draft (working item) will be presented to ASTM 2182 on gradient-coil induced heating of bulky passive implants.

Objective 1: To develop, evaluate, and explore the uncertainty of an implant safety concept in MRI comprised of sensor-equipped smart medical implants and pTx capable MRI scanner to assess and mitigate in situ RF induced implant heating. In addition, to formulate technical specifications for sensor-equipped smart medical implants and a communication interface between such implants and an MRI scanner.

Safety testing of active implantable medical devices for MRI largely relies on offline testing as described in ISO/TS 10974, where a four-tiered approach is prescribed. The least conservative margins are found within Tier 4, which utilises full electromagnetic field (EMF) simulations of the implant model in human body models. Except for very simple implants, the Tier 4 approach is very demanding and rarely applied in practice due to its complexity and computational costs. By embedding a sensor in an implant, *in situ* measurements enable safety related monitoring and on-the-fly adjustments of the RF pulses transmit by an MRI system. In such a scenario, safety testing could be dramatically reduced to simpler methods at lower conservative safety margins, allowing for better imaging quality or speed. Most high- and ultrahigh field ($B_0 \geq 3.0$T) systems are already pTx capable. These smart implants can communicate with the MR system in a way that allows to mitigate the heating risk in a single or even in multiple implants, and it is not covered in current standardisation or guidance documents. This requires the development of metrologically sound sensor calibration procedures, the development of a virtual test environment, open-source generic implants and implant leads for reference safety testing and a communication strategy between an implant and an MRI scanner, which will be implemented in the project.

Objective 2: Develop open-source reference hardware and traceable measurement procedures that allow testing of implants (mainly active ones) under pTx MR conditions. In addition, to develop, design and build a preliminary version of an open-source reference system of a pTx body coil and RF transmission hardware, suitable for offline implant testing by manufacturers and test houses.

In order to execute this novel sensor-based safety concept, simple and rigorous testing procedures for MR manufacturers, implant manufacturers and test houses are required. A pTx RF exposure testbed will therefore be developed and published as open-source hardware, thus facilitating dissemination to all stakeholder groups. The RF exposure system consists of a multi-channel RF coil, an exciter, modulators, RF power amplifiers and dedicated open-source software for control. This setup, together with the testing procedures and sensor calibrations developed for the sensor-embedded implants, facilitates MRI safety testing and electromagnetic compatibility testing of medical implants according to ISO 10974. Simultaneously, it will allow general testing of parallel transmission hardware and a systematic investigation of pTx specific RF safety issues, which are important open topics in forthcoming amendments of IEC 60601-2-33.

Objective 3: Develop standardised measurement procedures for the interaction of bulky metallic implants with RF and alternating gradient coil magnetic fields in the kHz range. In addition, to provide guidelines and technical specifications for comprehensive in vitro testing of gradient-induced heating of such implants

Previous investigations demonstrated that in certain cases the gradient-induced heating of an implant during an MRI scan can be even more hazardous for the patient than RF induced heating. For active implants some guidance exists in the ISO/TS 10974 to test gradient coil (GC) heating of implants; however, this methodology needs further extensions. At the same time, the ASTM F2182 standard, which is widely adopted for safety testing of passive metallic implants, does not provide any guidance at all. Standardisation convenors have urged for more research to fill these critical gaps, and in response the project will develop a two-tiered testing approach. Test houses will be provided with validated and efficient procedures to assess gradient induced heating of implants. A standard draft for testing of gradient magnetic field induced heating on or near metallic implants will be developed and submitted to ASTM. In addition, the simultaneous exposure of implants to switched gradient and RF fields will be investigated extensively in numerical simulations to identify and inform the community about high-risk scenarios.

Outcomes and impact

Outcomes for industrial and other user communities

Currently, regulators accept and approve applications from implant manufacturers about the MRI safety of their devices according to ISO/TS 10974 and ASTM F2182, despite the recognised gaps in its methodology. Guidance does not exist for the assessment of combined RF and gradient-induced heating in terms of its impact on risk assessment. This project will close these gaps by providing validated procedures for assessing implant safety. An updated standard will exist reducing the legal risks for the manufacturers. This will greatly impact both the European implant industry and regulators with respect to potential liability claims. In addition, the reduction of the uncertainty of the evaluation protocol will reduce manufacturer design costs.

New implant manufacturers with small but innovative product portfolios can particularly benefit from project outcomes. By incorporating suitable hazard sensors already at the early design stage of their MR compatible products, they can create a unique selling point by being among the first vendors offering such forward-looking technology.

The long-established and close communication of consortium members with European MRI manufacturers will facilitate the longer-term uptake of project results on patient-specific sensor feedback and active hazard mitigation. This will result in a market advantage by providing MRI scanners with improved diagnostic capabilities at lower risk. It will furthermore help to guarantee safe and diagnostic imaging capabilities, even when multiple implants are present, which is to be expected with an aging population and technologically fast advancing medical implant market.

To promote the uptake of the project outcomes by the industrial and other user communities, the consortium will invite members of these communities to participate in the stakeholder committee, to help steer the project, and in the final workshop. Additionally, the consortium will communicate the project’s results through scientific publications as well as in press releases, newsletters, social media, and other channels of communication.

Outcomes for the metrology and scientific communities

This project will develop procedures for implant safety assessments, based on validated simulations and a sound rationale for RF and gradient heating of bulky implants. Such testing will become a new service to be offered by calibration and verification offices accredited for dielectric measurements and electro-magnetic field measurements inside materials (for both the low-frequency and the radio-frequency range). The traceability for this new business will in turn be provided by the national metrology institutes (NMI) with their newly expanded measurement capabilities.

In the longer term, the knowledge obtained by the participating NMIs will be transferred to less experienced ones, due to the presence of implant manufacturers in these countries and the applied open-source practices in this project. The competitiveness of EURAMET members will be further increased with respect to NMIs outside Europe, since there are many implant manufacturers with a large market share outside Europe. Consequently, European NMIs will increase their revenue and reduce the expenses of European manufacturers.

The scientific community will learn about the newly developed methodologies through relevant journal publications and conference presentations. The research community on MRI safety will learn about the project’s findings and extend them by their own research. Additionally, to promote uptake by professional societies, the consortium will invite these to participate in the stakeholder workshop and communicate the project’s results in press releases, newsletters, social media, and other channels of communication. Most importantly, the International Society for Magnetic Resonance in Medicine (ISMRM) and its sister organisation the International Society for MR Radiographers and Technologists (ISMRT, formerly SMRT), will be involved to help to further disseminate the project outcomes via their Study Group and Committee on MR Safety.

Outcomes for relevant standards

The ISO 10974 and IEC 60601-2-33 standards, and their associated guidance documents, do not currently provide any guidance on sensor embedded implants communicating with a pTx capable MRI. The project will develop the necessary basis to calibration procedures, testing methodologies and a communication workflow to serve as the basis for future standardisation of this novel technology. Consortium members are represented on these boards, thus ensuring that project’s results will be known and implemented.

The ISO 10974 and ASTM F2182 standards, and their associated guideline documents, do not currently provide any guidance on personalized or *in situ* risk assessments that would be suitable for RF and/or gradient heating of bulky implants. The project will develop specific procedures and validated tools for the safety assessment of implants and provide the metrological underpinning to improve this and potentially to serve as the basis for a new ASTM standard. Consortium members are represented on these boards thus ensuring that project results will be known and implemented.

Longer-term economic, social and environmental impacts

Economic: Several branches of the European medical technology industry will become more competitive through innovative products and by reduced times and costs for safety assessments:

- European implant manufacturers (European active implantable medical device market is an estimated €7.5B by the close of the project in 2025, while the global market is estimated at €26.8B by 2022) will benefit from faster development and market introduction of their innovative products as metrologically approved methods to assess the safety of their products and reduced costs for testing MR compatibility will be available, as well as the potential application of novel safety features (smart implants).
- Manufacturers of bulky passive medical implants (€7.4B estimated market for hip replacement implants in 2025 by the close of the project) will benefit from a clarified and standardised compliance workflow.
- Technology leading European MRI manufacturers will benefit from new applications for their innovative developments (e.g., active hazard control by parallel transmission, Objective 1) as well as increased understanding in the community of combined RF-gradient risks which should reduce the incident rate and improve labelling.

(Socio)-economic: Existing safety measures in MRI sacrifice scanner performance by restricting the transmitted RF power. An improved assessment allows removal of unnecessary safety margins, resulting in shorter scan times and better image quality. Currently, every single implant carrier presenting for an MRI scan requires an individual assessment, involving at least the radiographer/technologist, MR safety officer and a responsible radiologist, often also a senior radiographer, MR safety expert and senior doctor or department head. The costs for the decision making (scan/no scan) vastly exceed the actual scan costs and a savings potential of € 400 million p.a. for the EU healthcare systems can be estimated if smart implants reduce the need for this procedure.

Social: The development of sensor-equipped implants, which can communicate with MR scanners, and the widespread implementation of pTx capable MRI scanners, would drastically improve the safety (smart implants) and efficiency (pTx) of MR examinations (>80 per 1000 Europeans in 2019)

Deciding, whether or not to scan a patient carrying an implant is a substantial stress factor for the clinical personnel who often are inadequately prepared and educated for this. With sensor equipped implants, error-prone human decision making can be replaced by a validated, automated procedure and the responsibility for is taken away from the MR operators and assigned – with well-defined and well separated roles – to the MR and implant manufacturers.

This project will support the inclusion of implant MRI compatibility in future revisions of the EU Medical Device Regulation, enhancing the safety of about 50 million EU citizens carrying implants.

List of publications

n/a

This list is also available here: https://www.euramet.org/repository/research-publications-repository-link/

<table>
<tr><td colspan="2">Project start date and duration:</td><td>01 October 2022, 36 months</td></tr>
<tr><td colspan="3">Coordinator: Lukas Winter, PTB   Tel: +49-3481-7573   E-mail: lukas.winter@ptb.de
Project website address: https://www.ptb.de/stasis/</td></tr>
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ISO TC150/SC6/JWG2</td><td>Chief Stakeholder Contact:
Michael Steckner</td></tr>
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1. PTB, Germany
2. CMI, Czechia
3. INRIM, Italy</td><td>External Beneficiaries:
4. DKFZ, Germany
5. MRC, Germany
6. STU BA, Slovakia</td><td>Unfunded Beneficiaries:</td></tr>
<tr><td colspan="3">Associated Partners: 7. ITIS, Switzerland</td></tr>
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Publishable Summary for 21NRM06 EMC-STD
Metrology for emerging electromagnetic compatibility standards

Overview

All electronic equipment within the European Market must fulfil the essential requirements of the European EMC Directive 2014/30/EU, with compliance demonstrated using harmonised electromagnetic compatibility (EMC) standards. However due to emerging radio services and state of the art technologies employed in Smart Grids, Internet of Things (IoT), electromobility, and other cutting-edge applications, the standards used to effectively address these new interference scenarios are lacking. This requires validated and traceable methods to assess the electromagnetic emissions in complex situations such as in situ testing of large size/high-power equipment mainly in the scope of CISPR37 & CISPR11 and interference in wireless communications mainly in the scope of CISPR16. This project aims to significantly contribute to the development of CISPR 37 and to the revision of CISPR 11 and CISPR 16 through new electromagnetic emissions test methods for harsh environments, fully traceable time-domain measurement techniques, new calibration methods for the response to pulses of receivers and the statistical evaluation of interferences in compliance assessments.

Need

All electronic equipment within the European Market must fulfil the essential requirements of the European EMC Directive 2014/30/EU [1]. The common approach is to show compliance with the harmonised standards using EMC tests at specialised laboratories. However, as new interference scenarios are identified due to emerging radio services and the state-of-the-art technologies employed in, for example, Smart Grids, IoT, electromobility and sustainable energy applications, the current standardised EMC testing methodologies are no longer sufficient or applicable. This has been emphasized by CENELEC TC 210 as well as CISPR which is continuously working towards updated and novel EMC standards. Likewise, IEC also tackles EMC problems at lower frequencies, currently focusing on interference below 150 kHz, as for smart energy meters.

One standard under development (the CISPR 37 Ed. 1.0) is intended to bridge the gaps left by CISPR 11 in terms of in situ testing outside standardised test sites. In this regard, CISPR\CIS\B\WG7 was created to develop CISPR37 and it needs support from universities and NMIs for developing traceable electromagnetic emissions measurement methods optimised for in situ assessment of large-size/high-power equipment (such as photovoltaic installations, electric road systems and electric car fast-charging stations).

According to CISPR\CIS\A, metrological research is required for the application of time-domain electromagnetic interference (EMI) measurement based on direct sampling techniques. The standard that defines the characteristics and key specifications of measuring receivers, CISPR 16-1-1, lacks clarity when it comes to the metrological definition of the calibration method and regarding the standard reference to use for traceability of pulse response of detectors. A complete waveform specification for receiver pulse calibration is needed.

In addition, the statistical analysis of interference and its correlation with communication quality metrics are of utmost importance as the increase of wirelessly connected devices poses challenges due to the increased use of IoT and the advent of 5G. The APD measuring function can assess the degradation suffered by digital communication systems, provided it is reformulated in two key aspects: extension below 1 GHz and measurement bandwidth set according to the characteristics of the communication channel. Both changes should be incorporated in standards such as CISPR 16-1-1 and CISPR 11. Likewise, a specific calibration method for the APD measuring function of the EMI receivers needs to be developed to provide the required traceability.

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EURAMET. Neither the European Union nor the granting authority can be held responsible for them.

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

Objectives

The overall aim of the project is to support standardisation in electromagnetic compatibility (EMC) through the introduction of new, validated, and traceable emissions measurement methods for the revision of and forthcoming development of CISPR EMC standards.

1. To develop traceable electromagnetic emissions measurement methods optimised for in situ assessment of large-size/high-power equipment and to validate the proposed test procedures in harsh environments (e.g., factory premises and photovoltaic installations), which requires development and improvement of live impedance measurement methods in low (30 Hz – 150 kHz) and high (150 kHz – 30 MHz) frequency ranges for conducted emission testing with a target uncertainty of 6 dB. This also includes the characterisation of influence factors such as non-stationary interferences and sources of background noise, correcting the impact of transient interference, and defining a measurement protocol for selecting adequate antenna location, height, and polarisation, and other relevant parameters for the radiated emissions test setup. A report on the methods will be submitted to CISPR/CIS/B/WG7 to support the development of the forthcoming CISPR 37.
2. To provide metrological evidence of the validity of time-domain electromagnetic interference (EMI) measurement systems, based on direct sampling techniques, and to define standardisable conditions at which the usage of oscilloscopes/baseband digitisers is acceptable or preferred in comparison to measuring receivers based on frequency sweep or stepped scan techniques. The estimation of the uncertainty in time-domain EMI measurement systems will be addressed. A report recommending an amendment of Annex B and Annex C of the current CISPR 16-1-1 standard will be submitted to CISPR/CIS/A/WG1 & WG2.
3. To improve the standard calibration method for the response to pulses of measuring receivers through a complete waveform specification of the calibration pulse generator. To develop alternative reference waveforms with well-defined mathematical description and spectral properties to include in standards as a means of validating the weighting function of the detectors, thus reducing the uncertainty of the receiver's response to pulses calibration to 0.2 dB. A report on the proposed calibration methods for the response to pulses of measuring receivers will be submitted to CISPR/CIS/A/WG1 & WG2 to support amendment of CISPR 16-1-1.
4. To redefine the standard amplitude probability distribution (APD) measuring function in EMI measuring receivers as part of the emissions compliance assessment based on the communication quality metrics. To define the criterion for establishing emissions limits based on APD measurements making it part of the emission compliance assessment. A report on the redefined APD measuring function will be submitted to CISPR/CIS/A/WG1 & WG2 and CISPR/CIS/B/WG1 to support amendment of CISPR 16-1-1 and CISPR 11 respectively.
5. To contribute to the standards development work of the technical committees CISPR/CIS/A/WG1 & WG2 (supporting revision of CISPR 16-1-1), CISPR/CIS/B/WG1 (supporting revision of CISPR 11), and CISPR/CIS/B/WG7 (supporting development of new CISPR 37) to ensure that the outputs of the project are aligned with their needs. To communicate quickly to those developing the standards and to those who will use them (test laboratories and manufacturers related to IoT, E-mobility, and technologies), and in a form that can be incorporated into the standards at the earliest opportunity

Progress beyond the state of the art and results

Development of emission test methods for harsh environments (Objective 1)

The 30 Hz-150 kHz frequency range will be extensively researched, and novel measurement methods will be developed for conducted emission testing. A precise correlation between reference and complex test environments will be based on accurate impedance measurements, never performed before.

For the 150 kHz – 30 MHz range, time-domain techniques and phase information will be also included to improve accuracy and uncertainty. The proposed use of time-domain measurement methods with the mains and Equipment Under Test (EUT) impedance characterisation will help to reduce the previously reported in situ uncertainty values of up to 25 dB towards the maximum 6 dB target found at conventional EMC test laboratories.

For radiated emission testing, the new methods proposed by draft standards such as CISPR 37 will be investigated, implemented, and verified in actual test environments. In addition, innovative measurement systems capable of measuring and processing new interference scenarios like impulsive-transient or short-duration emissions will be proposed along with a software solution featuring time and frequency domain triggering to ensure that worst emissions are captured.

Specifying time-domain interference measuring receivers in EMC standards (Objective 2)

The operation of the direct-sampling time-domain measuring receivers will be extensively studied to create a clear argument supporting their implementation in EMC standards such as CISPR 16, as an alternative to the conventional frequency-domain solutions. The effect on measurement accuracy will be evaluated for each stage of the receiving track, including hardware and signal processing, as well as for various receivers of different specifications, to clearly indicate whether they are suitable for the given applications, and with what uncertainty. Novel signal processing algorithms exclusive to the time-domain receivers will be implemented and evaluated to optimise the measurement speed, accuracy and precision, and allow to capture the rare EMI events that could be missed by the conventional methods.

Methods for calibration of measuring receivers (Objective 3).

Currently used methods for calibration of EMI receivers and their weighting detectors will be revised and further developed through a complete waveform specification of the calibration pulse generator. Those improvements target a future update of the CISPR 16-1-1 standard. Current methods for calibration of EMI receivers and their weighting detectors recommended in the CISPR 16-1-1 standard are not well suited for commercial calibration laboratories due to their demands on measurement equipment and complexity. Introducing a whole new set of more repeatable, reproducible, and less hardware stringent calibration and verification methods will enable calibration laboratories to perform calibrations of EMI receivers more efficiently. Moreover, the new calibration methods will allow easier interlaboratory comparisons avoiding traditionally used base-band pulse generators.

The APD interference detector in emissions compliance assessment (Objective 4)

The APD measuring function will be redefined as an interference detector suitable for compliance assessment of EMI in digital communication systems. A more general, improved formulation of the APD will be developed and emissions limits will be defined, based on the degradation suffered by digital communication systems when subject to the EMI of the EUT. The updated APD will be applicable for frequencies below 1 GHz and the measurement bandwidth will be made according to the characteristics of the communication channel. Time-domain measuring instruments will be employed to accelerate APD measurements through a multi-channel/multi-band approach. Finally, a traceable calibration method for the APD function will be developed through reference signals emulating noise models with well-known statistical properties. This translates into significant progress in comparison to current EMC standard testing methods that rely on emissions measurements according to weighting detectors at a fixed RBW and the pass/fail criteria based on fixed limit lines defined on broad frequency ranges.

Outcomes and impact

Outcomes for industrial and other user communities

The impedance and low frequency conducted emission based on impedance measurement methods will be taken up and offered as a service by EMC test laboratories (e.g, TUBITAK, EMC-BCN). This will allow test laboratories and product manufacturers to considerably improve their conducted emission tests by offering them more accurate measurement results and by alleviating the harsh grid impedance effects. These methods will also provide better knowledge about the impedance of electric networks which will allow manufacturers of electronic equipment (e.g., grid connected power converters and electrical vehicles) to improve the R&D phase of production thereby ensuring higher confidence in internal EMC pre-compliance results. This would facilitate a more reliable design considering EMC control measures and hence a reduction in time and subsequently cost.

The time domain method will be taken up and offered as a service by EMC test laboratories (e.g, TUBITAK, EMC-BCN) to end users (e.g., manufacturers of photovoltaic cells, wind turbines, smart grids). This will allow industry to acquire short duration/transient interference and worst-case emission measurements in harsh environments in real time. As opposed to conventional frequency-domain instrumentation like EMI receivers, this will allow industry to achieve a drastic reduction of measurement time, from hours to less than a minute.

The software solutions will be taken up by TUBITAK and EMC-BCN and provided to end users (e.g., other EMC laboratories and manufacturers) who need onsite EMC testing for their products. This will provide accurate and practical on-site test opportunities for them to validate their products as per the relevant EMC standards such as CISPR37.

The instrumentation will be taken up by TUBITAK, RISE, EMC-BCN, UNIGE and incorporated into their measurement and consultancy services and offered as a service to customers who need on-site EMC testing for their products and require verification and comparison tests for their EMC test systems. This will allow industry to validate their products which are not suitable for transferring to EMC laboratories due to physical and power constraints. Participants will also consider the possibility of transforming this development into a commercially available product it to third parties such as EMC test laboratories, either sold or as part of a verification service.

In addition, the test methods and assessment methodologies based on APD detectors will be taken up by CISPR/CISA committees to facilitate more reliable measurement procedures for radiated electromagnetic emissions at real sites, backed up by the quantification of disturbance to telecommunication systems. This will allow manufacturers (e.g., railways that feature large moving sources, potentially disturbing deployed telecommunication systems with signalling functions) to demonstrate the compliance and safety assessment in a more straightforward way. This will facilitate reduced duration of safety assessment and demonstration of compliance (usually blocking the permit to operate). Additionally, the broader use of APD as an interference detector will benefit industry because it mitigates the risk of over/under testing their products, which inevitably happens today due to the utilisation of non-optimum weighting detectors for emissions assessments.

Outcomes for the metrology and scientific communities

The time domain receivers and calibration methods will allow NMIs and DIs to update their calibration services and provide the necessary traceability and reduce the measurement uncertainties in comparison to the typical figures in the standards. In addition, through their contribution to the project both NMIs and calibration/testing laboratories will benefit from facilitating interlaboratory comparisons of EMI receivers and pulse generators. In addition, the report on comparison of a measuring receiver calibration using the traditional pulse generator and the new alternative reference waveform with a commercial arbitrary waveform generator (AWG) will be made publicly available. This will allow other NMIs, calibration testing/laboratories and members from the scientific community to take up results from the project and improve the calibration of their capabilities.

The joint interdisciplinary research of emissions measurements in harsh environments and the further development of APD as an interference detector will improve scientific understanding in this technical field. New research lines are expected to be generated. For example, doctoral Networks (Marie Skłodowska-Curie Actions) addressing EMC challenges in innovative applications (e.g., ETERNITY for EMC in medical equipment, PETER for electromagnetic risks management, ETOPIA for power applications).

At least six research papers will be submitted for publication in high impact open access peer-reviewed journals. This will be key for the scientific community to accept the calibration (APD calibration, new waveforms for calibrating the response to pulses of the measuring receivers) and the on-site testing methods proposed for harsh environments. Moreover, as part of the knowledge transfer actions addressed to the metrology and scientific communities, a two-day training course will be organised. The highly technical profile of this activity is more suited for people in academia, NMIs and technicians in companies' testing/calibration departments.

Finally, in a broader sense, the metrology capabilities of involved NMIs will be strengthened to provide metrology that supports emerging EMC standards and coordinated metrology research of involved participants in the future. By bringing together leading EU NMIs and universities in this area, the required metrological capacity will be established that aligns with the needs of stakeholders and standardisation bodies.

Outcomes for relevant standards

In a broad sense, the project will support the EU Directive 2014/30/EU which aims to ensure the functioning of the internal market by requiring equipment to comply with an adequate level of electromagnetic compatibility. The project will have a significant positive impact on the execution of the Directive by providing EMC test and calibration methods and supporting draft and active standards. More specifically, the consortium will promote the results of the project within the standardisation community and will provide input into the standardisation process, mainly of CISPR.

Through agile communication and coordinated interaction between the project consortium, the Chief Stakeholder and the target committees CISPR\CIS\A (Radio-interference measurements and statistical methods) and CISPR\CIS\B (interference in industrial, scientific and medical RF apparatus) the results from the project will be presented in the form of meetings, workshops (3), reports and guides (8) and datasets. Thanks to this project, at least 3 standards will be directly benefited from the research. One of them, CISPR 37 about radiofrequency disturbance measurements in situ and on defined sites, is a completely new standard that has been requested by the industry for decades. The other two, CISPR 11 and CISPR 16-1-1 are very fundamental and well stablished standards upon which other product testing standards are based. Improvements in those standards will result in a waterfall effect that eventually will propagate the project outcomes to other EMC standards.

Longer-term economic, social and environmental impacts

One sector that will considerably benefit from project outcomes is the industrial, scientific and medical (ISM) one because the most prominent target standards in the scope of the project is CISPR 37. Like CISPR 11 that was partially used for years as a reference standard for large equipment, CISPR 37 is expected to be used as a reference by many other standards and will have broad influence on applications such as renewables and wireless power transfer, and their integration in microgrids and power distribution infrastructure, railways, automotive, and those production lines currently using non-standard EMC test methods. Such sectors are strategic due to their contribution to the Gross Domestic Product (GDP) and European jobs.

In particular, as declared by the European Commission (EC), the objective for solar energy is to establish Photovoltaic (PV) systems as a clean, competitive and sustainable energy technology. Therefore, the improvement and production of new EMC standards for atypical equipment can improve the certification of PV installations and consequently achieve the objective of implementing solar energy, which will benefit economically the end-users, to reduce their energy consumption and produce their own clean energy, and the companies which provide the PV infrastructure.

The EC also supports European industry in the move to a low-carbon economy and improves the energy efficiency of products through eco-design legislation. This is strictly related to the energy industries like PV and green transport. The new EMC standards will contribute, from an EMC point of view to evaluation of all the novel electric engines and energy-efficient functional modes like regenerative braking that is employed by Electrical Vehicle (EV) such as trains, metros and e-buses.

Moreover, citizens can have direct social benefits from the energy and transport industries. A sustainable mobility is beneficial for the free movement around the European Union (EU), and according to the European Economic and Social Committee (EESC), these movers represent a poll for innovation, creativity, and willingness to work hard. The use of renewable energy technologies has a direct positive impact on the health of the European citizens. Therefore, the validation and procedures developed with the actual official standards in lieu of non-standard methods will allow speeding up the certification and the confidence in being compliant with the European Directives. In addition, taking advantage in the improvement of standardised, repeatable and traceable methods for in situ EMC testing of large-size/high-power equipment, reliable test results for a wide variety of locations will be obtained. Thus, manufacturers, conformity assessment bodies and consumers can benefit from reliable and faster compliance processes with the European EMC Directive 2014/30/EU and this presents significant opportunities for free movement of goods in European Single Market, promising potential cost savings and time.

List of publications

n/a

This list is also available here: https://www.euramet.org/repository/research-publications-repository-link/

Project start date and duration:		1 October 2022, 36 months
Coordinator: Serdar Büyük, TUBITAK Tel: +90 262 679 5000 E-mail: serdar.buyuk@tubitak.gov.tr Project website address: -		
Chief Stakeholder Organisation: Fuji Electric Europe GmbH		Chief Stakeholder Contact: Yasutoshi Yoshioka
Internal Beneficiaries: 1. TUBITAK, Türkiye 2. CMI, Czechia 3. GUM, Poland 4. INTA, Spain 5. RISE, Sweden 6. SIQ, Slovenia	External Beneficiaries: 7. EMC-BCN, Spain 8. UNIGE, Italy 9. UTwente, Netherlands	Unfunded Beneficiaries: n/a

Call 2022: Draft Project Summaries

Digital
Health
Integrated European Metrology
Normative
Research Potential

22DIT01 ViDiT

Trustworthy virtual experiments and digital twins

Summary of the project

Overview

The use of virtual experiments (VEs) and digital twins (DTs) in metrological applications requires uncertainty evaluation methods as well as reliable validation procedures to make them fit, e.g., as substitutes or extensions to certified measurement devices. The project develops such methods and procedures, which enable ensuring the reliability and trustworthiness of VEs and DTs in metrology. To facilitate the uptake of the developed methods by NMIs/DIs and industrial stakeholders, good practice guides (GPGs) are provided, and their applicability is demonstrated in twelve case studies covering a variety of different industrial metrological applications.

Need

VEs and DTs are key enabling technologies to achieve and realise European strategic policies devoted to sustainability and digitalisation within the complex framework of Industry 4.0 and the European Green Deal. VEs and DTs are both simulation models that accurately replicate physical systems and characteristics in a virtual environment. DTs further include dynamic updates of the virtual model according to the observed state of its real counterpart. Hence, they consist of two parts, a Physical-to-Virtual (P2V) connection modelling the considered system, and a Virtual-to-Physical (V2P) connection, which implements prevention and control strategies to achieve the target accuracy in the physical system.

VEs, in combination with Monte Carlo methods, are used for evaluating measurement uncertainties. However, the outputs of these approaches generally differ from an uncertainty evaluation that is compliant with the “Guide to the expression of Uncertainty in Measurement” (JCGM:GUM). Such a JCGM:GUM-compliant uncertainty evaluation is needed to facilitate the use of VEs in traceable measurement chains and to ensure the trust in the stated uncertainties. For DTs, in addition to this, time-dependent influences need to be considered. Hence, DTs need to be updated with data from actual measurements collected in real-time, and the evaluation of measurement uncertainty needs to be adapted accordingly to be compliant with the JCGM:GUM.

Uncertainty evaluation and validation of VEs and DTs are essential parts of the strategic research agenda of the European Metrology Network (EMN) MATHMET. This research agenda is based on a survey of European NMIs and stakeholder consultations that identified virtual metrology as one of their priorities in the field of mathematics and statistics for metrology. This emphasises the need for this project, which is also reflected in the 24 letters of support that the proposal received from industrial stakeholders covering a variety of different metrological applications.

Objectives

The overall objective of the project is to develop methods and tools that enable ensuring the reliability and trustworthiness of VEs and DTs in metrology necessary to support the digital transformation within Industry 4.0 and the European Green Deal.

The specific objectives of the project are:

1. To develop methods for evaluating the uncertainty associated with real measurements for three different applications (coordinate measuring machine – CMM, tilted-wave interferometer – TWI, flow measurement – FLOW) by using the results from corresponding VEs in line with the current state-of-the art for uncertainty evaluation, such as Bayesian or Monte Carlo approaches or documented in the JCGM:GUM.
2. To develop methods for uncertainty quantification for DTs representing complex measurement processes and mechanisms for four different applications (nanoindentation, contactless cylindricity measurement – NanoCyl, 3D robotic measurement, electrical measurement), in each case including the effect of dynamical influences on the digital model such as thermal drift or vibrations. The model is updated based upon data obtained during the project’s lifetime.

3. To develop approaches for the validation of VEs and DTs for all applications of objectives 1 and 2, using statistical procedures for the assessment of differences between calibrated standards and corresponding data from their virtual counterpart. Methods include accounting for errors, specifically for computationally expensive systems, where surrogate models need to be used.
4. To demonstrate the practical applicability of the developed methods, using twelve case studies covering different metrological applications (coordinate measurement, optical form measurement, flow measurement, electrical measurement, 3D robotic measurement). Guidance is documented on how to employ the methods in other cases and GPGs are drafted in collaboration with industrial project partners and stakeholders and disseminated within e.g. EU industry, CCL, TC-L and ISO communities.
5. To facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain (NMIs/DIs, accredited laboratories, material testing laboratories, calibration laboratories), standards developing organisations (ISO, IEC) and end users (advanced manufacturing, personalised health care and urban planning).

Progress beyond the state of the art and results

Since a VE usually produces virtual data rather than virtual values for the measurand, the direct application of uncertainty evaluation methods as described in the JCGM:GUM is not possible and extra steps have to be made to obtain a JCGM:GUM-compliant uncertainty estimate. Recently, a JCGM:GUM-compliant uncertainty evaluation has been reached for linear models in an automatic way by using the output of a VE. However, no procedure exists to derive uncertainties for the result of a measurement by automatically using virtual data when the model for the measurand is nonlinear. One goal of this project is to develop such an approach that allows an automated uncertainty evaluation for general models by using the outcome of a VE. (Objective 1)

For measurement instruments or measurement processes, very few examples of DTs are reported in the literature, and even less literature discusses uncertainty evaluation of DTs. Currently available methods for uncertainty evaluation often neglect the coupling of a DT with different parts, especially linked to the control and the V2P connection. Moreover, a rigorous definition and evaluation of metrological characteristics of the DT are missing. This project will deliver different methods to evaluate the uncertainty of DTs for several measurement processes, for which JCGM:GUM-compliancy will be analysed and reported. Additionally, coupling with the modelling and the control feedback deployment strategies will be included in the uncertainty evaluation. (Objective 2)

Currently, there are no general guidelines for the validation of VEs/DTs. This project will develop such guidelines with special focus on their applicability in metrology. The validation will include both the measurement estimate obtained by the VE/DT, as well as the uncertainty associated to it. Knowledge and experience from existing applications of VEs in metrology (e.g., virtual coordinate measuring machine – VCMM) will be applied in other applications that are new to the adoption of VEs/DTs (e.g., nanoindentation). Attention will be given to the generalisability of the validation guidelines also to non-standard measurements, e.g., measurements of freeform artefacts. (Objective 3)

The developed uncertainty evaluation methods for VEs and DTs will be applied in a variety of different case studies covering different metrological applications. Where appropriate, existing software tools will be extended based on the expected results. For other applications, new environments will be created, like DTs for a commercial nanoindentation platform or a traceable commercial 3D machine vision system integrated in an industrial robot. Guidance will be given on the practical applicability of the developed uncertainty evaluation methods when applied to industrial case studies. The reports will be drafted in close collaboration with the industrial participants and stakeholders. Results will be disseminated within the relevant EU industry identified by the EMNs AdvanceManu and MATHMET, as well as consultative committees of the CIPM (e.g., CCL), EURAMET technical committees (e.g., TC-L), and ISO communities. (Objective 4)

Outcomes and Impact

Outcomes for industrial and other user communities

The project will provide methods for JCGM:GUM-compliant uncertainty evaluation of VEs and DTs, as well as procedures for their validation. Furthermore, the newly developed approaches will be applied to a variety of industry-relevant test cases. These methods, procedures and case studies will enable industry and users of VEs and DTs to, e.g., optimise meter design or improve the efficiency of welding processes. This will provide the basis for gaining traceability in several metrological applications, where VEs/DTs are employed (e.g., asphere and freeform metrology, nanoscale mechanical characterisation, quality control of welded parts). In the long term, this will lead to a reduction in production time, better surface quality of manufactured parts (leading to waste reduction, better use of materials, reduction of energy consumption, etc.), miniaturisation of parts (e.g., optical lenses) and the development of new products, which could boost the European industry worldwide in several domains (photonics, medical, transport, energy, etc.).

Outcomes for the metrology and scientific communities

The project will provide a common understanding among European NMIs/DIs on how to make VEs and DTs fit for use in metrological applications. The recipes for assessing uncertainty will be summarised and published in guidelines so that the methods can be easily adapted by the metrological and scientific communities. Research papers will also be published in high impact peer-reviewed journals and as part of the knowledge transfer a workshop on uncertainty evaluation for VEs and DTs will be organised and held, to which representatives of industry (both manufacturers and users), academia and NMIs will be invited. Results will be disseminated to the EMNs AdvanceManu and MATHMET as well as to the International Academy for Production Engineering (CIRP), which makes them accessible to a wider audience including stakeholders from all these networks. The collaboration of European NMIs and DIs in this project will increase their visibility and authority in drafting common regulations and guidelines. This will improve the competitiveness of the European economy and lead to a more intense international cooperation.

Furthermore, the project results will provide high-performance and robust methods essential for all applications, for example freeform optical surface measurements. The optical scientific community will be able to make use of these advancements and benefit in their research, e.g. with regard to the need for highly accurate complex optical systems in research fields like lithography (e.g., extreme ultraviolet lithography), synchrotron, astronomy, ophthalmic, medical devices, and many more. The benefit is also valid for scientific communities involved in electrical measurements, flow measurements, nanoindentation measurements, etc.

Outcomes for relevant standards

The consortium will promote the results of the project within the standardisation community and will provide input into the standardisation process. The participants of the project are active in the JCGM WG1, which has the responsibility for the JCGM:GUM and its supplements. These documents mark the de facto standard for uncertainty evaluation in metrology and are used worldwide at all levels of the measurement chain, from NMIs to industry. Furthermore, results of the project will be disseminated to DIN, ISO, and CEN working groups. For ISO, the standards relevant to the project that are in preparation/revision will be identified, and the work on these standards will be suggested to the appropriate working groups or committees. The participants will also present the outputs of the project in CIRP, TCL, IMEKO, EURAMET and other networks, where they are active. All these activities ensure the uptake of the project outcomes by the metrological community.

Longer-term economic, social and environmental impacts

The improved capabilities at NMIs and DIs provided by this project will enable industries to reduce the number of iteration steps required in design, production, and testing. This leads to a drastically reduced production time and cost per individual part. The latter one will then allow the production of new products and the development of novel applications and systems in several sectors including aerospace, automotive and naval industry, medical, optical and precision instruments, as well as computer, audio, video and telecom equipment. The improvements in the reliability, efficiency, and speed of production processes will also significantly decrease the scrap rate and reduce the energy needed for production. The corresponding savings of energy help to reduce Europe's CO_2 footprint.

Positive social effects will result from the impact of high-end optical components on the production of new information technology components, mobile electronics, and medical devices. Better mechanical alignment through new 3D machine vision integrated robot scanning tools can be used in advanced particle beam therapies resulting in treatments with higher cure rates. In electrical measurement systems, the project outcomes help to better estimate overvoltages and unwanted induced currents in HV lines, as well as to then use adapted control solutions. This will drastically reduce the loss of electrical energy, which is highly valuable and demanded in Europe nowadays.

The enhancement of advanced manufacturing will help to keep high-skilled jobs in Europe and, hence, enhances the employment and wealth of the EU.

22DIT02 FunSNM

Fundamental principles of sensor network metrology

Summary of the project

Overview

Sensor networks are used in a large number of fields but are struggling with data quality of varying degrees, with unknown measurement uncertainty and lack of traceability to the SI limiting their applicability. To overcome these issues, this project will address the metrological aspects of sensor networks, covering the uncertainty propagation, data quality metrics and SI-traceability in generic sensor networks, as well as the assessment, infrastructure, and risk analysis of distributed sensor networks alongside software frameworks and semantics via automated application of developed methods. The applicability of the methods, tools, and concepts will be demonstrated in typical real-world sensor networks.

Need

Metrology is facing unexplored challenges introduced by the recent developments in sensors, network architecture, *in-situ* self- and co-calibration techniques, data routing, processing, and Artificial Intelligence (AI) methods, exemplified by Machine Learning (ML) algorithms based on Deep Learning (DL). Their influence on sensor network technologies ranges from areas such as air quality monitoring and energy networks to advanced manufacturing. This brings with it challenges for metrology in real-world sensor networks, in particular due to the large volume of data with innate characteristics such as velocity, volume, value, variety and veracity.

The quality assurance of sensor networks is of importance e.g. in Directive 2010/75/EU of the European Parliament on industrial emissions (integrated pollution prevention and control), Directive 2008/50/EC on ambient air quality and cleaner air for Europe, and Directive 2018/2002 – Amendment of Directive 2012/27/EU on energy efficiency. Therefore, novel metrology including traceability, uncertainty assessment, and new calibration techniques for sensor networks is needed to guarantee the quality of their data.

Practically this translates to a need for improvements in sensor network metrology for numerous areas. The examples include 1: Advanced manufacturing requires general research to improve the quality of the network-wide measurement data, obtained from existing sensors, to control processes and prevent progressive accuracy loss and degradation of product quality. 2: City-wide air-quality monitoring networks need *in-situ* dynamic calibration capabilities to account for their transient nature, as well as methods to facilitate regular recalibration under dynamic conditions. 3: With an aim of 80–95 % reduction of greenhouse gases from buildings and workplaces, methods for building management must be found through new and smarter digital tools and software frameworks. Many other areas have similar challenges with uncertainty propagation in sensor networks, and a combined effort to develop tools will provide a suite of generic tools that can be adapted to a wide range of applications.

Objectives

The overall goal of this project is to address the metrological aspects of sensor networks. The specific objectives of the project are:

1. To develop reliable and accurate methods for the assessment of data quality and measurement uncertainty in real-world sensor networks. The methods will be suitable for a wide variety of sensor networks and should include the propagation of uncertainties, proper treatment of correlations, and uncertainty-aware sensor fusion. Additionally, to produce metrological guidance for data quality metrics in sensor networks that include not only measurement uncertainty but other common factors that can influence data quality.

2. To extend the results obtained in objective 1 to the case of distributed sensor networks, and to develop reliable and accurate methods for their metrological assessments. The methods will cover a wide variety of sensor networks and geographical distributions.

3.To develop reliable methods for the automated application of the methods in objectives 1 and 2, in large transient networks. This requires novel approaches for the handling of information on the individual sensors, their interaction and metrological characterisation, and includes machine-interpretable and metrology-aware descriptions for complex sensor networks using semantic technologies.

4. To demonstrate the practical validity of the methods developed in objectives 1, 2 and 3, in at least 3 real-world case studies (e.g., industrial processing, environmental monitoring, building and utility sectors. Using the results of the case studies to develop end user guidance and software for sensor network metrology. The end user guidance will provide improved measurement reliability including (i) standardised methods for in situ metrology, (ii) the use of the software (iii) the use of metrological redundancy, and (iv) error detection.

5. To facilitate the take up of the technology and measurement infrastructure developed in the project by end users (industry, advanced manufacturing, environmental monitoring, and energy), standards developing organisations and accreditation bodies.

<u>Progress beyond the state of the art and results</u>

The current state of the art for sensor network metrology is limited to specific applications. For the first time, sensor networks are addressed in a metrologically sound and systemic manner, creating outputs for all areas, where sensor networks are implemented. In particular, objectives of the project will obtain the following progress beyond the state of the art:

1: At the end of the project, new tools will be available for generic uncertainty propagation in hardware- and software- based sensors, tools for the SI-traceability chain via self- and co-calibration of the sensors, and uncertainty-aware sensor fusion together with drift and detection of malfunctioning sensors. Data quality metrics will be also be identified for a generic sensor network that was not previously available. These new tools by giving traceability and by properly assessing the uncertainty, will broaden the applicability of sensor networks and make the data reliable

2: The project will make substantial progress in the characterization of fixed and mobile distributed sensor networks considering the data aggregation and trustworthiness across their whole life cycle. The infrastructure aspects, e.g., topology, communication, and access, will be addressed and transformed to architecture design criteria that current methods lack. Risk analysis for the sensor networks will be addressed for the first time in a coherent and standardised manner and its results will be collated in publicly available good practice guides.

3: Automated data handling software frameworks and semantics will be significantly enhanced during the lifetime of the project. This comprises machine-interpretable and metrology-aware descriptions employing semantic technologies. As an outcome, dynamic and distributed measurements in generic large-scale transient sensor networks will benefit from the automated methods developed in the project.

4: Five use cases in the project will showcase how the tools developed can be used for improving the state of the art in a suite of representative areas: a) Uncertainty propagation in sensor networks will assist in significantly reducing the temperature uncertainty in district heating networks, enabling reduction of the supply temperature, and leading to lower distribution losses. B) The improvements in calibration drift analysis will assist in the development of drift determination in multi-wire thermocouples for high-value products, where even small deviations in process temperature can have a significant impact on product quality. C) Sensor fusion will aid in the quality verification of gas-distribution meters. This will lead to calibrations being performed when needed, rather than at set times, thereby reducing the calibration costs of critical equipment. D) Metrology for air-quality monitoring networks will be addressed for the first time via automated uncertainty evaluation, data metrics and methods for establishing SI traceability for static and mobile devices. Data aggregation techniques, data fusion methods in the transient heterogeneous environment, and soft sensors will be investigated. E) Using optimal combinations of physical and software sensors will reduce installation and maintenance costs while potentially gaining accuracy in smart buildings. This will again lead to improved energy management of the buildings.

<u>Outcomes and Impact</u>

Outcomes for industrial and other user communities

Outputs from this project are expected to bring significant value to a broad range of industries, ranging from manufacturing of high-value products to optimization of district heating and cost reduction in smart buildings.

Developed tools for detection of malfunctioning equipment and derivation of information on the sensor drift in situ are relevant for multiple applications and their data quality assessment. This adds value for the manufacturing of high-value products and energy transmission networks.

Good practice guides will directly benefit end users by providing guidance on the metrological assessment of distributed sensor networks with particular focus on identifying the infrastructure requirements, network architecture, topology and data aggregation for fixed and mobile sensor networks.

The developed tools for uncertainty analysis will enable district heating networks to operate at a much lower supply temperature, significantly reducing heat losses, with immediate impact through financial savings.

Development of data fusion to determine calibration drift of gas flow meters, individually or in distributed networks, will reduce measurement uncertainty by at least one third and permit better planning of calibrations.

Novel SI-traceability lowers measurement uncertainties, improves data reliability, and impacts environmental monitoring, with improved understanding of pollution propagation, based on static and mobile sensor networks. This informs and empowers decision makers to monitor and decrease local pollution levels.

Improved knowledge of how to optimally combine hardware and software sensors for smart buildings will reduce installation and maintenance costs while improving accuracy.

Outcomes for the metrology and scientific communities

The metrological and scientific communities will receive input to working groups, such as BIPM JCGM/WG1, where results from this project can be used as input to a potential supplement to the Guide to the Expression of Uncertainty in Measurements (GUM), and inputs to European Metrology Networks, where several groups are currently dealing with aspects of sensor networks.

Additionally, the metrology community will see beneficial outcomes in the tools available for uncertainty analysis of low-cost/low-value sensors in large volume networks, which are expected to become widespread in the near future. Such sensors are rarely calibrated individually, but can bring valuable information when placed in sensor networks.

Outcomes for relevant standards

The project will impact standardisation in several fields due to the generic and widely applicable nature of the research reflected in the use cases. The earliest impact will be on the work programmes of CEN, ISO, IEC, IEEE and WELMEC technical committees and working groups involved in the standardisation related to the industrial, utility and environmental applications of the studied use cases .

Industry standards such as AMS2750 from Nadcap (National Aerospace and Defense Contractors Accreditation Program) governing heat treatment of high value components and IEC TC 65/SC 65B/WG5 (Temperature sensors and instruments) can take advantage of the project results. Early impact is expected on the work of ISO/IEC JTC1 SC41 to include metrology and data quality; the documentary standard impacted here is expected to be ISO/IEC 30178. The work on metrological assessment of sensor networks is highly relevant for the IEEE TC10 scope concerned with electronic instrumentation and electrical measurement (several standards e.g., IEEE 1241-2010TM, IEEE 181-2011TM, and IEEE P2414TM).

The standardisation organisations benefiting from the outcomes of the project research and the lessons from the two utility use cases include the WELMEC WG7 'Software' with respect to software and IT components, and WG11 "Gas and Electricity Meters", responsible for a harmonised approach towards legal metrology issues for utility meters. At the CEN level, results are expected to impact on the work of CEN TC 176 regarding standardization in the field of heat meters.

The outputs of this project will be disseminated to CEN-264-WG-42. This committee writes specifications and standards for the validation of air quality sensors, including statistical components. The results of the project are foreseen to impact CEN/TS 17660-1 and the draft technical specification

CEN/TS 17660-2 (TC-264-WI-00264179), and possibly future standards on the operation of air quality sensor networks that CEN 264 WG 42 is expected to initiate.

Longer-term economic, social and environmental impacts

Economic

An estimated 0.54 EJ of energy is lost in European district heating networks each year. A general reduction of the supply temperature from 85 °C to 80 °C will potentially cause a 6 % reduction in heat loss to the ground, resulting in energy savings corresponding to 33 PJ/year, reducing CO_2 emissions by 3 million tonnes per year, and give financial savings of 2 billion euros.

Extra sensors, required to further reduce supply temperatures without creating health risks, have a potential European market of up to €280 million for hardware components alone, with similar potential revenues for software solutions. In the gas sector, the EU imported 88 billion m^3 in the first quarter of 2022, valued at €78 billion. If a current 1 % annual drift in sensor output can be reduced by 30 % through data fusion techniques, a potential €1 billion can be saved per year.

Environmental

Air pollution, linked to 300,000 premature deaths annually in EU and millions more worldwide, can be monitored more reliably, utilising the tools developed in this project. This will enable decision makers to focus their efforts. The outcome of this project will support the intention from EU of becoming CO_2-neutral by 2030, by improving the control and maintenance of utility networks, and by reducing energy consumption in manufacturing, and industrial processing, who account for 22 % of European greenhouse gas emissions (joint second highest contributor together with domestic transport; energy supply is the most emitting at 26 %). The improvement in thermometry alone will thus directly improve fuel efficiency and reduce atmospheric emissions.

Social

In the present situation, where fossil fuel prices in Europe have increased significantly, low-income households in Europe (estimated 11 million inhabitants) will have to spend at least 50 % of their current expenditures to compensate for increasing energy prices. Solutions developed in this project will significantly enhance the efficiency of energy distribution networks, resulting in associated impact on energy savings and prices.

22HLT01 – QUMPHY

Uncertainty quantification for machine learning models applied to photoplethysmography signals

Summary of the project

Overview
At the core of this project stands the development of measures to quantify the uncertainties associated with machine learning (ML) algorithms applied to medical problems, in particular the analysis and processing of photoplethysmography (PPG) signals. To achieve this the following tasks will be addressed: (i) benchmark datasets will be generated using publicly available in vivo, in vitro and synthetic data (ii) different ML models and uncertainty quantification (UQ) methods will be used to analyse the processing of the PPG signals and specify the associated uncertainty and (iii) a good practice guide with accompanying software repository showcasing the used models, methods and benchmarks will be developed and made publicly available.

Need
PPG signals are used both in a clinical setting and are collected by many wearable devices. They contain valuable information on the cardiovascular, respiratory and autonomic nervous systems which is not yet routinely exploited. They are popular as they are easy to obtain non-invasively and PPG devices are cheap and widely available. Moreover, using smart devices or even contactless measurements by external cameras yields the possibility for long-term monitoring without restriction of

patient comfortability. Due to the vast amount of collected data machine learning methodologies are essential for the extraction and evaluation of key features used for diagnosis.

When applying machine learning in a medical context, however, confidence in the performance and predictions of the algorithms is particularly crucial since diagnostic mistakes can be fatal (false negative) or result in unnecessary anxiety and detrimental overtreatment (false positive). This is supported by the Executive Vice-President for a Europe fit for the Digital Age, Margrethe Vestager, who said "*On Artificial Intelligence, trust is a must, not a nice to have*" [1]. Hence an analysis of the uncertainty associated to ML algorithms and their predictions is indispensable to provide both clinicians and users of wearable devices critical information about the quality and trustworthiness of the produced results.

According to the US Center for Disease Control and Prevention (CDC) over 400 million people worldwide suffer from diabetes with predictions reaching 0.5 billion people worldwide by 2040 [2]. Similarly, the World Health Organisation (WHO) estimates that hypertension (elevated blood pressure) affects more than 1.2 billion adults between ages 30 and 79 worldwide with approximately half of the people being unaware that they have this condition or need treatment [3]. A recent EC report [4] states that: "*By using digital solutions, such as wearables (…) citizens can actively engage in health promotion and self-management of chronic conditions. This in turn can help control the rising demand for health and care*". Wearable devices such as smart watches allow early detection, monitoring and counteracting such conditions through lifestyle and diet changes or early medical treatment potentially saving millions of lives and billions in medical treatment costs. One of the major obstacles of this approach originates from the low signal quality obtained from PPG measurements through smart wearables at e.g., the upper side of the wrist. This again emphasises the need for both ML techniques to process the data as well as reliable and trustworthy methods to quantify the uncertainties associated to the algorithms' predictions.

Objectives

The overall objective is to provide trustworthy machine learning models for analysing photoplethysmography signals in a medical context by developing methods for the quantification of uncertainty in supervised machine learning models applied to PPG signals and generating reference datasets to benchmark those models, supported by an open-source interface for independent review of the models.

The specific objectives are:

1. **To develop methods for quantifying the uncertainty for at least 3 classification and 3 regression existing supervised machine learning and/or deep learning (DL) models** using PPG data, considering the effects of both aleatoric (data) uncertainty and epistemic (model) uncertainty on model predictions.
2. **To generate at least 5 measurement problems and their corresponding datasets**, using real and/or synthetic PPG data, that can be used to benchmark accuracy and uncertainty of supervised machine learning and deep learning models. In addition, to make those reference problems and datasets widely available to the medical device and digital health communities.
3. **To validate the uncertainties obtained for existing machine learning and deep learning models** of Objective 1 and to compare the accuracy and uncertainty of at least 3 classification and 3 regression existing machine learning and/or deep learning models in order to identify models and methods which have high accuracy and low uncertainty for a wide range of tasks.
4. **To engage with the medical device, digital and healthcare communities** to (a) promote and enable the uptake and implementation of the methods for uncertainty quantification developed during the project, (b) support the adoption of the benchmarking problems and datasets by providing guidelines for their use, and (c) develop a framework for independently reviewing machine learning models proposed by industry to assist them in getting regulatory approvals.
5. **To facilitate the take up of the technology and measurement infrastructure** developed in the project by the measurement supply chain (NMIs, DIs, medical device calibration services),

standards developing organisations (IEC, ISO), and end users (clinical practitioners, digital experts within the healthcare communities, manufacturers of medical and healthcare products).

Progress beyond the state of the art and results

Generate benchmark measurement problem datasets:

Accompanied by leading stakeholders the consortium will identify relevant benchmark diagnostic tasks for PPG signals, such as detection of atrial fibrillation and hypertension or blood glucose monitoring, and collect the required datasets from openly available databases and measurements provided by members of the consortium. These datasets may include in vivo (human), in vitro (phantom) and synthetic (simulated) measurements of PPG signals at different locations of the human body. Meta data to describe the benchmark problems will be included and the respective datasets will be formatted uniformly into widely available data structures providing convenient interfaces for all kinds of ML applications. This will be the largest unified benchmark problem database for classification and regression problems on PPG signals to date. This database may include benchmarks focussing on e.g., sex and skin tone, which will foster the investigation of heterogeneous and more diverse populations.

Develop methods for quantifying the uncertainty of supervised ML/DL models:

The detection of quantities of interest from PPG signals cannot be done via direct observation but relies on the solution of inverse problems. While for direct measurements the determination of the measurement uncertainties is clearly covered by the GUM [5] for indirect measurements this is very challenging and a topic of current metrological research, which requires substantial modelling and goes far beyond the framework of the GUM. Additionally, as no closed-form analytical models to describe the human body with arbitrary accuracy exist, the derivation of surrogate models through modern ML algorithms to approximate any functional relation between measurements and hidden quantities are necessary. These surrogates, however, introduce an unavoidable and often unobservable approximation error caused by network architecture and training on noisy data. Especially for neural networks, due to their excellent performance on many cutting edge industrial and societal problems, generalisation and explainability are at the centre of modern research. In other words, methods to quantify the trustworthiness and confidence of ML algorithms are essential for applications, in particular in high-stakes areas such as diagnosis and monitoring of diseases. The consortium will investigate which UQ methods are suitable for different ML algorithms applied to PPG signals for the developed benchmark problems. Therefore, the employed UQ methods will be comprised of model dependent and independent approaches encompassing both aleatoric (data) and epistemic (model) uncertainties. The ML models and UQ methods investigated in this project will cover a wide spectrum of algorithms providing a basis to establish confidence in applications even beyond what is covered by the benchmarks defined in this project. Further, these UQ methods can be seen as a first step towards standardisation and certification of machine learning in medical tasks using PPG signals.

Validation of uncertainties of ML/DL models for the benchmark problems:

Using the UQ methods investigated, and the benchmark problems defined in this project, the consortium will be able to accompany ML models trained on PPG signals with an uncertainty budget, which goes far beyond any state-of-the-art application. The uncertainty budget will distinguish between aleatoric contributions caused by measurements with varying levels of signal complexity and quality, and epistemic contributions due to the specific choice of ML model and optimisation routine during the training phase. Moreover, as the benchmark problems are not of academic nature, but include real measurements for clinically relevant scenarios, the validation of the investigated algorithms by several different UQ methods will yield first results on the credibility associated to diagnostic routines already used in consumer devices. Further, the validation procedure itself will create a precedent for the evaluation of an uncertainty budget in scenarios related to those of the benchmark problems possibly serving as a basis to inform future certification standards.

Engage with medical device, digital and healthcare communities:

The consortium and the stakeholder committee that will be formed after the start of the project will include members form the medical device, digital and healthcare communities, which will ensure that the considered benchmark scenarios will be relevant for and needed by medical device manufacturers as well as clinicians. The main output of the project will develop a good practice guide describing the defined benchmark datasets, the employed ML algorithms and the considered UQ concepts. This guide will additionally focus on explaining how the different methods should be applied to the respective benchmark problems functioning as a stand-alone guideline for the targeted end-user communities. To improve the impact of the good practice guide, the benchmark datasets will be made publicly available, including meta data on their origin, their proposed use and validation results acting as target baselines for user communities. Additionally, a software repository containing the ML algorithms and UQ methods used for the validation as well as required information on setup and training procedures will be made available to the medical device, digital and healthcare communities. The repository will include tutorials showing how to apply the implemented algorithms and methods to the benchmark problems, specifying all necessary software interfaces of the framework to allow easy adaptation to similar scenarios by potential users. These tools will be disseminated throughout the target user communities with a very high expected engagement rate, as good practice guide, benchmark datasets and software repository enable end users to create trust in both medical device production and usage in an unprecedented fashion.

Outcomes and Impact

Outcomes for industrial and other user communities:

This project will develop new methods for quantifying the uncertainty of machine learning predictions that are based on PPG signals which will provide a measure of confidence in the predictions. This will be of great benefit to digital health companies that are developing software for use in both medical devices and consumer wearable devices.

Outcomes for the metrology and scientific communities:

This project will develop new methods for quantifying the uncertainty of machine learning predictions that are based on the use of features, image transformations of the signal, and the raw signal. Machine learning is applied to many problems including autonomous vehicles, medical imaging and industrial sensor networks for which quantification of uncertainties is equally important and so the methods developed in this project are widely applicable in other application domains. The benchmarking datasets will be of benefit to the metrological and scientific communities who may want to use these datasets with their own machine learning models or for other studies. Research papers will be submitted for publication in high impact peer-reviewed journals and the work in the project will be presented at relevant international conferences.

Outcomes for relevant standards:

PTB, NPL, LNE, IPQ and IMBiH will contribute to national and international standards and guidelines throughout the project, especially for AI in medicine. This includes dissemination of the project's results to standard committees to propagate the results and make them available to the user community. Special attention will be given to developing a good practise guide for uncertainty quantification of ML algorithms applied to PPG signals, which can act as a foundation for standardization of PPG based medical applications in the future. We anticipate high impact of the mathematical tools and advanced uncertainty quantification and propagation methods through international committees such as IMEKO TC 6, ISO/TC 69, ITU/WHO FG-AI4H and JCGM Working Group 1.

Longer-term economic, social and environmental impacts:

PPG signals are collected by smart watches which are now widely available worldwide. By making digital health apps based on machine learning available on smart watches, individuals will be able to monitor different aspects of their own health. This would be possible both for the general population, for example monitoring blood pressure, or for a specific health need, such as the monitoring of blood glucose levels for diabetics. Combining uncertainty quantification with the machine learning predictions will result in more trustworthy predictions. Such continuous monitoring will result in early detection of health conditions and better management of chronic conditions, both of which will result in better health outcomes leading to reduced demand on health systems with corresponding economic benefits. Similarly in a hospital setting, patients could be monitored continuously which will enable early detection of health deterioration resulting in better health outcomes which will translate into economic benefit. This project will contribute to the rapidly growing digital health industry which is providing wearable devices that enable individuals to continuously monitor their own health and well-being resulting in early detection of health issues or better management of chronic conditions, as mentioned above. This will result in better health for users and, in some cases, to a longer life. In hospitals, continuous monitoring of all patients will result in trustworthy early alerts of health deterioration enabling early treatment which will improve health outcomes and may even save lives.

As a wider impact, this project will provide a boost to Europe's rapidly growing digital health industry, leading to higher skilled employment and wealth for society.

22HLT02 A^{4}IM

Affordable low-field MRI reference system

Summary of the project

Overview

Low-field magnetic resonance imaging (MRI) is experiencing a renaissance: these systems are cheaper, safer, more adaptable to different environments, and easier to use than their high-field counterparts. Compact and mobile scanners are changing workflows in radiology, where MRI comes to the patient rather than the patient to the MRI. These innovations are driven primarily by AI combined with low-cost hardware customised to clinical applications. This project will establish the necessary metrological framework for the harmonised development of clinical low-field MRI to facilitate access to this technology and ensure reliable and reproducible diagnostic information for patients in the EU and worldwide.

Need

Around 40 million MRI scans are performed in the EU each year. The number of examinations is unevenly distributed among the member states, to such an extent that the number of MR scans per million inhabitants is 26 times smaller in Cyprus compared to Germany, while in many non-EU countries MRI is not available at all.

Low-field MRI is currently experiencing a renaissance with strong arguments of bringing more access to this critical diagnostic technology [1–5]. Despite low-field scanners being more affordable than their high-field counterparts, proprietary low-field MRI units are still relatively costly to purchase, operate and maintain. This prevents most hospitals, doctors' offices, research institutions, metrology institutes and companies from purchasing/using these scanners to advance healthcare, science, and technology. Low-field MR scanners based on open-source hardware designs operated by open-source software will change this paradigm. First prototypes demonstrated a truly affordable (<50k material cost) alternative with image quality comparable to commercially available scanners [6,7].

To scale these innovations and impact, a metrological framework to support and boost the development and application of affordable open-source low-field MR systems is needed. This must include metrologically characterised reference systems for benchmarking and software for scanner control, image reconstruction and data processing. Modular strategies to medical device development need to be established including open-source documentation blueprints of hardware and software according to the requirements of the EU's medical device regulation (EU)2017/745 (MDR). This will improve access to this essential technology, facilitate adoption by clinical end-users and unleash the vast innovation potential of this technology. A strategy fully in-line with the recent resolution of the UN Economic and Social Council asking to *"better leverage open-source technologies for sustainable development"* [8] and latest EU4Health Programme 2021-2027 which focuses on "*supporting actions to enhance the availability, accessibility and affordability of medicinal products [...]*" [9].

Objectives

The overall goal of this project is to establish affordable open-source low-field MRI systems covering hardware components, data acquisition and image reconstruction within the EURAMET network, which are reproducible, fully documented and metrologically characterised.

The specific objectives of the project are:

1. To design, develop and evaluate mobile (<300 kg), low-cost (<50 k€) and fully replicable low-field MRI reference systems (main static field $B_0 \approx 50$ mT), capable of imaging the human head and extremities. This includes the full characterisation of these reference systems by metrologically validated methods including B_0, radiofrequency and switched gradient fields. To furthermore draft the technical documentation for the design and production process of the reference systems in accordance with the requirements of the EU medical device regulation (EU)2017/745 and to distribute the complete documentation of the system under open-source licences.
2. To develop model-based image reconstruction techniques using the reference systems in objective 1. To achieve accurate and fast image reconstruction and to enable quantitative imaging of biophysical parameters by combining hardware models and MR signal models with physics-informed deep learning approaches. To implement an open platform with cloud-based access to these reconstruction techniques, thus facilitating reproducibility studies and the benchmarking of commercial low-field systems against the reference systems.
3. To evaluate the clinical suitability of the developed low-field MRI reference systems by standardised tests involving clinical radiologists to assess imaging performance across sites. To perform multisite reproducibility studies and to evaluate the uncertainties of the constructed low-field MR scanners under different operational conditions (e.g., thermal fluctuations or electromagnetic interferences). To compare the performance of these systems and their uncertainties to commercially available low-field MR systems (B_0 = 0.05 - 0.6 T) in inter-vendor comparisons.
4. To facilitate the adoption of the technology and measurement infrastructure developed in the project by the measurement supply chain (e.g. accredited laboratories, instrumentation manufacturers), standards developing organisations (e.g. IEC TC 62/SC 62B), and end users (e.g. clinical community).

Progress beyond the state of the art and results

Mobile, low-cost and fully replicable low-field MRI reference systems

Current low-field MR systems (B_0~50mT) can be brought directly to patients but they use iron yoke magnets leading to a weight > 600kg. In this project a Halbach magnet design will be adopted making the scanner 3-4 times lighter and smaller. The construction does not require specialised machines and is safer, facilitating local production and repair. Investigations of improved RF shielding or novel contactless sensors for patient monitoring will allow for safe, stable and high quality low-field imaging under varying environmental conditions. The system will be fully characterised and all information to rebuild, operate and maintain these scanners will be shared publicly and freely under open source licences for other metrology institutes, research groups, companies etc. to be reproduced. The estimated total cost over 10 years will be 1/10th of the current cost of low-field systems [10,11]. Providing open-source documentation fulfilling the requirements of the EU medical device regulation (EU)2017/745 facilitates the approval for similar low-field MR systems by companies and an easier assessment by notified bodies, which culminates in cost savings for public healthcare systems [11,12]. The fully characterised reference systems will provide excellent and necessary testbeds to investigate safety related aspects of low-field MRI on vendor-neutral transparent systems to improve current standards (IEC 60601-2-33).

Open-source platform with model-based image reconstruction techniques

Image reconstruction for low-field applications is still in its infancy. There are image reconstruction and correction algorithms developed specifically for low-field applications but these are proprietary products relying on proprietary AI and solutions, making it extremely challenging to reproduce results, to innovate and to benchmark inter-vendor performance. This project will provide an open-source platform with model-based image reconstruction approaches optimised for the challenges of low-field low-cost MRI (e.g. low SNR due to the small magnetic field and hardware limitations due to cost-effective design). Deep learning approaches will be leveraged to enable fast and accurate quantitative imaging of biophysical parameters (e.g. T_2, $T_{1,rho}$). A database with MR raw data acquired from low-field scanners will be created and made publicly available to enable comparisons and foster further developments.

Cloud-based solutions to operate and maintain the MR scanners will ensure the utilisation of complex image reconstructions without the need for high-end local computing power.

Evaluation of the clinical suitability and comparison to other low-field systems

For the first time multiple low-field low-cost open-source MR scanners will be built at different sites and evaluated. This will establish a long-lasting framework for metrology in this growing field. The performance of the constructed reference scanner will also be compared to commercially available low-field MR systems of similar (B_0=50mT) and higher (B_0=0.2-0.6T) field strengths. This will give important results to evaluate signal-to-noise ratio (SNR), contrast-to-noise ratio (CNR) and image quality for clinical use over a variety of low-field strengths. The open source nature of the project allows the developed hardware, software, pulse sequences and image reconstruction techniques to be easily translated to other low-field MR systems improving their imaging performance.

<u>Outcomes and Impact</u>

Outcomes for industrial and other user communities

The innovations from the reference low-field MRI (e.g. novel magnet design, embedded sensor technology, novel pulse sequences and image reconstruction techniques) can be easily benchmarked and translated into novel products by MR vendors decreasing time-to-market drastically. Software development usually requests a substantial amount of resources. The developed open-source user interface and imaging platform is based on transparent interfaces to MR console hardware (Pulseq) and MR image reconstruction (ISMRMrd) making it easily applicable by MR vendors to their products, while a large scientific community can feed into the development of the image processing pipeline. This connects the scientific and industrial communities more efficiently, improving products and saving industrial resources. At the same time other communities can be involved into the development and evaluation of these low-field systems, such as radiologists, radiographers and technologists and patients. Other non-MR vendors have easier access to machines and the expertise around MRI to develop novel products e.g. implant vendors of neuromodulation devices, patient monitoring devices or industrial process imaging. Vendors of medical devices, but also test-houses and notified bodies will benefit from the freely available blueprint of the technical documentation according to (EU)2017/745 MDR substantially lowering the hurdle for similar MR products such as portable low-field scanners and non-MR products e.g. other class II medical devices such as ultrasound to enter the market. Globally, medical devices regulations are not harmonised and many regions exist without any clear regulations. Transparent and replicable MR systems developed alongside EU MDR documentation, clears the path for local adoption in non-EU countries of these technologies in particular in low-resource settings, accounting for quality, reliability and safety independent of location.

Outcomes for the metrology and scientific communities

For a thorough metrological assessment of low-field MRI, fully characterized and transparent reference hardware needs to be available. This project gives access to this hardware and builds a network within the metrology institutes, while connecting it to the large scientific community. Currently low-field systems are highly integrated devices using deep-learning based image reconstruction algorithms tightly bound to specific hardware modules using e.g. sensors for SNR improvement and motion correction. An evaluation of the generated uncertainties or the traceability of the uncertainties in deep-learning based methods is challenging if not elusive. Fully characterized reference systems will help to evaluate the robustness and explicability of deep-learning based methods, as well as assessing the uncertainties of portable low-field MRI under varying conditions. This is important to guarantee safe and robust imaging results and transition from qualitative to quantitative MRI. Reference hardware furthermore enables benchmarking against commercially available MR systems. This improves the scientific and clinical evaluation of MR techniques and spurs innovation by means of reproducible results. Currently 'open' scientific communities are divided into software development (Gadgetron, Pulseq) or hardware development (Open Source Imaging Initiative), since no single transparent system exists where both software and hardware development can be optimized towards a specific research or clinical target. This will change with the availability of transparent, reproducible low-field MR scanners.

Outcomes for relevant standards

Even though low-field MR scanners might be considered to be safer than higher field (B_0>1.0T) systems in many aspects such as stray magnetic field, acoustic noise, peripheral nerve stimulation or SAR, the most important MR safety standard, the IEC 60601-2-33:2022 "Particular requirements for the basic safety and essential performance of magnetic resonance equipment for medical diagnosis" [13], currently does not take this into consideration, making regulatory approval unnecessarily complicated. The project results will provide a major contribution to future editions of the IEC standard (e.g. edition 4.1 of IEC 60601-2-33), simplifying current procedures for safety evaluation of low-field MRI. This will improve the innovation potential of this technology, reducing costs and improving global accessibility. The developed reference hardware will furthermore enable investigations into the safety of low-field MR systems (B_0<0.1T) for patients with passive and active implants, providing important results to ASTM F2182 and ISO/TS 10974.

Longer-term economic, social and environmental impacts

Open-source laboratory hardware showed to reduce the costs by a factor of ten compared to comparable commercially available proprietary hardware [14]. Medical hardware based on open source designs has a huge cost saving potential both for the device and the service market through cheaper machines, access to information and more competition alike. This will help to demonopolize the MR market, leading to cost savings for the public healthcare systems in the EU. Based on data from the German healthcare system it was estimated that up to 222 mio € can be saved per year by an open source MR scanner and an additional of more than 100 mio € per year would be available for the public healthcare system if MR service costs could be reduced [15,16]. Open hardware can build innovation capacity in countries with low investments in science, technology and innovation, making these investments more efficient, while decentralized collaborations between academia, civil society and the private sector are strengthened [17]. In particular the Open Source software developed in WP2, which is used to operate the reference scanners but also to view and post process imaging data, will be a connecting hub for metrology institutes and researchers from resource poor settings and empower them to participate in a scientific exchange, to innovate and ultimately to improve healthcare locally. At the same time researchers from resource rich environments are being sensitized to challenges from less fortunate settings, motivating ideas and solutions for regions and patients currently excluded from the scientific and clinical discourse in MRI.

A modular approach to hardware development as implemented in this project, benefits a decentralized open source community, but provides at the same time interesting opportunities to modular MDR documentation to initiate an openly available blueprint for a sustainable long-term strategy to medical device development.

22HLT03 AlphaMet
Metrology for Emerging Targeted Alpha Therapies

Summary of the project

Overview

Targeted alpha therapy (TAT) is a rapidly growing cancer treatment modality, whereby alpha-emitting radiopharmaceuticals selectively target tumours whilst minimising the radiation to healthy tissues. Presently only $^{223}RaCl_2$ has regulatory approval, but its success resulted in unprecedented levels of interest and investment in TAT for a variety of cancers. It is showing promising efficacy and increased survival in clinical trials; however, several unmet and unique measurement challenges remain a barrier to enable the safe and optimised implementation of emerging targeted alpha therapies. This project will provide the metrology needed to support end-to-end traceability before wide routine adoption.

Need

Global cancer incidence is projected to increase 47 % by 2040 with 28.4 million new cases each year (1). Europe's Beating Cancer Plan recognises the need for personalised cancer treatments and encourages the development of novel radiation therapies like TAT. The success of $^{223}RaCl_2$, the first and only with marketing authorisation for advanced prostate cancer, resulted in unprecedented levels of interest and investment in this promising treatment modality with new treatments based on ^{227}Th, ^{225}Ac, ^{212}Pb, or ^{211}At undergoing clinical trials (2, 3).

The short range and high energy of alpha particles is showing promising treatment efficacies even in patients not responding to its beta-emitting analogue therapy (4). However, these advantages bring new measurement challenges including the lack of validated primary (secondary) activity standards, the in-growth of the decay progeny, the separation of the decay products, or the quantification of the microscopic distribution of activities and absorbed dose *in-vivo* (5, 6). The best approach to deliver TAT is under debate and good practice guides are not available, with treatments currently administered with fixed radiopharmaceutical activity levels and not guided by dosimetry. This in contrast to external beam radiotherapy, where treatments are traceable to primary standards and accuracy in dose delivery to patients is below 5%. The accuracy, reproducibility, and uncertainties in the delivery of TAT are presently unknown, with a recent ICRU Report 96 (6) highlighting the need to address the lack of traceability and standardisation/harmonisation.

An estimated 6 million annual therapies are already delivered across more than 1,500 nuclear medicine centres in the EU (7), and unprecedented levels of demand for TAT are expected in coming years (100-fold) (8-10). It is therefore of vital importance to facilitate accurate measurements with minimal uncertainties to improve confidence and evidence in the safe routine implementation of personalised TAT, required to support 2013/59/EURATOM and other regulations.

Objectives

The overall objective of the project is to address the unique and unmet metrological challenges of targeted alpha therapies. The specific objectives of the project are:

1. To develop and validate **primary and secondary radioactivity standards** with traceability to national standards and low uncertainties that consider decay chain progeny in-growth and the separation of decay products for alpha-emitters. In addition, clinical therapy requirements and achievable clinical measurement accuracies are to be assessed by an inter-comparison exercise.
2. To provide guidance for clinical stakeholders on organ **activity quantification methods** using external monitoring systems and nuclear medicine imaging. This is to be achieved by: (i) the development of methods to quantify the separation of the decay products during imaging at the required levels of therapy activity; and (ii) the performance of a comparison exercise to assess the accuracy, reproducibility, and the quantification of uncertainties of the developed methods in a clinical setting.
3. To establish **accurate alpha-emitter dosimetry calculations** that enable compliance with 2013/59/Euratom and the assessment of the true dose response relationships. This is to be achieved by: (i) the validation of dosimetry pharmacokinetics models for TAT; (ii) the determination of the uncertainties from measured activity to absorbed dose, including the identification of major factors affecting accuracy and precision for alpha emitting therapies; and (iii) the determination at the tissue level of the significance of mean dosimetry for highly heterogeneous distributions of alpha emitters.
4. To determine a **multi-modality imaging protocol that considers differences in bone density and marrow cellularity between individual patients based on**: (i) **a test object** manufactured by 3D printing technology that incorporates relevant tissue-equivalent materials and geometric complexity for the assessment of treatment toxicity and (ii) bone marrow dosimetry.
5. To facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain and end-users (e.g., pharmaceutical as well as medical and healthcare products manufacturers, clinical QA laboratories and clinical stakeholders) and the relevant organisations in the context of the regulation (e. g. EANM, EFOMP, IAEA, EURADOS).

Progress beyond the state of the art and results

Realisation, validation, and dissemination of radioactivity standards

Revision of secondary standards for ^{223}Ra in 2015 showed a 9% discrepancy with previous data and highlighted the importance of traceability to primary standards and international comparison exercises. Primary and secondary standards will be developed for emerging alpha emitters ^{225}Ac, ^{212}Pb and ^{211}At to enable traceable activity measurements for TAT in (pre)clinical centres, hospitals, and production sites. The robustness of activity standards will be assessed through inter-laboratory comparison and submission to the BIPM-SIR. To meet the needs of end-users, time-dependence of calibration factors will be investigated when parent-progeny equilibrium conditions are not reached. The metrological traceability and accuracy of radionuclide activities administered to patients and used by (pre)clinical research centres, will be improved via a multi-centre intercomparison using radionuclide calibrators and gamma counters.

In-vivo activity quantification with SPECT in TAT

Quantitative SPECT imaging is not established for alpha emitters, with a range of protocols used for acquisition and post-processing analysis (6). This project will use in-silico models of clinical SPECT scanners validated via experimental phantom measurements to optimise 3D imaging acquisition parameters and activity quantification methods, with traceability to the newly developed standards. The generated ground-truth data will be used to optimise methods to quantify long-lived decay progeny that may redistribute to other tissues, image reconstruction and correction methods to improve image quality and accuracy of activity quantification with known uncertainties. A standard protocol will be developed and used to perform the first multi-centre comparison of SPECT nuclear imaging for alpha emitters, providing knowledge on the levels of accuracy, reproducibility, and uncertainties achievable for harmonisation. This will provide recommendations for the harmonisation of quantitative imaging following TAT and will identify the major factors that impact accuracy and need further improvements.

Quantification of absorbed doses in TAT

The ability to quantify the distribution of alpha emitters *in-vivo*, enables the possibility to incorporate dosimetry to optimise the treatment instead of using a 'one size fits all' approach with fixed administered activities. Accurate dosimetry relies on accurate knowledge of the spatial and temporal activity distribution and dose conversion factors. Commonly used clinical (macro)dosimetry methods assume a uniform uptake and no redistribution of daughters from the parent radionuclide. A framework will be established in this project to assess the impact and errors associated with these assumptions through autoradiography, pharmacokinetic modelling and microdosimetry for TAT, including methods to assess the uncertainties in the activity to absorbed dose measurement chain.

Towards personalised bone marrow dosimetry through quantitative morphological imaging

The red marrow is considered a dose-limiting organ at risk that can limit the administered activity, making marrow dosimetry essential for safety. Reference models for marrow dosimetry are based on relatively simple skeletal models. Variations on bone density, and red and yellow marrow contents can introduce errors of up 200% on red marrow dosimetry for alpha emitters depending on bone site and age, making it highly patient-specific (11, 12). This project will evaluate the potential to incorporate patient-specific bone marrow morphology measures into dosimetry calculations through the development of a bespoke phantom and morphological imaging protocols based on MR and dual-energy CT imaging.

<u>Outcomes and Impact</u>

Outcomes for industrial and other user communities

This project will be the first international effort to provide metrology support for the determination of end-to-end measurement uncertainties and for improving methods to quantify activity and absorbed doses for alpha-emitting radiopharmaceuticals. The provision of validated radioactivity standards for currently unavailable alpha-emitting radiopharmaceuticals will enable the dissemination of traceability from NMI/DIs and will provide access to improved capabilities for national and accredited laboratories in Europe, supporting consistency in activity measurement capabilities. New standards with recommendations for improving measurements will benefit the end-users that rely on such calibration services, including manufacturers of ionising radiation measurement instruments (radionuclide calibrators, gamma counters, imaging scanners), radionuclide production facilities, and pharmaceutical companies.

Hospitals delivering TAT will be able to administer treatments with traceable activities, with accuracies within the limits recommended by the IAEA (13). The recommendations for good practice will be of benefit to end-users like healthcare professionals in hospitals and the pharmaceutical industry, providing them with methods to standardise and harmonise imaging and dosimetry methods with robust uncertainty budgets. This will improve reproducibility in multi-centre studies and enable comparison of results, providing greater statistical power to study correlations between absorbed dose and response/outcome measures which are still lacking for TAT. This will provide the basis for evidence-based treatments, facilitating regulatory compliance and marketing authorisation of upcoming alpha radiopharmaceuticals for the pharmaceutical industry, and potentially reducing the development costs by introducing metrology early before routine implementation of TAT.

Outcomes for the metrology and scientific communities

Standardisations and improved decay data for alpha emitters will be validated through inter-laboratory comparisons organised by the participating NMIs and linked to the BIPM International Reference System (SIR) to provide a route to demonstrate their accuracy, consistency, and independency, which in turn will support regulatory compliance. Some of the participating members are new to a EURAMET project, which will promote knowledge transfer between the scientific community and metrologists, building networks that will lead to opportunities for further research. Knowledge in activity standardisation techniques will be shared amongst NMIs.

A recent report by the European Commission identified the need for investment towards a sustainable and resilient supply of medical radionuclides in the EU as key to meet future demands, in particular for alpha emitters (14). These challenges are presently being addressed by other on-going initiatives such as Horizon 2020 PRISMAP or the NOAR COST Action project. The outcomes of this project will complement and expand on these initiatives by addressing the measurements challenges of establishing traceable and harmonised measurements to guide the use of upcoming TAT in a clinical setting.

These and other initiatives will create and strengthen opportunities and collaborations between metrologists and the scientific community, increasing the competitiveness and international recognition of the European metrology infrastructure. The project outputs will be disseminated to the scientific research community and other stakeholders via reports and recommendations, peer-reviewed publications in high-impact scientific journals, presentations at national and international conferences, and through engagement with the IAEA and international societies such as the EANM, EFOMP and EURADOS.

Outcomes for relevant standards

The improved end-to-end measurement traceability provided in this project, from the provision and dissemination of activity primary and secondary standards to the provision of recommendations for accurate imaging and dosimetry with known uncertainties for alpha emitters, will support EU directive 2013/59/EURATOM mandating dosimetry-guided radiopharmaceutical therapies (including TAT), but also 2001/83/EC for medicinal products, and 2001/20/EC for clinical trials.

The experienced consortium will promote the results of the project within the standardisation community and through involvement with international technical committees, including organisations establishing international equivalence for radioactivity measurements (BIPM, EURAMET TC-IR) through the development of radionuclide metrology techniques (ICRM). Good practice guides and recommendations to standardise and harmonise imaging and dosimetry for TAT will be disseminated and promoted within the International Atomic Energy Agency (IAEA), European Association of Nuclear Medicine (EANM), the European Federation of Organisations for Medical Physics (EFOMP), and the European Radiation Dosimetry Group (EURADOS). In particular, the results of a multi-centre comparison exercise of clinical quantitative SPECT imaging for alpha emitters will be of interest to the EANM Forschung GmbH (EARL) initiative establishing accreditation programmes for the harmonisation of nuclear medicine imaging. However, it should be noted that some of these processes can be lengthy and extend beyond the duration of this project.

Longer-term economic, social, and environmental impacts

One in 2 people will develop cancer in their lifetimes and as life expectancy increases, the number of patients needing cancer treatment rises. According to an international project by the Lancet Oncology Commission, a comprehensive scale-up of imaging, treatment, and care quality would avert 9.55 million (12.5%) of all cancer deaths, saving 232.30 million life-years. Scale-up of imaging would cost US$6.84 billion in 2020-30 but yield lifetime productivity gains of $1.23 trillion worldwide (15). Therefore, any advancements towards improving image quantification for emerging novel cancer treatments like TAT will have a major positive economic impact.

The development and translation of new TAT for a variety of cancers is rapidly growing with a global market size of US$ 672 million that is expected to grow 36.7% by 2027 (3, 16). As an example, due to the high incidence of prostate cancer, which is a prime candidate for TAT, an unprecedented level of demand is expected, with 350,000 patients being potentially eligible for ^{225}Ac-PSMA therapy in coming years if following the same trend as its beta-emitter analogue ^{177}Lu-PMSA (17). In the UK, the number of $^{223}RaCl_2$ treatments increased by 100-fold in three years following its approval (8), further highlighting the potential rate of demand. The traceability for TAT provided by this project is therefore of major importance to support the logistical and scientific challenges that European nuclear medicine departments will face in the imminent future.

The implementation of metrology to support the development and use of alpha-emitting radiopharmaceuticals has a fundamental role in the provision of cost-effective cancer treatments that improve patient outcomes with minimal toxicity. Improved knowledge of the decay data, traceable measurements of activity as well as harmonised imaging and dosimetry protocols for multi-centre studies will provide robust tools and confidence to enable personalised dosimetry-based treatment planning and treatment verification as required by the Basic Safety Standards Directive. The outcomes will also indirectly contribute towards increasing confidence in radiation protection measurements for handling of radioactive material during the delivery of TAT.

On a wider impact scale, the developed innovative approaches and new collaborations established between measurement laboratories and stakeholders will be open to further exploitation and lead to new services and products relating to activity measurements, imaging and dosimetry calculations for TAT that can result in higher employment rates and wealth for society across Europe and worldwide.

22HLT04 MetrINo

Metrology for Innovative NanoTherapeutics

Summary of the project

<u>Overview</u>

MetrINo responds to the immediate **metrological needs** expressed by industry, regulatory agencies and policymakers to develop, and validate **traceable measurement methods** and **reference materials** for the assessment of the **critical quality attributes of nanotherapeutics**. The project will focus on clinical formulations, including **synthetic lipid-based** and **metal oxide nanoparticles** used for localised cancer treatment, gene therapy, vaccines (COVID-19) or as contrast agents. Candidate reference materials will be developed and used for measurement control. MetrINo will develop and validate traceable methods to measure nanoparticle physical properties, biotransformation in biological media, and methods for their identification and quantification in cells and tissues.

<u>Need</u>

Nanotechnologies offer improved treatment for diseases through the effective targeting of therapeutic agents. Approved clinical formulations includes (i) liposomes for cancer treatment, (ii) lipid-based nanoparticles for vaccination (COVID-19) and gene therapy, and (iii) metal oxide nanoparticles for local tumour treatment or as contrast agents. The **European Medical Agency (EMA)** states that, with the approval of innovative nanotherapeutics, we need to «***develop and standardise*** *new testing methods related to the* ***quality and safety assessment*** *of nanomedicines*», to reach an understanding of «*the* ***critical quality attributes*** *of a given product and* ***the relationship*** *between those and* ***its biological activity and in-vivo behaviour***». Recently, the European Commission's Joint Research Centre (JRC) identified priorities for method development and standardisation, including methods to measure: (i) **surface properties**, (ii) **stability and kinetic properties in biological media**, and (iii) **uptake, absorption, and distribution in cells and tissues**. The project industrial partners confirmed these measurement needs for different classes of nanotherapeutics as a global industry requirement. nanoPET, for contrast agents based on iron oxide and gadolinium- nanoparticles, states «*the need for understanding the* ***definition of particle size****; feasibility, and improved methodologies to determine amount, homogeneity, and functionalisation of the* ***nanoparticle surface*** *and for the functionality and detection of nanoparticles in vivo*». Curadigm who develop liposome-based nanotherapeutics, highlighted «*the* ***lack of standardised methods*** *to ensure* ***the integrity of lipid-based products****, to characterize their physico-chemical properties, and* ***their behaviour in complex biological medium***» and the need «*to follow nanoparticle biodistribution and bio-transformation in vivo*». Nanobiotix, a global company designing clinically approved radio-enhancers for the treatment of soft tissue sarcoma, based on hafnium oxide nanoparticles, underlines the critical «***absence of reference materials** and standardized methods **for metal oxide nanoparticles***» that are needed «*for method validation of fit-for–purpose characterisation techniques following regulatory agency recommendations*».

Objectives

To answer the specific needs expressed by EMA, the European Commission and by industrial stakeholders, MetrINo responds to five specific objectives:

1. Develop representative testing materials (RTM) for synthetic lipid-based and metal oxide nanoparticles and to measure their chemical composition, particle size distribution, polydispersity and particle concentration with a controlled uncertainty using existing methods.

2. Develop and harmonize traceable methodologies for measuring:

a. particle size and concentration of small (<10 nm) nanoparticles and of agglomerated or aggregated non-spherical objects,

b. lipid composition and structural integrity of lipid-based nanoparticles,

c. nanoparticle surface properties, including the amount, chemical composition, and homogeneity of the surface coating.

3. Develop and harmonise robust and efficient sample preparation methods for the measurements of the nanoparticle stability and their biotransformation in biological matrices, and to minimise matrix interferences. Fractionation methods, including size exclusion chromatography (SEC), field flow fractionation (AF4) and ultracentrifugation (UC) that are used to separate nanoparticles from free proteins in plasma, reach a demonstrated recovery of the analyte of interest above 70 %, as required by ISO/TS 21362:2018 and CEN/TS 17273:2018.1,2

4. Improve correlative methods and model tissue phantoms to measure nanoparticle uptake and distribution in single cells and tissues associated to their biodistribution profile, safety, and efficacy. This includes using a combination of complementary techniques (e.g., MS, single cell ICP-MS, EM, Raman- and fluorescence-based approaches) with the aim to reduce the uncertainty in the detection, localization, and quantification of nanoparticles in single cells and tissues. The developed methods, RTM and model tissue phantoms to be consolidated through the performance of an interlaboratory comparison.

5. Facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain (NMIs, accredited laboratories), standards developing organisations (e.g., CEN/TC 352-Nanotechnologies, ASTM E56, ISO TC 229), VAMAS TWA 2 and TWA 34 and end users (e.g., the pharmaceutical industry, regulators, clinicians, nanomedical product manufacturers, nanomedicine research community).

Progress beyond the state of the art and results

To fulfil **objective1**, NMIs will work in collaboration with industrial stakeholders to develop **a library of reference material (RM) candidates representative of nanotherapeutics** in the clinic. The library will be used for the methodological development to fulfil objectives2-4. Stability and homogeneity studies will be initiated for the development of selected formulations of RM candidates and a roadmap will be defined for their certification and commercialisation beyond the project lifetime. The library will include:

(i) **iron oxide (Fe_xO_y)** and **hafnium oxide (HfO_2)** formulations characterised by small particle sizes (constituent particle core<10nm) or aggregated sub-populations or characterised by representative surface coatings;

(ii**) lipid nanoparticles (LNPs)** and **liposomes** loaded by different active pharmaceutical ingredients (siRNA, mRNA) with defined drug/lipid ratio and characterised by different lipid composition mimicking Onpattro and the COVID-19 vaccines for structural integrity determination;

(iii) **fluorescent multi-element nanoparticles** like $NaGd_xY_{1-x}F_4$ doped with Yb(III) and Er(III) for correlating and comparing elemental and optical methods for measuring NP uptake and distribution in single cells and tissues on the same formulations.

MetrINo will fill the identified methodological gaps, and go beyond the state of the art by:

1. Validating the use of **traceable methodologies**, including small-angle X-ray scattering (SAXS) and a hybrid microscopic approach (AFM-SEM-EDX), for the measurement of **particle size and concentration** of Fe_xO_y and HfO_2 NPs (<10 nm) and their aggregates, also **advancing** the approaches for **data analysis** to **reduce** the associated **measurement uncertainty** (**Objective 2a**);
2. Providing a **structured tier approach** for the **determination of the lipid composition, drug loading and for the structural properties** of lipid-based formulations including (i) bulk techniques, e.g. advanced mass spectrometry (MS), calorimetry, capillary electrophoresis, raman spectroscopy, SAXS), and (ii) innovative emerging particle-by-particle measurements such as cryo-time of flight secondary ion mass spectrometry (cryo-TOF-SIMS) and cryo-transmission electron microscopy (cryo-TEM), by evaluating the **sensitivity**, **precision** and **robustness** of selected protocols and performing a preliminary **uncertainty budget determination** (**Objective 2b**);
3. Evaluating the applicability of emerging methodologies for the characterisation of particle surface chemistry ad coating, including the quantitative determination of the average coating mass by differential scanning calorimetry and thermogravimetric analysis coupled to MS, and the particle-by-particle coating homogeneity by cryo-TOF-SIMS (**Objective 2c**);
4. Optimising established separation methods, including AF4, SEC, or analytical ultracentrifugation (AUC), for the isolation of HfO_2, Fe_xO_y, liposomes or LNPs-RNA from complex biological media (serum, plasma and blood), and validating the methodologies according to the resolution capacity, sample recovery (>70%) and precision criteria (<5%) required by available standards (**Objective 3**);
5. Developing tissue phantoms systems spiked with a known amount of HfO_2, FexOy, fluorescent multi-element NPs, LNPs-RNA or liposome, that could serve altogether as candidate RMs for particle localisation, quantification and uptake in solid tissues (**Objective 4**);
6. Using the developed tissue phantoms for evaluating method sensitivity, precision and robustness, developing standard operating procedures (SOPs) for a range of complementary methods to identify, localise and quantify NPs correlatively, and providing the basis of an external ILC for the evaluation of the associated measurement uncertainty (**Objective 4**).

<u>Outcomes and Impact</u>

Outcomes for industrial and other user communities

Every step provided by MetrINo towards the development of reference materials and validated protocols will support the industry in the design, characterisation, regulatory evaluation and clinical translation of innovative nanotherapeutics. Such standardized methods will also provide knowledge about the structure-function relationship of the nanomaterial. This knowledge will provide confidence for regulatory acceptance and improving quality control methods. The understanding gained will be directly exploited by the industrial partners involved in the project in their exchange with regulatory agencies and by adopting the validated protocols for the characterisation of their formulations under development for their release. Use of the developed protocols and RM and alignment with industry beyond the consortium partners is assured through the support of additional industrial end users belonging to, (i) the pharmaceutical industry and to the medical device industry, (ii) to SMEs that are members of the main European nanomedicine associations and to (ii) instrument providers. All target groups of stakeholders have guaranteed their support to MetrINo through participation in knowledge exchange workshops (>20 LoS) and, for most of them, by joining the Stakeholders Advisory Board (SAB).

Outcomes for the metrology and scientific communities

This is the right time and a unique opportunity for European metrology to create impact on future research in the field of nanotherapeutics. Every key exploitable result (KER) developed in MetrINo will expand the measurement capabilities of the NMIs involved in the project to provide pre-clinical, regulatory and quality control services at the highest metrological level. Simultaneous interactions between NMIs, academia and industrial companies within MetrINo will support the use of the created metrological infrastructure. MetrINo will additionally support academia and several on-going EU projects by (i) providing SOPs, guidelines and templates for data reporting for less mature measurement methods and (ii) moving more advanced methodologies towards standardisation. Importantly, the ETPN (European Nanomedicine Technology Platform) will lead the impact WP, addressing the whole European nanomedicine community, and benefitting from its well-established network and methodology for community building and common strategic thinking. Through its involvement, an important long-term impact of MetrINo will be ensured by community building actions, notably through the organizations of several in-person workshops, webinars and high-level meetings between stakeholders all along the value chain of nanomedicine translation to the clinic. Finally, the involvement of North American NMIs which are pioneering in the field of nanotherapeutics, including NIST and NRC will enable global standardisation for nanomedicine.

Outcomes for relevant standards

Relevant project partners will report project outcomes in ISO, CEN, IEC and ASTM committees and working groups in VAMAS, BIPM CCQM IAWG (Inorganic working group) as well as in national standardisation organisations. Importantly, the chairs of CEN/TC 352 and ASTM E56 have expressed their support to MetrINo (LoS), explicitly mentioning their ambition to collaborate on ongoing standardisation projects (ASTME56) and to initiate new projects (CEN/TC 352). During the project lifetime, MetrINo will actively collaborate in drafting three ongoing standardisation projects focused on lipid-based NPs in ASTM E56.08, ASTME56.02 and ISO/TC 229. Furthermore, the project will initiate a nanomedicine roadmap, and two new standardisation projects on metal oxide nanoparticles (MONPs) and inorganic NPs, based on the validation of methods responding to Objective2 and Objective3. Finally, the RM candidates, model tissue phantoms, and results of the internal inter laboratory comparison (ILC) responding to Objective4 will serve as a basis to initiate an external ILC study under VAMAS TWA 40 - Synthetic Biomaterials, that will run beyond the lifetime of the project.

Longer-term economic, social and environmental impacts

MetrINo actively supports the translation of European nanomedical innovation to clinical application. It reinforces and extends cooperation of the European nanomedicine community to worldwide measurement experts, innovators, and regulators. It will leverage previous public and private European investment in nanomedicine, notably the hundreds of million Euros committed by the EU in their research and innovation programmes on nanotechnology for the last 15 years and will accelerate and optimize the translation of innovation into advanced and safer therapies, available to European citizens as globally. By reducing the risks of the nanotherapeutic development process, MetrINo will actively contribute to the local creation and development of innovative European SMEs. This is an impactful response to the need expressed by the EMA of more collaboration across the European regulatory landscape to improve the innovation environment and enhance patient access to new medicines in line with the EMA Strategic Roadmap to 2025. The project will strengthen the position of Europe in determining international policy, regulation, and the direction of standards committees related to medicinal products. Such leadership will contribute to the development of European and international standards directly relevant to EU centred activities. The project will support the work of EMA and European national and international regulators within the pharmaceutical sector, while also creating a framework of global cooperation across stakeholders that will boost confidence in innovation, attracting investment. MetrINo will reinforce the cooperation of NMIs with EMA, the U.S. Food and Drug Administration (FDA), and other international regulators in the pharmaceutical sector and support the translation of such cooperation to standard bodies and measurement expert communities in Europe and the world. The project outcomes will help ensure that Europe sustainably and enduringly engages in the medical innovation process and that European citizens and economies will benefit from these innovations. In summary, MetrINo represents a unique chance to ensure Europe as a global leader in nanomedicine, leading to value creation, both in cost savings for the healthcare systems and job creation notably through the creation of specialized SMEs, benefiting from a whole nanomedicine-friendly ecosystem.

22HLT05 MAIBAI

Developing a Metrological framework for Assessment of Image-Based Artificial Intelligence systems for disease detection

Summary of the project

Overview

Image-based artificial intelligence (AI) systems for disease detection are increasingly being developed, and it is vital that these tools are robust and effective in heterogeneous clinical settings. To date, performance has been assessed in an ad hoc manner as there are no approved guidelines for evaluation. Most studies have methodological weaknesses and results that are not comparable. A standardised and impartial framework for performance, generalisability, and suitability assessment of AI tools will address these needs and enable more efficient, reliable and reproducible validation of image-based AI systems for disease detection. This project will use breast cancer screening as the exemplar to inform the design of such a framework.

Need

AI has the potential to transform healthcare systems significantly and play a key role in future clinical decision-making. The exponential increase in healthcare data over the last decade and fast-paced technology developments have resulted in new AI approaches for diagnostic applications and risk prediction developing rapidly, yielding promising outcomes. However, the implementation of AI in clinical settings remains limited, mostly due to a lack of robust validation procedures and trustworthiness as well as a lack of clear understanding from the national bodies on steps for adoption (*https://www.bmj.com/content/374/bmj.n1872*).

There are many challenges to accessing suitably anonymised healthcare data, due to necessary information governance and complex data structures. These difficulties may partially explain the limitations of previous evaluation studies on small scale datasets and populations. The development of accessible clinical data warehouses will provide sufficient data and ensure future validations are robust.

Thorough and consistent validation of image-based AI systems for disease detection is essential, not only in terms of sensitivity and specificity, but also in how they will be intended to be used in the clinical environment. Crucially, the AI systems must be sufficiently generalisable and fit for purpose for the population they are to be applied to. Well-designed comparative test accuracy studies and cohort studies in large and diverse populations are urgently needed, as well as evidence from direct comparison of different AI systems; the effect of different imaging machines on the accuracy of AI systems; the effect of differences in screening programmes on disease detection with AI; and the effect of making available additional information to AI systems for decision making.

Objectives

The overall objective of the project is to develop the metrology research necessary to support standardisation in image-based AI systems for disease detection. Using breast screening as an exemplar, the performance of AI tools will be analysed on a large real-world database of mammographic images, informing the design of the standardised assessment framework.

The specific objectives of the project are:

1. **To develop technical infrastructure** to be able to query and extract the relevant data from various databases, such as the OPTIMAM Mammographic Image Database (OMI-DB) (*https://pubs.rsna.org/doi/full/10.1148/ryai.2020200103*).
2. **To identify the key factors differentiating clinically relevant subgroups** in the data and use these to categorise the data into subsets based on these key factors, identifying where there is sufficient data for training and validation. **To develop a methodology to generate data derived from physics-informed models based on measurement knowledge**.

3. **To use an explainable and traceable AI tool for disease screening**, providing the capability to train and retrain the tool as necessary, **to evaluate its performance** under different scenarios, including low versus high image quality data, validation for specific patient demographics, etc. **To develop and validate methods for the interpretation of the behaviour of the trained AI tool.**
4. To summarise the performance testing evaluations and to provide metrology recommendations for the assessment of AI tools for disease screening- with a focus on understanding their generalisability and sensitivity to varying populations, manufacturers, image processing and acquisition techniques. To use the recommendations **to design a global, standardised, and impartial AI assessment framework**.
5. **To facilitate the take up of the technology and measurement infrastructure** developed in the project by the measurement supply chain, standards developing organisations (British Standards Institution, ISO/IEC JTC 1/SC 42 – Artificial intelligence), and end users (e.g. clinical stakeholders, manufacturers of medical and healthcare products, regulators).

Progress beyond the state of the art and results

Technical infrastructure for interacting with medical imaging databases

In order to evaluate the generalisability of an AI tool, the medical imaging dataset used should cover the range of populations and imaging technology that the AI tool will encounter clinically. There are currently a relatively small number of large-scale medical imaging databases. Each of these databases contain images from a single country with the imaging technology and data storage used in that country. This can make it challenging for end users to identify data suitable for their task, as the data are stored using different methodologies. This project will overcome this, by establishing a methodology for centralised, common metadata indices. This will allow high-level investigation of disparate imaging datasets across Europe using a common middleware layer.

Differentiation of clinically relevant subgroups in data and generation of derived data

For training and validation of AI tools in a healthcare context it is important to have enough clinically relevant subgroups to ensure the tools will be generalisable and unbiased. Often, the subgroups can be unbalanced and there is missing data for key clinical and/or measurement factors. This project will develop a methodology to differentiate the subgroups based on key factors using existing clinical data and will also develop methodologies to generate derived data to supplement the missing subgroups. A comprehensive strategy will be implemented, involving in silico modelling, data augmentation techniques and machine-learning (ML) based approaches.

AI based tools for mammography

For breast screening, the exemplar that this project will work on, AI tools are increasingly being developed to detect disease and make risk predictions from mammographic images showing promising results (*https://www.nature.com/articles/s41586-019-1799-6*), but there are still methodological concerns around the assessment of these tools that mean there is still a lack of wide scale adoption in the clinic. This project will define prediction tasks and associated performance metrics of high clinical relevance for breast cancer assessment and procure relevant AI models for the selected prediction tasks that can be trained and re-trained on selected datasets in a systematic way. In this way, a thorough evaluation of these AI tools can be carried out, providing specific working examples for the assessment framework.

Interpretation methods for explainable and traceable AI tools

A clear methodology to benchmark the quality of predictive AI models that inform clinically relevant decisions is essential if AI is going to be used in clinical settings. This project will define and implement a taxonomy of metrics covering relevant dimensions of model quality that, together, ensure that the model is fit for purpose and “trustworthy”. Quantitative performance metrics will be calculated and model quality will be assessed in terms of prediction performance, robustness, fairness, and “explainability” as well as, optionally, uncertainty quantification (*https://arxiv.org/abs/2206.01653*).

In applications where high-stake decisions may be drawn from a machine learning model's output, the use of so-called "explainable AI" (XAI) tools is often strongly encouraged. However, formal requirements for XAI methods are lacking and existing approaches are insufficiently validated, preventing them so far to be of use for actual quality assurance purposes. To overcome this limitation, this project will develop a framework to define a notation of correctness of XAI methods and to formally verify the correctness of XAI tools for mammography using carefully selected ground-truth data and via directly interfacing with radiologists.

Global, standardised and impartial AI assessment frameworks

The increasing number of government initiatives and guidelines for the safe implementation and deployment of AI in healthcare demonstrates that it is a top priority worldwide. This project will develop a standardised and impartial assessment framework that will enable more efficient, reliable, and reproducible validation of image-based AI systems for disease detection, using breast cancer screening with mammographic images as the exemplar. It will provide specific guidance on the practical steps for AI evaluation in healthcare and would be in line with high-level regulatory guidelines (*https://www.fda.gov/media/145022/download*). Importantly, the project not only proposes the AI assessment framework, but provides a technical implementation to make the metrics and guidelines accessible and operational.

Outcomes and Impact

Outcomes for industrial and other user communities

The standardised and impartial assessment framework proposed here would enable more efficient, reliable, and reproducible validation of image-based AI systems for disease detection. This in turn would result in the scalability of AI systems for disease detection, enabling the reliable and safe use of AI in healthcare.

More broadly, such a framework would provide a way for the AI-tech and digitalization industry to safely develop and implement their products, and for health service providers to build the trust needed to use them, providing a level playing field for competition and innovation in this key new technological arena.

Specifically for breast screening, the exemplar that this project will work on to inform the design of the framework, it would provide a standardised platform for assessing the generalisability of AI based tools which would enable earlier implementation of these into clinical use. The implementation of AI could address issues in delays in reading images due to shortages of high-skilled staff to read the images. These staff shortages are expected to become worse over the next few years. Furthermore, in the context of breast screening tool assessment, the proposed research would develop explainable and traceable AI tools for breast screening, and also generate methods for data curation and data augmentation of the existing mammographic databases that could be useful for the medical community working in this area, and that could be replicated to other AI assessment problems in healthcare, provided datasets with similar characteristics (size, population coverage, longitudinal nature, etc.) exist. It is providing a way to carry out real-world evaluations for effectiveness and unintended consequences, necessary for increased scrutiny of AI applications in healthcare.

Outcomes for the metrology and scientific communities

The complexity of healthcare, compounded by the user- and context-dependent nature of AI applications, calls for a multifaceted approach beyond traditional evaluation of AI. In this project such an approach will be followed, having external partners bring data science domain-specific expertise, clinical reach, and access to data. Metrology institutes bring independence, experience of developing certification and accreditation programmes, expertise in standardisation and key comparisons.

Furthermore, metrology institutes have a key interest in the explainability of AI and providing confidence in data, evidenced through their own working programmes related to AI and their engagement with AI programmes at a national level. The commitment of NMIs in analytical and statistical models as well as AI-based digital technologies for healthcare is indeed well-aligned with the strategies of the *European Metrology Network for Mathematics and Statistics* (EMN Mathmet), of which most of the NMIs involved in this project are members. The advances in AI and digitalization tool application in society sectors, like healthcare, are strongly recommended by the metrological and scientific communities, as addressed by the *EURAMET's 2030 Strategy* (https://www.euramet.org/publications-media-centre/documents/) and clearly stated in the *White Paper on Artificial Intelligence*, published in 2020 by the European Commission (https://ec.europa.eu/info/sites/default/files/commission-white-paper-artificial-intelligence-feb2020_en.pdf).

This project will further develop the capability of the NMI community working collaboratively at the European level, by developing and validating methods for the interpretation of the behaviour of AI tools and trained networks, which is crucial within the remit of achieving traceable and explainable AI.

Outcomes for relevant standards

The work developed in this project will provide specific guidance on the practical steps for AI evaluation in healthcare and would be in line with the high-level regulatory guidelines. The proposed assessment framework will be applicable globally, having impact therefore at the European level in the context of regulatory guidelines and addressing one of the European Commission's priorities defined for 2019-2024 *"A Europe fit for the digital age"*, which envisages as an action for healthcare the use of AI tools. Additionally, multi-country efforts in harmonisation and standardisation have more commercial leverage on potential AI vendors and providers than any single country. The relevance of this outcome is well evident also through the recent actions of the *International Organisation for Standardisation* (ISO), which signed in April 2022 the *Joint Statement of Intent "On the digital transformation in the international scientific and quality infrastructure"*, previously signed by the *International Bureau of Weights and Measures* (BIPM), the *International Organisation of Legal Metrology* (OIML), the *International Measurement Confederation* (IMEKO), the *International Science Council* (ISC) and its *Committee on Data* (CODATA).

Longer-term economic, social and environmental impacts

The beneficiaries of the proposed research are wide ranging, including national health services, national screening programmes, radiologists, screening professionals, patients, screening population, and the ICT and digitalization industry. The benefits will be earlier diagnosis of conditions affecting millions of people across the world, reduction in the excess of undiagnosed patients, reduction in healthcare costs, faster implementation of data-driven tools into the healthcare ecosystem and, ultimately, improved patient outcomes.

Impacts are also envisaged in view of the foundation of a digital society where citizens can access safe and top quality digital services in health and care, as prioritised by the European Commission, which identified three pillars: 1) citizens' secure access to their health data, including across borders; 2) personalised medicine through shared European data infrastructure; 3) citizen empowerment with digital tools for user feedback and person-centred care (https://digital-strategy.ec.europa.eu/en/policies/ehealth).

22HLT06 GenomeMET

Metrology for genomic profiling to support early cancer detection and precision medicine

A1 Summary of the project

Overview

Cancer is a major burden on European society. Advances in genomics, driven by technologies such as Next Generation Sequencing (NGS), are transforming cancer care, enabling earlier and more accurate diagnosis, guiding therapy selection and driving development of targeted therapies (precision medicine). This improves patient outcomes and health system effectiveness. However, quality and comparability of genomic profiling currently varies significantly and development of standards and metrological means to support the field are in their infancy. GenomeMET will apply metrological principles to develop reference measurement systems (RMS) to support cancer genomic diagnostics in compliance with the In-vitro Diagnostic Device Regulation (IVDR EU 2017/746).

Need

Cancer is one of the most significant challenges for European societies and healthcare systems, being the second largest cause of death with > 1.9 million deaths per year. **Horizon Europe's Mission on Cancer** has identified earlier diagnosis and implementation of precision medicine as key priorities for reducing deaths, improving health, and improving the cost-effectiveness of health systems.

Precision medicine relies on molecular characterisation of a patient's disease, with **genomic profiling** central to new treatment models, enabling earlier and more accurate diagnosis/stratification and guiding targeted therapies. The EU **Beating Cancer** plan recommends genomic profiling for all cancer patients, with the "**Cancer Diagnostic and Treatment for All**" initiative improving access to new genomic diagnostics.

High quality genomic testing using technologies such as NGS and liquid biopsies is vital for successful implementation of precision medicine. However, NGS relies on complex multi-step workflows to simultaneously analyse large numbers of genomic variants, which are susceptible to major and poorly understood sources of uncertainty, resulting in significant variability and a current lack of comparability, impacting patient care and hindering wider implementation.

The standards and RMS to support assay validation and Quality Assurance (QA), including reference measurement procedures (RMP), SI-traceable reference materials (RM) and measurement uncertainty (MU) guidance have yet to be established and are urgently needed to support new test development and approval under IVDR EU 2017/746 and implementation by clinical laboratories accredited to quality standards such as ISO 15189 or 17025.

Developing and establishing novel metrological concepts, capabilities and RMS for genomic profiling will require a large-scale, multi-disciplinary and coordinated approach in collaboration with key end-user stakeholders to achieve the collective goals. GenomeMET addresses the above challenges and aligns with the scope of the EPM Health call (**personalized** medicine and ensuring reliability of **diagnostics** at the **molecular** level).

Objectives

GenomeMET will develop metrological capability and establish metrology frameworks to improve quality and reproducibility of critical processes within genomic profiling workflows, and RMS for high accuracy SI-traceable cancer gene measurement to improve comparability and support assay validation as required by the IVDR (EU) 2017/746.

The specific objectives are:

1. To develop higher order methods to measure critical quality control (QC) parameters within genomic profiling workflows, such as pre-analytical steps (yield (mass (ng) or genome equivalents (n=1))) as well as analytical steps such as yield and uniformity of NGS library preparations. To improve reproducibility, comparability, and quality assurance (QA) of genomic profiling workflows such as NGS and multiplex-PCR and to develop RMS for assessing performance of genomic profiling platforms.
2. To develop RMPs for high accuracy (variation coefficients (VCs) <20 %) and SI-traceable (to n=1) measurements of key cancer biomarkers by using higher order methods, such as digital PCR (dPCR). To assess the performance of RMPs using contrived RMs, such as synthetic, cell line-derived and clinical matrix materials, and to demonstrate the applicability of RMPs to support validation of genomic profiling workflows in objective 1.
3. To develop guidance for MU determination for genomic profiles using data (from objectives 1 and 2) for assessment of random and systematic errors influencing measurements such as variant allele frequency (vAF) and models e.g., Bayesian statistics for nominal properties (e.g., nucleic acid (NA) sequence).
4. To assess i) SI-traceable value assignment (using RMPs from objective 2) and MU (using models from objective 3), for genomic RMs and external quality assessment materials in line with ISO 15194, ISO 17511 and JCTLM, ii) to support comparability and traceability of EQA schemes and profiling workflows identified in objective 1, iii) to develop strategies for assessing commutability

using 1) synthetic materials, 2) contrived "patient like" genomic RMs and 3) clinical samples carrying key cancer biomarkers.

5. To facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain (via EMN-TLM), standards developing organisations (e.g., CEN TC 140 and ISO TC 212), and end users (e.g., healthcare and medical laboratories, IVD developers, genomics/cancer/pathology institutes, EQA providers, RM producers, instrument/reagent developers, regulators).

Progress beyond the state of the art and results

GenomeMET will progress the state of the art by initiating development of novel metrological concepts, RMS and standards needed to support analytical validation and QA of genomic profiling IVDs for cancer patients. This will help enable implementation of accurate, comparable and traceable genomic profiling for improved diagnosis, targeted treatment, and management of cancer. This will include:

- Establishing a multi-disciplinary network of excellence through EMN-TLM of European National Measurement Institutes (NMI)/Designated Institutes (DI) and key stakeholders including clinical laboratories, IVD developers, genomics/cancer/pathology institutes, EQA providers, RM producers, instrument developers, regulators, and standards developers (Objective 5) to establish new metrological frameworks/RMS to support clinical genomics (Objective 1), considering metrology needs for:
    - Nominal properties e.g., NA variant identity, alongside quantitative properties e.g., vAF
    - Multi-parametric profiling e.g., simultaneous detection of large panels (or entire genomes) of disparate genomic variants ranging from single nucleotide variants (SNV) to large structural variants (SV)
    - Complex bioinformatics and analysis of large multi-parametric datasets
    - Novel concepts in SI-traceability and genomic measurand/examinand definition, building on early work to establish traceability to counting (N=1) of NA target molecules
    - Novel approaches for commutability assessment of complex multi-parametric genomic RMs
    - Novel approaches/frameworks/statistical models for determining MU or examination uncertainty of genomic profiling workflows
- Developing novel/improved methods for assessing critical quality attributes of key NGS genomic profiling workflow steps such as NA isolation (yield and quality) from clinical samples (tissue and liquid biopsy from lung and colorectal cancer patients) and NGS library preparation (yield and uniformity of coverage) feeding into frameworks to support assay QA (Objective 1)
- Developing high accuracy (variation coefficients (VCs)<20%) RMPs using SI-traceable (n=1) dPCR to quantify key actionable cancer gene variants in patient samples, supporting orthogonal validation of NGS assays (e.g., sensitivity, accuracy, LOD) and SI-traceable value assignment of RM/EQA materials (Objective 2)
- Establishing novel sequencing (NGS/Sanger) strategies/capabilities for orthogonal validation of genomic variant calls, and identity and purity certification of genomic RM/EQA materials (Objective 2)
- Supporting roll-out of improved/new EQA schemes for cancer genomic profiling through provision of reference values to support traceability and comparability across schemes (Objective 4)
- Establishing routes for assessing commutability of complex multi-analyte genomic RMs taking into consideration nominal (variant identity) and quantitative (vAF) properties, and development of novel cell/tissue-based RM formats (Objective 4)
- Establishing frameworks using statistical approaches for assessing MU for multi-parametric genomic profiling assays considering both quantitative (read count and vAF) and qualitative (sequence/variant identity) parameters (Objective 3)

Development of RMS to support clinical genomics have yet to established and substantial effort will be needed to achieve parity with more traditional areas of laboratory medicine such as clinical chemistry. GenomeMET will ensure that the metrology needs of this rapidly growing sector are recognised and supported to progress the state of the art, establish novel capabilities, disseminate outputs, and contribute to new standards development.

Outcomes and Impact

GenomeMET outcomes support implementation of precision medicine for cancer patients and will have impacts across multiple stakeholder communities:

- **IVD developers** - RMS will support generation of enhanced performance validation data incorporating MU and metrological traceability, enabling genomic IVD developers to better demonstrate performance in line with the IVDR. This will lead to improved quality and comparability of IVDs and faster translation to market through more streamlined and consistent regulatory submissions.
- **Clinical laboratories** – Higher order methods and QC materials for monitoring key workflow quality metrics and performance will enable clinical laboratories to establish improved and standardised QA frameworks, resulting in better quality and more comparable genomic profiling across laboratories and supporting accreditation (ISO 15189 or 17025)
- **Healthcare providers –** Frameworks for assessing analytical performance will enable healthcare providers to undertake improved Health Technology Assessments (HTA) of novel genomic IVDs, incorporating more robust data with defined uncertainties to support future test performance specifications and uptake of genomic profiling into health practice.
- **RM producers** – Frameworks for improved characterisation and SI-traceable value assignment of genomic RMs will enable RM producers to demonstrate metrological traceability and commutability in line with the IVDR and ISO 17511, leading to more streamlined RM development and a wider range of high quality RMs.
- **EQA providers** – Provision of SI-traceable reference values will enable EQA providers to demonstrate long term comparability and traceability of EQA materials and schemes, reducing reliance on arbitrary consensus values. This will improve robustness and quality of genomic EQAs, and support development of new schemes and harmonisation of EQAs in molecular pathology.
- **Drug developers** will be able to undertake more streamlined development of targeted therapies through improved quality of genomic data from clinical trials, enabling more accurate selection of responders/non-responders, leading to reduced development times, fewer failures, lower costs, and more effective cancer therapies.
- **Clinical researchers** will be able to generate more robust, reliable and reproducible genomic datasets, helping to address the current reproducibility crisis in clinical translational research, supporting faster translation of novel biomarkers to the clinic.
- **Regulators** – RMS and guidance for assay validation, incorporating metrological traceability, will inform IVD competent authorities /regulators / reference laboratories on performance metrics for genomic profiling assays, enabling more streamlined assessment of new IVDs and development of recommendations for implementation of genomic approaches in clinical practice.

Outcomes for the metrology and scientific communities

GenomeMET will provide a vehicle for joint activity, inter-laboratory comparisons, and knowledge sharing to support development of novel metrological concepts and capability for clinical genomics (**Objective 5**). Outcomes will support improved EU metrology infrastructure enabling provision of new RMS and measurement/calibration services allowing NMI/DIs to provide more reliable SI-traceable reference values and improving agreement between different laboratories worldwide. Outcomes include:

- Improved NMI/DI capabilities for quantification of cancer genomic biomarkers, quantification of total NA and detection of panels of genomic variants, demonstrated through inter-laboratory comparisons.
- Dissemination of case studies to advance development of metrological frameworks for multi-analyte clinical genomic profiling.
- Submission of new RMPs for quantification of cancer genomic biomarkers and SI-traceable RMs to JCTLM database.

The metrological capabilities developed will also support the wider clinical genomics sector (e.g., rare diseases and NIPT) where NGS profiling is being applied and complement metrology development for other ‘omics sectors where multi-parametric testing is needed e.g., transcriptomics, proteomics and metabonomics.

Outcomes for relevant standards

The RMS to support assay validation will enable IVD developers, clinical laboratories and other end-users to better comply with regulations and standards in the IVD field e.g., IVDR and ISO 15189, 17025 and 17511 through generation of more robust and comparable datasets incorporating metrological traceability and MU.
Higher order methods and materials will support GenomeMET linked stakeholder-driven standardisation initiatives e.g.,INSTAND NGS-4P by providing the underpinning methods/materials required to assess performance.
Outputs from GenomeMET will be incorporated (where possible) into relevant CEN TC140 and ISO TC 212 standards in development for NGS and liquid biopsies through partner representation on drafting committees, and into periodic revisions of standards such as ISO 15193, 15194 and 20914.
Finally, proposals for new standards under CEN TC140 or ISO TC 212 are expected during the lifetime of GenomeMET to support improved validation and QA of genomic profiling and accurate quantification of cancer gene biomarkers

Longer-term economic, social and environmental impacts

Outputs from GenomeMET will support earlier cancer detection and implementation of precision medicine, through confident and valid uptake of genomic profiling. Cancer is the second largest cause of death in Europe, with more than 3.7 million new cases and 1.9 million deaths each year and carries an economic burden of €141.8 billion/pa (1.07% of GDP). Earlier detection and genomics-guided targeted therapies with greater efficacy and less toxicity compared to traditional systemic therapies will significantly reduce healthcare costs and improve patient outcomes. High quality genomic testing will result in fewer diagnostic errors e.g., missed/incorrect diagnosis and support provision of the “right drug to the right patient at the right time” reducing the economic burden of cancer and allowing citizens to live longer and healthier lives.

GenomeMET outputs will also support growth of the European IVD and oncology therapeutics markets, valued at 33 billion Euros/pa and 75 billion Euros/pa respectively through more streamlined routes for approval of new companion and precision genomic diagnostics, and improved genomic data from clinical trials resulting in more accurate selection of responders and more streamlined development of novel targeted therapies.

Environmental impacts include a reduction in the use of medical tools/devices and diagnostic kits/ components through more accurate “right first time” testing. These components are often single-use plastic products, the disposal of which presents an environmental risk.

22IEM01 TOCK

Transportable optical clocks for key comparisons

Summary of the project

Overview

Significant progress with optical clocks has been achieved and they clearly outperform current primary standards of time and frequency. The established key comparison for time and frequency uses satellite-based techniques to provide international consistency with 10^{-16} fractional uncertainty. Optical fibre links between a few national metrology laboratories in Europe enable clock comparisons with low 10^{-18} uncertainty limited by relativistic effects. To overcome these limitations and to compare optical clocks that cannot be interconnected via optical fibre links, within this project travelling frequency standards with performance exceeding the current state-of-the-art will be developed, evaluated, and employed.

Need

The fundamental properties of atoms provide characteristic microwave or optical frequency references used in atomic clocks to realise the most precise measurement devices available today. Within the SI system of units, the realisation of the unit of time with Caesium atomic clocks plays an essential role, as the unit second is contained in the definition of 6 of the 7 base units via the defining constants. Having highly accurate, stable, and reliable reference frequency standards is a pre-requisite not only for the SI System of Units, but also for many everyday technologies that rely on precise time keeping such as banking transactions, communication, and navigation.

Resulting from the higher reference transition frequency, highly precise optical clocks have made great progress with a variety of different reference systems with neutral atoms and single ions. The established methods for the international key comparison in time and frequency employ satellite-based techniques which provide a clear limitation for comparisons of these high-performance clocks and will prevent full benefit from a future redefinition of the unit of time. To overcome these limitations, travelling frequency standards with performance exceeding the current state-of-the-art need to be developed, evaluated, and tested for an employment in future key comparisons. This is of particular relevance given the growing needs in global communication and navigation.

Transportable optical clocks resulting from the proposed objectives are also required to provide accurate and stable frequency references outside NMIs and DIs for example at specialized research facilities, for geodetic base stations or in future telecommunications and navigation systems. Thereby, the research will develop an advanced technique for providing traceability of measurement results to the users of metrology services.

Objectives

The JRP will focus on the development of an integrated European metrology infrastructure for the development and deployment of highly stable and accurate transportable optical clock systems. The specific objectives of the project are:

1. To develop and to demonstrate the performance of commercially unavailable components of transportable optical clock systems (e.g., ultra-stable laser, optical bench for atom/ion cooling, trapping and interrogation, UHV physic package for atom/ion clock) capable of operation within 5 days after transportation.
2. To develop transportable optical clocks that demonstrate short-term frequency instabilities below $\mathbf{5} \times \mathbf{10^{-15}}\sqrt{\boldsymbol{\tau(s)}}$ and a systematic uncertainty equal or below $\mathbf{5} \times \mathbf{10^{-18}}$.
3. To evaluate the transportable optical clocks by comparison with fully evaluated stationary laboratory systems to assess their performance in terms of frequency stability and accuracy and to estimate their reproducibility. This includes measurements before and after a real or simulated transportation of the transportable optical clock for investigation of possible errors.
4. To demonstrate the feasibility of future key comparisons using transportable optical clocks as an alternative to established time and frequency key comparisons performed via satellite-based techniques.
5. To demonstrate the establishment of an integrated European metrology infrastructure and to facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain (NMIs, DIs), international metrology committees (CIPM CCTF) and end users (research facilities in geodesy, space and physics, telecommunications and aerospace enterprises, scientific and precision instrumentation manufacturers)

Progress beyond the state of the art and results

This project (TOCK) builds upon the achievements of previous EMRP and EMPIR projects, most recently 18SIB05 ROCIT and 20FUN01 TSCAC. In TSCAC fundamental aspects of future realisation of composite optical clocks based on two atomic species is investigated and in ROCIT the robustness of established optical clock systems was improved, and the application of these for the steering of international timescales is expected to be demonstrated within the remaining duration of that project. TOCK will focus on the development and deployment of highly stable and accurate transportable optical clock systems and investigate future key comparisons for time and frequency.

To develop and demonstrate the performance of commercially unavailable components of transportable optical clock systems

Transportable clocks provide special requirements to their components. They need to be capable to withstand transportation and have higher demands on weight, size and power consumptions while a similar performance as known from their stationary counterparts in laboratory environment is demanded. In particular, operation shortly after transportation is requested. Some of the required components have been made commercially available, however, so far unavailable ultra-stable laser, optical benches for atom/ion cooling, trapping and interrogation and UHV physic packages for atom/ion clock will developed and their proper operation within 5 days after transportation verified. In this way, key components become available for prototypes and can be used for later commercialisation by industry stakeholders.

To develop transportable optical clocks that demonstrate short-term frequency instabilities below $\mathbf{5 \times 10^{-15}}\sqrt{\boldsymbol{\tau(s)}}$ *and a systematic uncertainty equal or below* $\mathbf{5 \times 10^{-18}}$

A few prototypes of transportable optical clocks have been realised worldwide, with the most advanced system realised in Japan demonstrating mid 10^{-18} uncertainty. In Europe, first prototypes of transportable optical clocks have been realised, but their uncertainty has been larger than 10^{-17} so far. Within TOCK, new systems will be developed and existing improved with the aim to reach frequency instabilities below $\mathbf{5 \times 10^{-15}}\sqrt{\boldsymbol{\tau(s)}}$ and systematic uncertainties equal or below $\mathbf{5 \times 10^{-18}}$. The work will focus on the development of physics packages that enable operation with low frequency instability as well as the investigation of systematic frequency shifts for the specific operational conditions of transportable optical clocks. This work will increase the number of available transportable optical clocks in Europe and strengthen the measurement capabilities significantly.

To evaluate the transportable optical clocks by comparison with fully evaluated stationary laboratory systems to assess their performance in terms of frequency stability and accuracy and to estimate their reproducibility. This includes measurements before and after a real or simulated transportation of the transportable optical clock for investigation of possible errors.

Only a handful measurements involving transportable optical clocks have been reported in literature to date and in a single case, an uncertainty below 10^{-17} has been reported. This clock comparison has been pursued against another system that was almost identical so that some systematic shifts have been common-mode. To prevent unobserved systematic effects, within TOCK transportable optical clocks will be evaluated and compared to stationary systems that differ significantly in their design. In this way, a detailed assessment of the frequency stability and the systematic uncertainty of the transportable optical clock will be performed. To investigate on limitations related with transportation, the procedures will be repeated after real or simulated transportation. The repeated evaluation enables the compilation of guidelines, which operation parameters of TOCs must be re-evaluated after transportation and how the clock performance can best be retrieved after transportation.

To demonstrate the feasibility of future key comparisons using transportable optical clocks as an alternative to established time and frequency key comparisons performed via satellite-based techniques.

Across Europe a few NMIs and DIs are interconnected using dedicated optical fibre links that enable frequency comparisons with low 10^{-18} uncertainty limited by relativistic effects. To overcome these limitations and to compare optical clocks that cannot be interconnected via optical fibre links, within TOCK travelling frequency standards will be employed to demonstrate future key comparisons in time and frequency. For these comparison campaigns complementary measurements over the existing fibre links will be performed to maximise the impact of each campaign and to mitigate the risk of a failure of the stationary clock system.

Outcomes and Impact

The impact of this work will be predominantly on the metrological capabilities at the frontiers of measurement science and on a future redefinition of the SI unit second. Longer-term economic impact from knowledge transfer to industry is foreseeable.

Outcomes for industrial and other user communities

The techniques and hardware developed for transportable optical clocks within this project will benefit research groups and industrial organisations developing portable optical clocks for field applications but also might lead to new ideas for improved robustness of laboratory optical clocks. The clocks developed within the project will become role models for optical clock development at industrial stakeholders. A large number of components of transportable optical clocks have already been made commercially available and finally complete systems will become available for applications including geodetic height measurements, synchronisation of telecommunications networks and future satellite navigation systems. Applications of clock subsystems also extend to other areas such as precision spectroscopy and quantum information processing. Moreover, industrial development of optical and electronic systems is supported by the participating NMIs via guidance on target specifications for novel applications and ad-hoc support in the characterisation of commercial prototypes.

Outcomes for the metrology and scientific communities

This project will investigate new ways to perform key comparisons for time and frequency using highly stable and accurate transportable optical clock systems. Their development and deployment will improve the accuracy with which distant clocks can be compared and thereby supports the selection of suitable reference systems for a redefinition of the SI second, an essential contribution to fundamental metrology and to the long-term development of the SI system of units.

An external collaborator will be invited to each project meeting to foster the scientific interchange with the large stakeholder community in the field of geodetic measurements. The collaborator will inform all partners of the project on the most recent advances in geodesy and investigate potential use of clock comparisons involving transportable optical clocks.

The work performed will also have spin-off benefits to fundamental physics. For example, comparisons between optical clocks with verified uncertainties can be used to set limits on possible present-day variation in fundamental physical constants, to test the predictions of special and general relativity and to search for dark matter candidates.

Outcomes for relevant standards

Since the project investigates means for alternatives to the established key comparison for time and frequency, the route to impact will be through the CCTF and its working groups. The consortium is well represented on these bodies, where information on the project progress and outputs will be disseminated through tailored presentations and written reports.

Contributions to the Frequency Standards Working Group (WGFS) will include improved measurements of optical frequency ratios for seven out of the eleven optical clocks currently designated as secondary representations of the second. Together with new guidelines on handling correlations between individual measurements and our least-squares analyses of the worldwide body of available clock comparison data, this is expected to have significant input on the list of recommended frequency values maintained by this working group. Employing the transportable optical clocks, the measurements conducted within this project will enable several partners to assess the full performance of their stationary optical clock for the first time via direct comparison to another system of similar quality.

Reports on the project outputs will also be presented to other working groups of the CCTF. In particular these are expected to have a significant influence on discussions within the Working Group on Strategic Planning (WGSP), which is responsible for updating as necessary the international roadmap towards a future redefinition of the SI second. The work will thus pave the way towards a future key comparisons for time and frequency and the redefinition of the SI second.

Longer-term economic, social and environmental impacts

Long-term impact of this research will result from the pivotal role of atomic clocks in the revised SI and in several growing technology sectors. The results will allow the international metrological community to make better informed decisions towards a future redefinition of the SI second. Improved techniques to compare atomic clocks and the development of transportable optical clocks have relevance for technological applications, in sectors such as navigation, space, aerospace, telecommunications and energy networks. Transportable optical clocks have a large potential for further miniaturisation which is of major importance in their development as payloads on board satellites and aerospace vehicles. Improved optical clocks also allow for geodesy with cm-level precision and applications in geodesy and climate research.

22IEM02 DireK-T

Dissemination of the redefined kelvin

Summary of the project

Overview

The aim of this project is to take advantage of the kelvin redefinition using practical primary thermometry approaches for the dissemination of thermodynamic temperature. We progress beyond the state of the art, through: demonstrating dissemination of the kelvin from 4 K to 300 K; developing a robust framework for establishing traceability by primary thermometry; working towards the next generation primary thermometry to 700 K. We will demonstrate how smaller/emerging NMIs can benefit from such dissemination approaches. We will lead the global thermometry community in disseminating the kelvin using primary thermometry ensuring EURAMET remains dominant in this important field of metrology.

Need

The kelvin redefinition in May 2019 initiated a comprehensive research phase for the realisation and dissemination of thermodynamic temperature to replace the ITS-90/PLTS-2000 scales currently in use. The CIPM (International Committee of Weights and Measures) Consultative Committee for Thermometry (CCT) recommendation T1 (2017) stated that member state National Metrology Institutes (NMIs) “take full advantage of the opportunities for the realisation and dissemination of thermodynamic temperature afforded by the kelvin redefinition and *the mise en pratique* for the definition of the kelvin (*MeP*-K)”. In addition, the research needs for temperatures above ambient was highlighted by the CCT recommendation T1 (2021) that NMIs establish capability to determine T-T90 above 400 K, and in so doing establish the background capacity for dissemination of thermodynamic temperatures approaching 700 K.

The *MeP*-K allows for the dissemination of temperature either by thermodynamic means or one of the defined scales. However, many issues remain about how the two approaches interrelate and how to demonstrate the degree of equivalence. To facilitate disseminating thermodynamic temperature these issues need addressing.

The EMPIR 18SIB02 Real-K project began the transition away from defined scales by establishing the capabilities to disseminate thermodynamic temperature at high temperatures >1235 K and low temperatures, particularly <5 K. The research proposed here, building on the achievements of Real-K, addresses the high-level metrology needs stated by CCT, ensuring that thermodynamic temperature can be realised and disseminated to room temperature and beyond.

This research is beyond the capability of a single institute to deliver. We will establish within EURAMET a highly integrated research and metrology infrastructure for disseminating thermodynamic temperature. The project includes a wide range of NMIs ensuring the developed approaches are appropriate for NMIs at different stages of development. This research ensures the EURAMET region retains its globally dominant position in realising and disseminating the redefined kelvin.

Objectives

The overall objective of this project is to establish the capability to disseminate thermodynamic temperature from 4 K to ~300 K, which requires an internationally agreed framework to demonstrate that thermodynamic temperature dissemination is reliable. Additionally, we will build future capability to enable thermodynamic temperature dissemination above 300 K.

The specific objectives of this project are:

1. **Demonstrate practical thermodynamic temperature dissemination from 4 K to 25 K** using three independent thermodynamic methods to, at least, two NMIs without primary thermometry capabilities using practical temperature sensors as transfer standards. Target uncertainty 0.3 mK (k=1).
2. **Demonstrate practical thermodynamic temperature traceability in the range 25 K to 300 K** using two independent thermodynamic methods to, at least, two NMIs without primary thermometry capabilities using practical temperature sensors as transfer standards. Target uncertainty 0.25 mK at 25 K and 0.6 mK at 300 K (k=1).
3. **Develop a coherent framework for thermodynamic temperature dissemination** to ensure consistency of dissemination from NMIs to users over the temperature range 4 K to 300 K whether it is by thermodynamic temperature or the defined scale (ITS-90) and develop a recommendation to CCT documenting how to perform the dissemination and uncertainties attainable.

4. **Establish a capability for the realisation and dissemination of thermodynamic temperature between 300 K and 700 K** with T-T_{90} target uncertainty of 0.6 mK at 300 K and 7 mK at 700 K (k=1).
5. **Establish an integrated European temperature metrology infrastructure** and facilitate the take up of the developed technology and measurement infrastructure by the measurement supply chain (accredited laboratories, instrument manufacturers), CIPM Consultative Committee for Thermometry (CCT), EURAMET and other RMO TC-Ts and relevant end users (academic and industry).

Progress beyond the state of the art and results

Each objective of this project goes well beyond the state of the art.

We are building on the foundation laid by the EMPIR Real-K project which: 1) Laid the framework for dissemination of thermodynamic temperatures >1300 K. 2) Developed the capability for disseminating the redefined kelvin below 25 K – the effectiveness of which will be demonstrated in this project. 3) Performed theoretical modelling and experimental activities to determine the thermophysical properties of gases required to disseminate thermodynamic temperature to at least 300 K and beyond – here we take advantage of those results to demonstrate practical dissemination of thermodynamic temperature to at least 300 K.

Demonstrating dissemination of thermodynamic temperature from 4 K to 25 K

The *current state of the* art for temperature realisation and dissemination between 4 K and 25 K is through the defined scale (ITS-90). The situation is complex with different technical approaches and overlapping in ranges; (0.65 K to 5 K ^{3}He/^{4}He vapour pressure thermometry, 3 K to ~24.6 K interpolating He gas thermometer and above ~13.8 K fixed-points and capsule standard platinum resistance thermometer). Because of the complexity there are very few full ITS-90 realisations globally in this temperature range.

We *progress the state of the art* building on the developments of Real-K, to, for the first time, demonstrate low uncertainty thermodynamic temperature dissemination. We will use three thermodynamic approaches (DCGT, RIGT and AGT) to perform the thermodynamic temperature calibrations. Target uncertainty 0.3 mK (k=1) in the range for the dissemination.

Towards demonstrating dissemination of thermodynamic temperature from 25 K to 300 K

The *current state of the art* for temperature realisation and dissemination in this temperature region is through calibration of platinum resistance thermometers to the defined scale (ITS-90).

We *advance the state of the art* building on the developments of Real-K to demonstrate low uncertainty thermodynamic temperature dissemination. We will use two thermodynamic approaches (RIGT and AGT) to perform direct thermodynamic temperature calibrations without reference to ITS-90. Target uncertainty in temperature dissemination of 0.25 mK at 25 K and 0.6 mK at 300 K (k=1).

Development of a coherent framework for thermodynamic temperature dissemination

The *current state of the art* is that there is **no** coherent framework for disseminating thermodynamic temperature. The *mise en pratique* for the definition of the kelvin (*MeP*-K) states the allowable thermodynamic methods that can be used but does not address the many practical issues such traceable dissemination requires.

We *progress the state of the art* by developing a coherent framework for disseminating thermodynamic temperature to ensure the reliability of such dissemination, making it accessible in the future to the user community through a recommendation to the CCT.

Establish capability for dissemination of thermodynamic temperature to approximately 700 K

The *current state of the art* is a few NMIs have made tentative steps towards developing capability for thermodynamic temperature above 300 K.

We *progress the state of the art* by developing the capability to measure thermodynamic temperature to 700 K and develop values of T-T_{90} with a target uncertainty of 7 mK at 700 K (k=1).

Outcomes and Impact

Outcomes for industrial and other user communities

Temperature is one of the most measured parameters in industry and by other users (e.g. climate change research). These developments will therefore have outcomes in almost all industrial sectors as well as more widely. However, most impact will be long-term (discussed below).

European accreditation bodies, and calibration laboratories have a long-standing interest in the SI and its development. Links with such bodies have been established and the outcomes of this project with its implications for traceability will be fully communicated.

Temperature sensor manufacturers have signalled their interest in this project both directly and indirectly through trade bodies/learned societies. The outcomes of this project will be communicated to them through an e-newsletter and through the project website. Articles on the project outcomes will be published in trade body journals.

It is known that the introduction of ITS-90 caused significant indirect costs to industry through for example having to update standards, change algorithms and recalibrate reference standards. We anticipate, one of the outcomes of the project is that dissemination of thermodynamic temperature will become widespread, negating the need for a new scale with industry avoiding significant costs.

In summary because temperature is such a key parameter for industry and over many areas of human endeavour it is anticipated there will be significant outcomes from this project. There will be stimulation of practical primary thermometry *per se* and the development of practical primary thermometry calibration facilities potentially leading to new products for European companies.

Outcomes for the metrology and scientific communities

The project outcomes for the global thermometry community will be very significant, both through advances in the SI system of units (the kelvin) and contributions to the Consultative Committee of Thermometry.

For the global thermometry community. The realisation and dissemination of thermodynamic temperature, as opposed to defined scales, is a long-term objective. The outcomes here will mark a significant advance towards that long-term objective by using multiple practical primary thermometry approaches to disseminate thermodynamic temperatures.

Specific outcomes will be:

- Capabilities for the dissemination of thermodynamic temperature demonstrated from 4 K to 25 K and from 25 K to ~300 K, with defined scale level uncertainties
- Thermodynamic temperature dissemination practicality demonstrated including possibility to supersede the defined scale in these ranges
- A coherent framework for dissemination of thermodynamic temperature (4 K - 300 K) will be developed and recommended to the CCT
- The practicality of thermodynamic temperature dissemination at higher temperatures will have been investigated to ~700 K

For the Consultative Committee of Thermometry

Many of the consortium members are members of the CCT, indeed three (PTB, NPL, UL) are chairs of CCT Working Groups. This means the outcomes of DireK-T will be incorporated into CCT advice and recommendations for use by the global thermometry community at the earliest opportunity. Possible outcomes are: revision of the *MeP*-K, revision of the CCT Strategy and revised consensus values of $T-T_{90}$. Standards outcomes relating to CCT are given below and more fully in Section B3.c.

The outcomes of this project will be disseminated to the *wider scientific community* through the following:

- Research papers (at least 15) in relevant high impact journals
- Presentations (at least 20) at relevant conferences
- Dissemination workshop for EURAMET TC-T members
- Summer school on “Contemporary issues in primary thermometry” for academics and metrologists

Outcomes for relevant standards

This project will have a very significant outcomes for the whole thermometry community. This will be effected chiefly through the CCT, the global authority on temperature, and the relevant standards body for this work.

Key inputs into the CCT, influencing its guides and recommendations are:

1. Evaluation report on sensors for disseminating thermodynamic temperature from 4 K to 25 K
2. Practical demonstration of practical thermodynamic temperature dissemination from 4 K to 25 K
3. Practical demonstration of practical thermodynamic temperature dissemination from 25 K to 300 K
4. Recommendation report to CCT with framework for thermodynamic temperature dissemination to 300 K
5. New determinations of T-T_{90} in the whole range 4 K to 303 K
6. New determinations of T-T_{90} in the range 303 K to ~700 K
7. Report to CCT on approach to disseminating thermodynamic temperature >300 K

In addition, the key international stakeholders, chiefly the RMO TC-Ts, will be kept informed of the progress of DireK-T by annual written reports. There will be an annual oral report to Euramet TC-T.

Longer-term economic, social and environmental impacts

Thermometry is the most widely measured physical parameter so any change will have far reaching impact. This project will accelerate the paradigm shift in the practice of thermometry begun in the Real-K project. There will be an increase in the use of primary thermometry, most appropriate for the needs of the user, to derive traceability to the redefined kelvin.

From an economic perspective. This change will first occur at the NMI level, but over time will be established in accredited laboratories. This will reduce the dependency on NMIs, providing traceability at reduced cost to the user. In the very long-term practical primary thermometry may be used to bring *in-situ* traceability at the point-of-measurement, through the deployment of thermometers with *in-built* traceability. Such innovations are necessary as fully autonomous production and reliable sensor networks are not possible without them.

From a social perspective. These developments may stimulate new industries/products/services, protecting high-value manufacturing employment. The kelvin definition has parallels with the metre redefinition. After the metre redefinition there was an expansion of optically based dimensional measurement approaches. Similar innovations could take place in thermometry with practical primary thermometry supplanting current approaches.

From an environmental perspective. As practical primary thermometry becomes a reality, *any* industrial process requiring reliable temperature measurement will, through the deployment of such sensors, always run optimally, minimising energy use and harmful emissions whilst delivering a consistent quality product with zero waste. Reliable thermodynamic thermometry is essential to improve the reliability of global temperature monitoring and hence monitoring climate change. In addition, the issue of primary temperature measurement and thermometer calibration at liquid hydrogen temperatures will become highly relevant for the optimization of processes and for custody transfer, once liquid hydrogen is introduced at large scale as part of a global hydrogen economy. Hydrogen is one of the technology pillars on which hopes to abate climate change rest.

Any user requiring long term reliable thermometry will benefit from *in-situ* practical primary thermometry having significant *social and environmental impact*. Practical primary *in-situ* thermometry will give nuclear power plant operators confidence of safe and efficient operation over the >30-year life. Long term nuclear waste repositories require reliable thermometry over decades.

22IEM03 PriSpecTemp

Primary spectrometric thermometry for gases

Summary of the project

Overview

Accurate air temperature measurements are critical for climate change monitoring and the related evidence-based policymaking for early mitigation/adaptation planning. Spectrometric thermometry probes gas thermodynamic temperature, overcoming several practical challenges posed by contact thermometry in air and industrial processes. The consortium will integrate the knowledge and infrastructure across the EU and improve, standardise and implement the novel, non-contact methods including primary ro-vibrational spectroscopic thermometry. This will be cross-validated against other non-contact and the ITS-90 standard methods. Ultimately, a new hybrid calibration service with minimal long-term drift will support SI-traceable calibration of classical contact thermometers in gas/air.

Need

The effect of climate change has never been as severe as this summer, exemplified by record drought and flooding on several continents, including the EU. The latest IPCC report suggests that the EU is the most affected region in the World with almost doubled warming effects. Mitigation and adaption plans have received increased priority on WMO's agenda and by ministers and policymakers. Therefore, informed decision making tailored by clear uncertainty assessment is essential not only for optimising resources but also to avoid cherry-picking on climate change predictions. Accurate gas/air temperature measurements are crucial for underpinning these issues.

The limitations of contact thermometers for gas/air measurements are investigated in the EURAMET project Air Temperature Metrology. Low heat transfer of gas/air leads to amplification of self-heating and radiation effects, causing biases up to 200 mK. Spectrometric methods directly measure the thermodynamic temperature of molecules/gases and has been advanced in recent years with respect to both methodology and optical technology, demonstrating accuracy at a few tens of mK level. Currently, the method is mainly limited by the accuracy of spectral line intensities of probing gases (e.g., CO, CO_2, O_2), the lack of SI-traceability and validations against existing primary standards and ITS-90.

Furthermore, gas/air temperature is a critical parameter in many international ISO/DIN/CEN standards and a strategic target quantity of the CIPM CCT committee. It is also needed to optimise industrial production processes where contact thermometry suffers from well-known limitations in real conditions. Knowledge of accurate temperature at 10 mK and below is vital for fundamental metrology fields e.g. pressure (QuantumPascal project) and length (LaVA and GeoMetre projects).

Combining the state-of-the-art *ab initio* calculations, broadband ro-vibrational spectroscopy and recent advances in optical techniques forms a strong basis for an accurate primary gas/air temperature method to provide high accuracy calibration of contact thermometers.

Objectives

The overall objective is to provide the solid, scientific and metrological basis needed to define spectroscopic thermometry as a primary method for temperature measurement in gas/air together with establishment of an integrated European metrology infrastructure for primary spectrometric thermometry for air/gas. The O_2 molecule has been included as a "sensor" molecule to demonstrate the application of spectrometric thermometry in ambient air.

The specific objectives are:

1. To perform **high accuracy quantum mechanical calculations on essential line parameters** of selected ro-vibrational bands of candidate "sensor" molecules (e.g., CO, CO_2, O_2) for temperatures in the range of 200 K to 400 K. (WP1)

2. To perform **high accuracy measurements of optimal selected molecular transitions of CO, CO_2 and O_2 and to retrieve essential line parameters**. To compare and validate the ab initio results from objective 1 using the best experimental values. (WP1)

3. To develop **the methodology of a ro-vibrational spectrometric gas thermometry (RVSGT)** and to evaluate its performance under metrologically controlled laboratory conditions in the range of 200 K to 400 K, adopting spectral parameters from objectives 1 and 2. To develop the infrastructure for primary gas temperature measurements using NMI's FTS infrastructure with a target uncertainty of 25 mK. (WP2)

4. To **cross-validate spectrometric gas thermometry** from objective 3 against selected non-contact methods and via ITS-90 for the determination of thermodynamic temperatures using DBT and RIGT

methods. To improve the experimental capacities of the spectroscopy laboratories to achieve an uncertainty of 10 mK or better. (WP3)

5. To **facilitate the take up of the technology and measurement infrastructure** developed in the project by the measurement supply chain, European and international technical committees on thermometry (CCT, EURAMET and other RMOs TCs) and end users (remote sensing, automobile industry and aerospace industry). (WP4)

Progress beyond the state of the art and results

Development of the primary RVSGT with targeted accuracy of 25 mK (k = 1)

Critical evaluation of the methodologies used for broadband spectroscopic thermometry will be made, identifying advantages of each method, and providing full GUM uncertainty estimations. HT line shape models will be adapted to take full advantage of the high SNR (>10^5) obtained, to meet the uncertainty target of 25 mK.

Accurate spectral line intensities of CO and CO_2 with 0.1% uncertainty

Calculations of CO and CO_2 absolute and relative line intensities with accuracies better than 0.1% and 0.03%, respectively, will be performed; these go beyond the state-of-the-art accuracy of 0.5%. This is achieved by implementing a multi-reference method (MRCI-SD), which includes high order corrections.

Line intensities of CO and CO_2 spectra will be measured in multiple temperature steps with accuracies better than 0.1% using complementary techniques: FTS, CRDS, CMDS and TDLAS. Spectral line parameters will be retrieved using IUPAC-recommended HT profiles and cross validated among the techniques and with ab initio calculations. The potential of the cutting-edge CMDS technique, demonstrated for the CO molecule [1], will be applied to CO_2.

Improved accuracy of ambient air spectrometric thermometry based on improved O_2 spectroscopy

Studies of the oxygen (O_2) A-band are performed in order to develop the oxygen spectroscopy-based air thermometer researched by VTT into an accurate and traceable technique for ambient air thermometry.

First primary hybrid (thermo-spectroscopic) calibration service bridging spectroscopic and contact thermometry

A facility for hybrid air temperature calibration of classical contact thermometer will be constructed and vali-dated. This facility will allow the calibration of secondary thermometers directly against a RVSGT facility. This will provide an alternative calibration method compared with traditional methods, and give insight about the various influence parameters, potentially leading to lower uncertainties.

First primary RIGT

Based on Refractory Index Gas (RIG) system from the QuantumPascal project (EMPIRSIB04), PriSpecTemp will build the first RIG thermometer.

Outcomes and Impact

Outcomes for the metrology used to detect climate change

Air temperature measurements are the key quantity for determining the effect of Greenhouse gases on the climate. Accurate spectral line parameters for O_2 and CO_2, which considerably improves spectrometric thermometry in air, together with the development of a robust hybrid facility for contact thermometer calibration using spectroscopic techniques will directly affect the meteorology applied to detect climate change. For instance, the calibration services of the National Hydrological and Meteorological Agencies (NHMA) will considerably benefit from the new calibration facility.

Outcomes for industrial and other user communities

The results from the project will have wide impact on industry including food industry, steel industry, power plants, aerospace industry, pharmaceutical industry and biotechnology. In these sectors, gas/air temperature measurement is vital to improve production efficiency, reducing energy consumption and product quality control. In the food industry, temperature is regulated under European directives, such as 89/108/EEC [17], dealing with consumer well-being. In relation to the pharmaceutical industry, there are WHO recommendations [18] regarding the temperature conditions in connection with transport and storage of medicines.

PriSpecTemp hybrid facility for calibrating secondary thermometers against a primary thermometer will contribute to a reduction of the calibration uncertainty compared with traditional calibrations, thus having a strong impact on many users of secondary thermometers for air/gas temperature measurements.

Outcomes for the metrology and scientific communities

The number of primary techniques for gas temperature measurement are currently very limited, the provided uncertainties are not optimal, and the involved economical and personal investments are huge. PriSpecTemp provides a novel non-contact primary method in a broad temperature range of 200 K – 400 K with an uncertainty of 25 mK (k=1). Furthermore, this project aims to increase the understanding of the gas temperature concept and improve the quality of calibration procedures. Thus, the project outcomes will be influential in all the related metrological and scientific communities including those with air temperature interests.

The multidisciplinary concept of PriSpecTemp will secure the impact on several scientific communities, including academia, research institutes and NMIs. Research outputs will be disseminated via trade journals, peer-reviewed papers, and international conferences.

The impact on NMIs ties to the reduction of calibration uncertainties of thermometers used for air/gas temperature measurements. The new calibration facility will have a great impact on primary laboratories for other quantities, where the air temperature knowledge is vital for the understanding of the overall uncertainty of their ser-vices, e.g. mass and length calibrations.

PriSpecTemp provides a new primary method for gas temperature measurements. This is extremely important since, the number of primary techniques for gas temperature are currently very limited, the provided uncertainties are not optimal, and the involved economical and personal investments are huge. Furthermore, PriSpecTemp will increase the understanding of the gas temperature concept and improve the quality of calibrations.

Outcomes for relevant standards

There are numerous international and regional standards where gas/air temperature is included. This is currently the case for 164, 1220, 3657, 19970 and 4880 standards associated with ISO, DIN, CEN, ASTM and IEC. These standards cover standardisation in relation to industry, climate, health and safety and encompass:

- Meteorology and climate observation
- Energy consumption in building and thermal comfort
- Energy consumption in industrial processes
- Production, storage and transportation of pharmaceutical products
- Storage and processing of food and other agricultural products
- Industrial production for quality control
- Almost all standards for testing
- Explosion protection
- Health and proper operation of medical instruments

Therefore, this novel spectroscopic primary standard for gas/air temperature measurements will have a profound and wide impact on many of the mentioned standards. In addition, there are several committees that the partners are members of, thus can have a direct impact on.

Several partners (CEM, JV, TUBITAK, PTB) are members of the three most important technical committees for thermal metrology (CIPM CCT, EURAMET TC-T and IMEKO TC12) and chairman or member of relevant working groups of standardisation bodies (DIN, ISO, IEC). The partners will endeavour to ensure that the reference documentation or guidelines of these committees in the future incorporate the most relevant achievements. This includes joint presentations at the working group meetings and, where appropriate, written reports to the committees and working groups. (See Task 4.1).

The EURAMET Project No. 1459 (Air Temperature Metrology) is a research project aiming to write EURAMET guidelines for calibration of thermometers in air. PriSpecTemp project will provide beneficial input to these guidelines linking the results from the ATM to spectroscopic measurements.

CEM is active in several technical expert teams of WMO/CIMO and will make sure that relevant outputs of this project will be submitted to the most appropriate working groups of WMO/INCOM/SC-MINT. They can consider using these documents as reference documentation and include them as WMO reference guides.

Three partners (PTB, CEM, JV) are active members of the European Metrology Network for Climate and Ocean Observations (EMN-COO). Further, PTB and JV are member of the EMN for Energy Gases, while PTB is a member of the EMN for Pollution monitoring (EMN-POLMO). The consortium will keep these EMNs informed on respective EMN-relevant output from the project e.g., accurate spectral data for remote sensing, improved calibration of gas/air temperature sensors, and new possibilities for gas temperature measurement.

Longer-term economic, social and environmental impacts

PriSpecTemp will result in the improvement of multiple industrial processes due to improved gas temperature measurements. It will contribute to improved industrial competitiveness as a consequence of optimised production processes in industries such as the automobile industry, pharmaceutical industry and airplane industry. In addition, it will contribute to more efficient energy production by optimisation of temperature.

The PriSpecTemp project will provide improved information required by society to address the rising temperature and the impact on environment and climate. Hence the project outcome is part of the climate-change solution puzzle and carries on the same long-term effects on the different aspects of the human-being life as the other pieces.

22IEM04 MQB-Pascal

Metrology for quantum-based traceability of the pascal

Summary of the project

Overview

Accurate pressure measurements are essential for key applications in important areas such as climate, medicine, manufacturing, energy issues, science, safety, and quality control. This JRP aims to establish an integrated metrological infrastructure for a SI-traceable quantum-based pascal in the very relevant range of 1 Pa to 1 MPa. These density-based methods, successfully developed in previous projects, allow much faster calibrations with improved uncertainties. The methods will be further developed in terms of accuracy, stability, working range, miniaturisation, transportability, its use of nitrogen (to meet industrial requirements), as well as for practical applications to accelerate dissemination to scientific and industrial stakeholders.

Need

Accurate, reliable, and cost-efficient pressure measurements are key for a variety of many important applications within a broad spectrum of industrial, scientific, and regulatory sectors. Examples are altitude determinations to prevent airplane collisions as well as often occurring unnecessary flight manoeuvres, operational safety of power plants, preventing leaks in storage of toxic or nuclear waste, and assurance of medical sterility. The importance is expressed by the Comité international des poids et mesures (CIPM) in the 2017-2027 of the Consultative Committee for Mass and related quantities (CCM) [1], and by the EURAMET Technical Committees for Mass and related quantities (TC-M) in their guidelines (roadmap) [2].

While current methods rely on realising the pascal through conventional means as force over area, the revision of the SI-system in May 2019 opened up to an alternative path to realise the pascal by measuring the refractivity and the temperature of a gas. Such a realisation of the pascal, and other similar quantum-based approaches, do not depend on weights or movable parts but instead measure the gas properties directly. This will decrease uncertainties and at the same time will improve the efficiency of calibration chains. While significant efforts by both non-EU and EU-actors have proven that the quantum-based methods have the capability to supersede conventional methods in certain relevant pressure ranges, there is not yet any realisation that successfully has combined all the advantages of the techniques.

To be able to take full use of the inherent potential of these methods, it is of importance to successfully continue to consolidate and integrate the expertise and efforts in Europe so that quantum-based high-performance instrumentations can be realised, and consequently utilised. This does not only include improved uncertainties and an establishment of standards in Europe but also improved metrological reference data and to bring the methods within reach for stakeholders and end-users to meet the needs of the societal, industrial, and scientific future challenges.

Objectives

The overall objective of the project is to establish a metrological infrastructure for a traceable quantum-based pascal in the 1 Pa to 1 MPa range by realisation of a handful of strategically selected instrumentations and disseminate the technology with a minimal loss of performance to stakeholders. The methods should also be evaluated in terms of practical applications.

The specific objectives of the project are:

6. To develop high-accuracy primary pressure instruments based on Fabry-Perot (FP) refractometry for the traceability to the pascal and covering the 1 Pa to 30 kPa range. The target uncertainty is 2 mPa + 10 ppm (k=2).
7. To develop validated quantum-based methods (including FP-based techniques, Rayleigh scattering, and polarising gas thermometry methods) to enable traceability within the 1 Pa to 1 MPa range with a target uncertainty of 5 mPa + 30 ppm (k=2). Applications should include gauge mode measurement, measurement of dynamical pressure and measurements with nitrogen and dry air medium. The concepts of miniaturisation and transportability should also be investigated.
8. To improve the metrological reference data and estimate the relevant uncertainties for the thermodynamic and electrodynamic properties of primarily nitrogen, i.e., density and dielectric virial coefficients, temperature dependent static and dynamic polarizabilities. The target uncertainty of the molar polarizability is in the order of a few ppm.
9. To verify that the developed instruments utilising the developed quantum-based methods are consistent with their combined uncertainties and with existing primary standards, as well as to assess their long-term stability.
10. To demonstrate the establishment of an integrated European metrology infrastructure and to facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain (EMN Quantum, European initiatives like the quantum flagship), standards developing organisations (CCM WGPV, EURAMET TC-M, ISO TC112) and end users (key stakeholders from science and industry).

Progress beyond the state of the art and results

By development of quantum-based methods for pressure measurement, this JRP aims to establish not only one, but at least three, fully operational quantum-based primary FP-refractometers. The JRP will also investigate, and improve upon, quantum-methods in general and investigate their possibility for a multitude of applications. Furthermore, theoretical calculations of relevant properties of nitrogen, as well as verification and comparison against conventional methods will be carried out. This JRP builds upon the results and conclusion from its predecessor, 18SIB04 "QuantumPascal", which successfully demonstrated the potential of quantum-based methods.

Realisation of several primary FP-refractometers (Objective 1)

By consolidating the efforts and the recent progress across Europe, the performance of FP-cavity based refractometers will be improved. The goal is to demonstrate a confirmed uncertainty of at least 2 mPa + 10 ppm (k=2) in the 1 Pa to 30 kPa range. Furthermore, in an integrated effort, where the partners will collaborate closely, at least three instruments in at least three different countries will be realised. This will effectively establish an infrastructure consisting of several primary FP-based refractometers across Europe. A significant step beyond the current state-of-the-art.

Development of quantum-based methods for traceability and for practical applications (Objective 2)

To fully utilise the advantage of the quantum-based methods beyond their use as potential primary standards, efforts will be put into further investigation and improvement on systems based on Rayleigh scattering, polarised gas thermometry, and non-primary FP-based refractometers. These methods will be developed to jointly provide traceability in the range from 1 Pa to 1 MPa with a target uncertainty of 5 mPa + 30 ppm (k=2). Furthermore, to bring the technology within reach of stakeholders and industry, these novel methods will be developed and investigated to address important practical applications.

Metrological reference data for nitrogen (Objective 3)

While the relevant gas properties for helium can be calculated with an uncertainty of less than 1 ppm, which was addressed within 18SIB04, nitrogen is by far the most used gas by NMIs (National Metrology Institutes), calibration actors, and industry. Furthermore, since its refractivity is eight times higher, and it is much easier to work with, it offers significant advantages over helium. Despite this fact, there is a surprising lack of exact dielectric data. Due to its more complex structure, a combination of highest-level experiments and theoretical *ab-initio* calculations will be used to provide the required values. By providing a complete and validated set of all required properties for nitrogen beyond the state-of-the-art, the objective aims to enable the use of nitrogen for the quantum-based methods addressed in this JRP.

Comparisons and stability assessments (Objective 4)

To pave the wave for quantum-based methods, several comparisons vs conventional standards will take place within the JRP, this aims to provide a strong foundation with reliable data to assess the performance and stability of the quantum-based system. The quantum-based instrumentation will also be subject to an extensive circular comparison to be carried out with highly stable conventional standards. By utilising the stability of conventional standards, the goal is to be able to show that the newly developed instrumentations agree within their claimed uncertainties.

Outcomes and Impact

Outcomes for industrial and other user communities

The primary outcome of the JRP is to develop quantum-based pressure standards. As these methods offer potential for improved means, in terms of performance, speed, and cost, to perform calibrations, they will impact a wide range of stakeholders that rely on accurate and precise pressure measurement. This JRP also aims to address the relevant practical applications, such as measurements of air, measurements in gauge mode, and dynamic measurements (of non-constant pressures). It is expected that this will have a significant impact for industrial- and end-users.

To foster the uptake of the results, considerable engagement throughout the project with a multitude of stakeholders will take place. These activities will enable the stakeholders to continue the early uptake by training and hands-on demonstration of the novel methods to allow for future products and services which will remain internationally competitive.

Outcomes for the metrology and scientific communities

The metrological and scientific communities will be the first to benefit from developments within this JRP. The main overall aim is to integrate the capacity and efforts within Europe to establish an infrastructure of quantum-based methods, highlighted with the planned realisation of at least three fully operational FP-based refractometers in at least three different countries. As these instruments have a target uncertainty of 2 mPa + 10 ppm (k=2) in the 1 Pa to 30 kPa range, it will represent a significant improvement in the important realisation of primary pressure standards, particularly at pressures below the typical working range for piston-cylinder systems. To provide traceability up to the 1 MPa range, this establishment will be complemented by the continued development of other quantum-based systems.

The progress within this proposed project will be disseminated to the CIPM, CCM, EURAMET TC-M, and the European Metrology Network for Quantum Technologies (EMN-Q), as they are the prime repositories of developments related to pressure metrology and quantum-metrology. The active engagement of these key stakeholders will ensure that the outcome will be disseminated worldwide to NMI laboratories and subsequently to any user who needs improved, traceable measurements of pressure in order to increase their commercial capacity or to address specific upcoming scientific or societal challenges.

The JRP, as it will aim to improve quantum-based methods in general, will also offer impact to several other scientific and metrology areas.

Outcomes for relevant standards

Currently, no documentary standards are directly affected due to the novelty of the quantum-based realisation of the pascal. To create the best possible impact the consortium will liaise closely with the key metrological bodies. Namely CCM, and its working group on pressure and vacuum and EURAMET TC-M SC Pressure to ensure that they are kept up to date. The developments and results obtained will be presented at the regular meetings and while their feedback will be directly taken into account.

Furthermore, the ISO TC 112 "Vacuum Technology" will be informed about the results achieved and receive reports, in order to implement possible changes to existing standards (like documentary standards on vacuum gauges such as “ISO 3567: 2011” and “ISO 27893: 2011”) to also account for the quantum-based methods. Furthermore, this initiates the preparatory process for the development of new explicit standards.

Longer-term economic, social, and environmental impacts

A more accurate realisation of the pascal in certain pressure ranges, will have direct impact and benefit to a wide range of communities. Besides improved uncertainties, they also indirectly affect quality and safety controls in a multitude of processes and applications.

There are a number of companies in Europe that manufacture pressure gauges, vacuum pumps, and process tools, with their products being among the best quality in the world. More accurate pressure standards will help the users to compare different instruments of different manufacturers and to select the most appropriate instrument for their application, which will have a positive economic impact for both manufacturers and end-users.

The development of new technologies will also enable manufacturers to produce completely new generation sensors that are more precise, less expensive than, and potentially self-calibrating. Therefore, the output of this proposed project will lead to higher margins of European companies compared to their competitors.

For vacuum applications, outgassing rate measurements are critical. Access to accurate and sensitive instruments will lead to significant metrological advancements which can lead to more economic production and development. Improved means to assess partial pressure can also have a significant impact. Gas composition and volume flow can for example, be determined more precisely, which is important for quality control and billing. This is a factor with ever increasing relevance.

The developments within this project will provide more accurate means to monitor the operational conditions and will hence contribute to safer and more efficient conditions at power plants and critical facilities that handle toxic substances. Furthermore, vacuum and pressure related processes are key to many industrial applications that require clean and well-controlled environments. Better control of the vacuum and pressure processes will lead to both increased profit margins and to the reduction of waste.

The technology developed in this proposed project will also enable more accurate and precise means to assess differential pressures. Differential pressure is important in many processes, climate control in critical environments is a particularly relevant example: As an additional 1 Pa of differential pressure in a medium-sized cleanroom requires around 3000 kWh of additional energy per year, more accurate differential pressure measurements can lead to a considerable energy-savings.

Additionally, flight altitude of an aircraft is measured by an altimeter that is based on an absolute pressure measurement. The increasing number of aircraft in European airspace has already made it necessary to half the standard vertical separation between aircrafts from 600 m to 300 m. Further reduction will be needed in the future, which will increase the demands on the accuracy of pressure measurements.

The methods developed in this project will also improve partial pressure assessments. In medical applications, especially in early detection, even the smallest changes in the relevant marker molecules are of utmost importance. An example here would be a non-invasive COVID test based on exhaled air at the airport.

22IEM05 NEWSTAND

New calibration standards and methods for radiometry and photometry after phaseout of incandescent lamps

Summary of the project

Overview

The SI-traceability of spectroradiometric measurements of optical radiation in a multitude of applications (monitoring essential climate variables, industrial processes, lighting, healthcare, occupational safety, photovoltaic energy generation, etc.) has been realised by means of incandescent lamps-based transfer standards. The availability of the lamps, though, is diminishing due to a production phaseout of incandescent lighting products. The project aims to provide adequate and affordable replacement sources and alternative procedures for a detector-based transfer of the spectral irradiance unit in the ultraviolet-visible-near infrared spectral range and to establish an integrated European metrology infrastructure around this key radiometric unit.

Need

Accurate knowledge of spectral irradiance of optical radiation emitted by artificial and natural light sources is essential in various fields of industrial (UV-curing, disinfection, photovoltaic equipment, general and horticultural lighting, etc.), environmental (solar radiation, Essential Climate Variables (ECVs), etc.), medical (sun beds, photobiological treatment, etc.), or scientific (analytical spectroscopy, plasma, etc.) applications. The range of applications for spectral irradiance measurements has grown dramatically during the last couple of decades due to the market introduction of affordable new-technology spectroradiometers based on array detectors and digital capabilities for *in situ* processing of the spectral data. The routine availability of the spectral characteristics of optical radiation sources is seen as one of the technological enablers for higher-quality products, information, and services.

For the calibration of spectroradiometers, incandescent lamp-based transfer standards have been used for decades. Selected quartz-tungsten-halogen (QTH) lamps of certain types have been applied to disseminate the spectral irradiance unit in the spectral range from 250 nm to 2500 nm. However, the market availability of such lamps and their applicability for this metrological purpose is diminishing due to the production phaseout following the ban of the incandescent lighting by the EU Commission in 2009 and by a technology change to solid-state-lighting (SSL) products. Thus, alternative transfer standards built on new-technology sources with preferably smooth spectra throughout the UV-VIS-NIR spectral range and/or detector-based dissemination methods are urgently needed. The urgent needs for the research activities addressed by the project are explicitly described in the orientation papers by two major stakeholders, European Association of National Metrology Institutes (EURAMET) Technical Committee for Photometry and Radiometry (TC-PR) as well as Division 2 of the International Commission on Illumination (CIE). The need for new standards triggered by the transition to solid-state lighting has been expressed also in the research strategy papers by the Consultative Committee for Photometry and Radiometry (CCPR) of the International Committee for Weights and Measures (CIPM), EURAMET, and CIE.

Objectives

The overall goal of this project is to assure SI-traceable measurements of spectral irradiance of natural and artificial sources of optical radiation and to develop the metrological infrastructure required for these measurements after the technology change-driven phaseout of the incandescent lamps currently used as transfer standards. The specific objectives of the project are:

1. **To develop new standard sources for spectral irradiance** in the ultraviolet-visible-near infrared (UV-VIS-NIR) spectral ranges, built on new-technology products, to replace current transfer standards that are based on incandescent lamps. The specific requirements for the spectral irradiance of the new standard sources are: i) well-defined and fit-for-purpose spectral and geometric properties, ii) long-term stability, iii) reproducibility, iv) robustness, and v) compatibility with existing calibration facilities. The new standard sources should enable dissemination of the spectral irradiance unit with transfer uncertainties as low as 0.5 % ($k = 2$).
2. **To develop novel methods for enabling detector-based traceability of spectral irradiance measurements** as an alternative to the incandescent lamps-based dissemination of the unit. This should involve i) the definition of the minimum requirements for relevant properties of (array) spectroradiometers to be suitable as transfer standards, ii) the development of procedures for their calibration that enable traceable measurements at end-user sites, and iii) the determination of uncertainties associated with the new traceability methods for spectral irradiance.

3. **To demonstrate the metrological applicability of the new standard sources and methods,** developed in objectives 1 and 2, in spectroradiometric applications involving spectral irradiance measurements in at least 3 end-user sites with total uncertainties as low as 1 % (k = 2).
4. **To develop good practice guidelines for using the new standard sources and calibration procedures**, as well as to implement the measurement methods and devices developed by the project.
5. **To demonstrate the establishment of an integrated European metrology infrastructure** and to facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain (calibration and testing laboratories), standards developing organisations (CIE Division 2), technical committees (EURAMET TC-PR, CCPR) and end users (manufacturers and users of spectroradiometers).

Progress beyond the state of the art and results

Developing new standard sources for spectral irradiance

Current state-of-the-art transfer standards for spectral irradiance in the spectral range from 250 nm to 2500 nm are based on 1000 W quartz-tungsten-halogen lamps or other lower-power and lower-quality lamps.

This project will develop transfer standards for spectral irradiance using new-technology sources and approaches for calibrating spectroradiometers in the UV-VIS-NIR spectral range to enable dissemination of the unit with transfer uncertainties as low as 0.5 % (k = 2). The new-technology-based candidates include devices such as narrow- and broadband LEDs, radiant dyes, laser-driven light sources, broadband lasers, and other commercially available products. Moreover, a narrowband spectrally tuneable source will be developed as transfer standard for the calibration of spectroradiometers throughout UV-VIS-NIR spectral range.

Developing novel methods for enabling detector-based traceability of spectral irradiance measurements

Common traceability chains for spectral irradiance measurements are built on sources as transfer standards which are used to transfer a spectral irradiance calibration from the primary standards to end-user applications.

This project aims to establish an alternative approach with compact and portable array-spectroradiometers as detector-based transfer standards. This concept is based on a novel method employing a digital twin of a transfer standard instrument. The digital twin combines results of extensive characterisations and calibrations of the instrument with respect to all relevant instrumental properties and a digital model. The model will enable the user to account for all the instrument characteristics during the measurements in their end-user applications depending on their respective boundary conditions, which differ from those in the calibration laboratory. To enable instrument-to-instrument transfer of the calibration, respective methods and quality assurance procedures will be developed. Finally, comprehensive user guidelines and software code will be developed and provided for the wide end-user community to facilitate the uptake of the methods to properly use the transfer standard instruments.

Demonstrating the metrological applicability of the new standards and methods

The project will demonstrate the metrological applicability of both newly developed transfer standard sources and detector-based transfer standards in different end-user applications both at calibration laboratory level and in different end-user applications. To achieve this, measurement comparison campaigns will be arranged with the goal to demonstrate spectral irradiance measurements with total uncertainties as low as 1 % while utilising the newly developed transfer standards and methods. Measurement comparisons involving array spectroradiometers as transfer standards for spectral irradiance shall be a first demonstration and a proof of principle for the new methods.

Developing good practice guides for using the new standard sources and methods

Currently guides and documented procedures are available only for the use of incandescent lamps-based transfer standards. The project will produce good practice guides tailored for the use by the end users of the newly developed transfer standards based on new-technology sources and also for the new dissemination methods based on transfer standard spectroradiometers. The good practice guides are aimed to support the implementation of the project results in the integrated European metrology infrastructure.

Outcomes and Impact

Outcomes for industrial and other user communities

The project will provide new calibration standards and procedures together with the extensive good practice guides accompanying each of the project outcomes for industrial and other end users relying on spectral irradiance measurements in industrial, occupational safety and health applications, photovoltaic energy generation as well as efficient energy use, and Climate and Earth Observation communities.

Industrial users that apply spectral irradiance measurements to control radiation-related technological processes, such as curing of materials, disinfection of air, water, and surfaces will profit from the new transfer standards. The new spectral irradiance calibration standards, procedures and calibration services shall also promote industrial development of new products around the new technologies.

End users from occupational safety and health applications will receive new spectral irradiance standards for the calibration of their spectroradiometers or radiometers that are used for onsite spectral measurements and assessment of personal exposures to incoherent optical radiation at working places, outdoors and in sunbeds.

The project will provide new standards and calibration methods, which are highly relevant for the photovoltaic energy branch. Spectral irradiance measurements are essential for the metrological support of photovoltaic energy generation. The results of the project are also highly relevant to energy saving through energy-efficient lighting. Production, planning, and installation of the energy saving lighting products are highly reliant on the spectral information, for which metrological dissemination of the spectral irradiance unit is mandatory.

The results of the project will be used also by the Earth Observation communities. The applicability of the new transfer standards to calibrate spectroradiometers measuring terrestrial solar radiation will be demonstrated during a measurements campaign. Consortium members will disseminate the outcome of the project within the stakeholder community associated with the European Metrology Network (EMN) Climate and Ocean Observation.

Outcomes for the metrology and scientific communities

The project will deliver new transfer standards and dissemination methods for National Metrology Institutes (NMIs), Designated Institutes (DIs) and calibration laboratories to disseminate the unit of spectral irradiance to end-users, affected by the phaseout of the standard lamps. The top-level metrological application of the transfer standards is to enable the comparisons of the measurement capabilities between NMIs, DIs and calibration laboratories at the International Bureau of Weights and Measures (BIPM) and the European Regional Metrology Organisation (RMO), i.e. e EURAMET, level down to bilateral interlaboratory comparisons. The new standard sources and procedures for detector-based dissemination of the spectral irradiance unit developed by the project will respond to the needs by a wide end-user community from metrology and science measuring spectral properties of emitted radiation (analytical spectroscopy, plasma, luminescence, etc.).

Outcomes for relevant standards

The project will provide metrological bases for many European Regulations, Directives and Standards that are referring directly or indirectly to spectral measurements of optical radiation aimed at protecting the population against the deleterious factors, sustainable energy use, and protection of the environment:

- DIRECTIVE 2006/25/EC, “on the minimum health and safety requirements regarding the exposure of workers to risks arising from physical agents (artificial optical radiation) (19th individual Directive within the meaning of Article 16(1) of Directive 89/391/EEC)”. This directive states that the risk assessment shall consider the level, wavelength range and duration of exposure to artificial sources of optical radiation.
- Commission Regulation (EU) 2019/2020 "EcoDesign for light sources and separate control gears". This regulation requires a minimal general colour rendering index (Ra). This quantity can only be evaluated using spectral measurements in the wavelength range from 360 nm to 830 nm.
- EN 12464-1 "Light and lighting — Lighting of work places — Part 1: Indoor work places". This standard requires that authenticated general colour rendering index (Ra) and correlated colour

temperatures (CCT) data shall be provided for the light source in the scheme by the manufacturer of the light source. The light sources shall be checked against the design specifications. These quantities can only be evaluated using spectral measurements in the wavelength range from 360 nm to 830 nm.

- EN 14255-1 to EN 14255-4 "Measurement and assessment of personal exposures to incoherent optical radiation". These standards require onsite measurements in the spectral range from about 200 nm to 2000 nm. Some of the measurements, particularly in the UV, can only be performed using a spectroradiometer.
- EN 60335-2-27 “Household and similar electrical appliances - Safety - Part 2-27: Particular requirements for appliances for skin exposure to ultraviolet and infrared radiation”. It requires that a sunbed session shall have a maximum UV output that corresponds to the mid-day Mediterranean sun (UV index of 12) to avoid any risk of burns and to reduce the likelihood of accident due to long exposure.

Longer-term economic, social and environmental impacts

The project will provide new standards and methods to support spectral irradiance measurements of artificial and natural light sources. Reliable and high-accuracy spectral data of the optical radiation sources, supported by the developments in the project, is seen as one of the technological enablers for high-quality products, information, and services in different end user applications. Accurate assessment of terrestrial solar radiation and derived atmospheric parameters used as essential climatic variables is mandatory for monitoring climate change and its effects on ecosystems, human health, agricultural production and food safety on a global scale.

22IEM06 S-CALe Up

Self-calibrating photodiodes for UV and exploitation of induced junction technology

Summary of the project

<u>Overview</u>

Photonics and optics are exciting, rapidly evolving technologies of great value (> 100 billion € in EU) and of importance across industry, environment, health, medicine, energy, lighting and science. The photonic industry and standardisation organisations request miniaturised, cost-effective, integrated and self-calibrating measurement systems that cannot be provided by traditional methods. Recent developments exploiting predictable photodiodes in various ways have demonstrated improved uncertainty to 10 ppm and the proof-of-concept of an NMI-on-a-chip suitable for miniaturisation. We propose to exploit the new detectors as built-in standards in various applications, exploit the new methods and develop improved standard detectors for the UV.

<u>Need</u>

There is a rapid and exciting technology development within Photonics as being one of six EU defined Key Enabling Technologies (KET), used in climate monitoring, medical treatment, health and photonic industries, energy saving illumination by light-emitting diodes (LEDs), electricity production, science, and many more applications. The technological development trend moves in the direction of miniaturisation, more integrated measurement systems and distribution of standalone sensor systems in possibly remote locations. Current metrological systems are not capable of calibrating detectors in integrated systems nor remote locations. Therefore, in both the European technology platform Photonics21’s, Quantum Flagship’s and their recent joint Strategic Research agenda, integration of self-calibrating systems and products are highlighted as one of the technology, research and innovation challenges ahead [1-3].

Previous European projects have developed the Predictable Quantum Efficient Detector (PQED), which has proven to have an extremely low external quantum deficiency (EQD) of around 10 ppm [4] and an undetectable drift over 10 years [5]. These properties make the PQED a very attractive calibration standard detector and complies well with the low-cost, high-accuracy, transfer standard requested by CIPM's Consultative Committee for Photometry and Radiometry (CCPR) [6].

The ultraviolet (UV) range is of great importance to health and earth observations but suffers from detectors with poor stability and lack of predictability. The international commission on illumination (CIE), as the world standardisation organisation for light and lighting, has requested research on new low-cost high accuracy primary standard detectors of optical radiation allowing better traceability from 200 nm – 2000 nm [7,8] to meet this need.

Objectives

The overall objective is to build on the improved PQED detectors and associated technology currently at a technology readiness level (TRL) of 3 to 4 and exploit it as an NMI-on-a-chip in applications at a TRL from 5 to 7. Furthermore, we will exploit the successful detector manufacturing method and new world leading metrology methods to provide improved traceability into the more challenging UV and NIR range at a TRL 3 to 4. More specifically:

1. To develop 3D simulation models of photodiode charge carrier transportation in Predictable Quantum Efficient Detector (PQED) for better physical representation, higher calculation speed, wider availability and improved uncertainty approaching 1 ppm, and to extend the quantum yield prediction from 400 nm down to 200 nm with an uncertainty better than 0.1 %.
2. To use PQEDs with very low spectral responsivity uncertainty in the 400 nm to 850 nm range as built-in references in different applications (e.g. optical power measurement, fibre optics, pulsed laser radiation, photometry without V(λ) filters) taking into account practical aspects, such as current measurements, stray light, geometry, heat and dark current variations.
3. To develop and fabricate improved photodiodes for the UV range and validate their stability and suitability as a spectral responsivity standard from 400 nm to 200 nm. Additionally, to develop thermal simulations and packaging technology of dual-mode detectors with heat equivalence better than 0.03 % suitable for implementation into the UV spectral range.
4. To extend the spectral response range of photodiodes between i) 200 nm and 400 nm, and ii) 850 nm and 1050 nm, with a target uncertainty better than 0.2 %. For this, the improved detectors and packaging developed in objective 3, and improved charge carrier simulation and quantum yield modelling developed in objective 1, may be used.
5. To demonstrate the establishment of an integrated European metrology infrastructure and to facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain (accredited laboratories, instrument manufacturers), standards developing organisations (CIE), technical committees (e.g. EURAMET TC-PR, CCPR) and end users (photonics industry).

Progress beyond the state of the art and results

Improved simulation models (objective 1)

The project builds on the excellent outputs from the chipS·CALe project, where improved self-induced PQED trap detectors with record low external quantum deficiency below 10 ppm was developed for the 400 nm to 850 nm spectral range [4]. Simplified 3D simulation models were developed and new experimental techniques where simulation fitting to experimental photocurrent measurement at one wavelength only was proven to be sufficient to predict the responsivity from 400 nm to 850 nm [9]. In previous projects, quantum yield (QY) is found significant at wavelengths as high as 470 nm and increasing with decreasing wavelength. However, the quantum yield is also found calculable to an uncertainty around 100 ppm down to 360 nm [10]. Current 3D simulation capabilities are limited to one NMI, on one type of software, with known limiting simplifications due to calculation speed and current TRL-level in the 400 – 850 nm spectral range is around 3 to 4.

In S-CALe Up we will use simulation models to

I. improve predictability of the PQED to achieve an uncertainty to go beyond the IQD losses,
II. independently predict spectral response from 300 nm to 1000 nm of existing PQEDs. A quantity covered by key comparison CCPR-k2.b.
III. develop improved standard detectors and prediction methods designed for the UV spectral range from 200 nm to 400 nm. A spectral range covered by key comparison CCPR-k2.c.

Furthermore, reflectance losses and quantum yield will be studied and modelled so that we will have independently predictable standard detectors for the full spectral ranges covered by CCPR-k2.b and CCPR-k2.c.

Applications for photometry, fibre optics and PICs exploiting PQEDs (objective 2)

The PQEDs have proven to be extremely stable with an undetectable drift, independent of wavelength, over ten years [5] with a responsivity directly linked to fundamental constants. This makes the PQED an ideal transfers standard and ready to be exploited in applications.

In S-CALe Up, three different applications for providing services to industry with the PQED as a built-in reference will be demonstrated and by that taking the TRL-level to 5 to 7 in those applications. These demonstrators will simplify realisations, improve traceability and is expected to produce improved calibration and measurement capabilities (CMCs) with reduced uncertainty for the laboratories developing the demonstrators.

Develop and fabricate improved photodiodes for the UV range and packaging technology (objective 3)

Silicon transfer standard pn-photodiodes for the UV spectral range from 200 nm to 400 nm are known to deteriorate under UV exposure, but new process advancements have proven to produce more stable photodiodes [11]. Alternative materials and diode types like PtSi and GaAsP are also used but they suffer from a large non-uniformity. The self-induced photodiodes in the PQED may be less susceptible to radiation damage, but this is not tested. New purely experimental self-calibrating techniques based on room temperature dual-mode detectors (DMD) with an uncertainty below 0.05% are developed and demonstrated [12]. Current packaging technology for dual-mode detectors are limited to exploit silicon photodiodes, as it is heated through forward bias, and have a beam position dependent thermal non-equivalence around 280 ppm/mm.

In S-CALe Up, improved photodiodes for the UV range with improved and validated stability will be developed taking advantage of the predictability of the photodiodes. Combining simulation models and fast material characterisations enables many different processes to be tested to produce optimum and robust passivation. Furthermore, the influence and optimising of the current read-out contacts will be studied. Improved packaging suitable for future industrialisation and implementation with other types of photodiodes than silicon will be developed.

Extended and validated spectral response scales (objective 4)

In S-CALe Up we exploit the improved photodiodes and modelling to establish and validate the fully predictable spectral response scales covering the CCPR-k2.c range from 200 nm to 400 nm and the CCPR-k2.b range from 300 nm to 1000 nm with a target uncertainty below 0.2 %. This will simplify the realisations of spectral response scale as fewer calibration points are needed and enable implementation of independent traceability techniques exploiting the state of the art PQEDs.

Outcomes and Impact

Meeting the aims of realising primary standard techniques based on silicon photodiodes outline new ways to provide traceability based on the built-in responsivity linked to fundamental constants. With the realisation of the units and dissemination as transfer standard through the same artefact the PQED provides an instrument to both shortening the traceability chain and improving the measurement uncertainty. The microelectronic processing makes the primary standard suitable for miniaturisation and integration into measurement system where traceability was previously not achievable.

Outcomes for industrial and other user communities

Industry in general require improved and simplified measurement standards suitable for miniaturisation. The development trend moves in the direction of more compact and integrated systems and the outcome of this project aims to enable future implementation of traceability to such systems where existing measurement techniques are not capable of providing traceability. By exploiting PQEDs in specific metrological realisations we demonstrate cost efficient realisations of primary photometers and power meters of importance to industry. The outstanding self-calibrating technology developed in the previous project chipS·CALe is expected to be less complex so that more applications can profit from it, as highlighted by partners in previous project Industrial Advisory Board. The implementation of PQEDs in applications is a climb in the TRL-level bringing the technology closer to the market.

Outcomes for the metrology and scientific communities

The metrological infrastructure at the highest level, represented by national metrology institutes (NMIs), regional metrology organisations (RMOs) and the consultative committee for photometry and radiometry (CCPR) has a fundamental task of realising the international system of units (SI) and provide metrology services with global acceptance. Radiometric services are most accurately provided by standard detectors but has suffered from unstable transfer standards. With the new improved standards and measurement techniques the metrology infrastructure has the possibility to build the primary standard directly into the applications, taking full advantage of their properties and both simplify and improve the measurement uncertainty. The new techniques with predictable spectral response throughout the whole spectral range of interest will ensure better global harmonisation of measurement results and even less developed NMIs may benefit from and having access to the highest metrological standards.

The structure in the project enables NMIs to develop and exploit their specific niche of expertise which will be used to meet the project's overall goals, and develop a European robustness in services where more than one NMI can provide the needed services to stakeholders. This collaboration strengthens the metrological expertise of all contributing NMIs, including small and emerging institutes, and supports EURAMET's goal for smart specialisation assuring an internationally leading position.

Outcomes for relevant standards

The International Commission of Illumination (CIE) is the international standardisation organisation on all aspects of light and lighting. Today's conventional techniques for realising absolute standard detectors require expensive equipment, high skill levels to operate, time-consuming methods and interpolation functions to establish a continuous spectral response scale.

The early outcomes of this work would be directly taken into the following relevant CIE Division 2 Technical Committees:

- TC 2-81 Update of CIE 065:1985 (Absolute radiometers)
- TC 2-90 LED Reference Spectrum for Photometer Calibration
- TC 2-96 Revision of ISO/CIE 19476:2014 Characterization of the Performance of Illuminance Meters and Luminance Meters

It is anticipated that the research will contribute to prepare updates to and replacements for CIE 250:2022 Spectroradiometric measurement of optical radiation sources and CIE 127:2007 Measurement of LEDs. Many European regulations and standards are referring directly or indirectly to spectrally resolved absolute measurements of optical radiation power, including European standard EN 14255 "Measurement and assessment of personal exposures to incoherent optical radiation" parts 1 to 4, and EN/IEC 62471:2008/CIE S 009:2002 - Photobiological safety of lamps and lamp systems". These standards require spectrally resolved measurements in the spectral range of about 200 nm to 2000 nm, both in the laboratory and onsite.

Longer-term economic, social and environmental impacts

The European photonics industry has grown from €76 billion in 2015 to €103 billion in 2019 with a growth rate of 7 % per year and a share of 16% of the global market. Besides components and materials, the major application segments are Photonics for Consumers IT, Medicine and Biology, Environment, Lighting and Energy and Industry 4.0, showing that photonics is participating directly in the challenges for the future. The largest segment in Europe – Photonics Systems for Industry – was worth €19.2 billion and accounted for the largest share in the global markets with more than 40 %. Europe is well positioned in the field of photonics systems for production, i.e. industrial laser systems, semiconductor manufacturing and machine vision.

This JRP proposal is fully supported by Hamamatsu Photonics Europe as an industrial supporter. They also have a role as Vice-President in Photonics21 [13]. Photonics21 is one of the European Technology Platforms, supporting the KET defined by the EU, and has more than 3000 members from the photonic industry, research institutes, academia and public service. The established contact between the consortium and Photonics21 simplifies the transfer of knowledge about project outputs to this important technology platform. A successful project will meet Photonics21 WG5 strategic roadmap targets for the period 2021 to 2027, where they request “maintenance-free, self-calibrating sensors, high quantum efficiency” as both a technology challenge and a research and innovation challenge for optimised value; a need outlined also by Quantum Flagship. The microelectronics-based primary standard detector is suitable for miniaturisation and may be integrated with the evolving technology of Photonic Integrated Circuits (PICs) in the future.

The incoming and outgoing radiation measurements are key components of Earth Energy Imbalance (EEI). Using PQEDs as a reference in lab-based calibrations or in future EEI spaceflights could improve future EEI measurements.

The age of the population is increasing and this fact puts more pressure on the health care system. New state-of-the-art techniques in medical diagnostic instruments require high accuracy radiometric measurements as they are known to be much faster and less invasive than conventional techniques. This ensures cost efficiency as for instance analyses of blood samples are done at the point of care and the medical doctor receive the answer while the patient is present.

22NRM01 TraMeXI

Traceability in Medical X-ray Imaging dosimetry

Summary of the project

<u>Overview</u>

X-ray imaging examinations form the largest component of exposure to artificial ionizing radiation in Europe. Therefore, accurate and consistent quantification of patient radiation exposure with calibrated dosimetry equipment is essential. The calibration procedures are based on relevant standards and international protocols that do not fully consider the recent technical developments within medical X-ray imaging. This project performs a critical assessment of conditions applied in calibrations compared to those used in clinical practice and studies the performance of different dosimeters. Based on the results, updated and traceable measurement and calibration procedures are proposed to be implemented in the standards and protocols.

<u>Need</u>

The medical use of radiation is typically well justified but due to the potential detriment, the radiation doses, measured with dosimeters, must be evaluated and optimized as required in the Council Directive (2013/59/Euratom). To achieve consistent, comparable, and traceable measurement results, the dosimeters must be calibrated, measurement methods must be harmonized, and uncertainties must be estimated.

X-ray systems provide a possibility to adjust their energy spectra so that image quality and patient dose can be optimized. A limited set of reference radiation qualities are used for calibrations. However, currently these qualities do not cover the clinical range and thus, the traceability chain is broken. This leads to the situation where calibration coefficients need to be interpolated or even extrapolated for different clinical conditions.

The challenge is that the change of the dosimeter response between calibration and clinical conditions is commonly not well known. The dosimeter might comply with the requirements within the limited range specified in the standards, but if the energy dependence of the response is strong, the related variation can be significantly larger when the equipment is used under clinical conditions and the targeted uncertainly might not be achieved.

Semiconductor-based X-ray multimeters (XMMs) have become the most common dosimeters in use at hospitals. The response of a semiconductor detector has a pronounced energy dependence, but the manufacturers have created algorithmic corrections to overcome this challenge. However, in this case, it can be challenging to confirm the uncertainties and traceability of the measurements.

In addition to radiation dose, these multimeters offer a possibility to measure further quality control parameters which are used for X-ray system testing. However, there are no agreed or validated calibration or measurement procedures for these devices. Thus, there is a need to establish basic metrological support for the new technology already being adopted in clinics.

Objectives

The overall objective of the project is to harmonize and standardize calibration and measurement procedures to ensure traceability and accurate dosimetry in medical X-ray imaging.

1. To review a representative range of radiation fields relevant in medical imaging and, based on the outcome, to propose an update of reference X-ray qualities used for calibrations and X-ray system testing. This provides input to the future revisions of International Electrotechnical Commission (IEC) standard IEC 61267 and to the international Code of Practice TRS-457 of International Atomic Energy Agency (IAEA).
2. To investigate the performance of commercially available X-ray dosimeters in calibration and clinical conditions. Based on the results, updated limits of variation of the response will be proposed to define specific requirements for reference- and field-class dosimeters. This provides input to the future revisions of IEC 61674 and IAEA TRS-457.
3. To define harmonized calibration and measurement procedures for XMMs, i.e. specific dosimeters which are clinically widely used to measure the relevant quantities and parameters considered in quality assurance of X-ray systems. This will enable an unbroken traceability chain for measurements of relevant clinical parameters and will generate input to the future revisions of IEC 61676 and IAEA TRS-457.
4. To establish and validate updated calibration and comparison procedures in medical X-ray imaging dosimetry.
5. To collaborate with the stakeholders and organizations involved in standard development to ensure that their needs will be acknowledged in the execution of the project, and that the final output will be implemented into future standards.

Progress beyond the state of the art and results

Updated reference radiation qualities

The reference radiation qualities used for calibration and described in standards do not cover the range of X-ray spectra that are in use under clinical conditions. A comprehensive overview on the clinically used radiation qualities will be made and their energy distribution will be analysed to find a representative set of reference radiation qualities for calibration purpose. Based on this, an update of the list of radiation qualities described in IEC 61267 will be recommended.

Requirements for dosimetry equipment

Limits of performance characteristics of diagnostic radiology dosimeters are defined in both IEC 61674 and TRS-457 but currently they do not allow a clear distinction between reference and field-class dosimeters, nor take sufficiently into account the characteristics of the dosimeters that exist on the market today. An overview of available dosimeters and their performance characteristics will be achieved. This will enable a clear-cut definition of reference and field-class dosimeter and the newly defined reference-class dosimeter could be used to provide traceability for hospitals. A recommendation will be provided to include the classification of dosimeters based on their performance in the IEC 61674.

Calibration and measurement procedures for X-ray multimeters

Currently there are no well-defined calibration or measurement procedures for XMMs. The clinical relevance of quantities measured with XMMs will be assessed, and calibration procedures and traceability chain will be established for the most important quantities. Calibration procedures will be adapted for use in clinics, to allow performance checks of XMMs in clinical beams, and to estimate the impact of the differences between clinical beams and reference beams applied for instrument calibration. Obtained data will be used to propose updates for IEC standards for air kerma and practical peak voltage measurement devices, and to propose inclusion of additional quantities measured by the XMMs in IEC standards.

Validated calibration services

Newly developed radiation qualities and calibration procedures for XMMs need to be validated to obtain international recognition for the new services. A comparison exercise will be organized to ensure that the calibration procedures established will provide consistent results and to study the response of field instruments in slightly variating conditions at different calibration laboratories.

<u>Outcomes and Impact</u>

The results of this project will provide important scientific input for the standardization bodies. The updated procedures are crucial for the National Metrology Institutes, Designated Institutes, and other calibration laboratories and important findings are shared among the metrology community. The outcomes will have a direct relevance and impact for industries, hospitals and regulators. Finally, the ultimate beneficiaries are patients who will benefit from optimized radiation exposure.

Outcomes for industrial and other user communities

The medical physicists are responsible for taking care of calibrations of their dosimetry equipment. However, currently the use of calibration certificates is very limited since the radiation qualities do not cover the clinical range and in some cases calibration services do not exist. Newly established and developed calibration services will support the medical physicist by providing useful calibration data for the end-user. The knowledge of dosimeter response over the clinically relevant range of radiation qualities and defined limits of variation will provide confidence for clinical measurements in varying conditions. This will also allow better understanding of the uncertainties involved.

All European Union countries are obligated to establish appropriate channels for calibration of dosimetry equipment. The current X-ray imaging dosimetry still contains gaps in the traceability chain. The same challenge applies to legal metrology verifications and type testing performed in some European countries. This challenge cannot be solved by one laboratory alone, but international cooperation and shared experience is required. Individual laboratories have already undertaken efforts which aim for better coverage of clinically relevant conditions. However, in the long run this is not a sustainable solution, and a collective approach must be found by the dosimetry community. Harmonized and standardized procedures enable the regulator to rely on the documentation and receive additional support for implementation of legal requirements.

The results achieved in this project will increase the European influence on the global market since several XMM manufacturers are located in Europe. The global market for XMMs is following the same increasing trend as observed at the European level; therefore, the proposed methodology will provide the appropriate answer to the urgent demand that non-European countries will also be facing. The proposed improvements in calibration procedures will help XMMs manufacturers to improve the position of their products on the international market and integrate their products as a part of the dosimetry chain in an accurate and cost-efficient way.

Different stakeholder groups are interested in the quality control related parameters of X-ray systems which can now be measured with the XMMs. The reliability of these parameters will be improved when harmonized calibration procedures will be established. This will be useful improvement for the companies producing X-ray systems and for the medical physicist and technicians performing quality control measurements

Outcomes for the metrology and scientific communities

The definition of reference-class dosimeters for X-ray imaging will help to categorize different levels of dosimeters. This will provide support especially for dosimetry laboratories in their selection of appropriate standards for metrology. In addition, this will support those who intend to perform measurements with improved accuracy. The study of the response of semiconductor-based detectors will consider the growing use of such instruments in clinical routine by providing improved procedures to ensure the traceability of such measurements. Ideally, the number of calibration points can be decreased which will reduce the workload of calibration laboratories and simplify the clinical measurement procedures.

In addition to updated calibration procedures for the radiation dose measured in terms of air kerma, the results will open new opportunities for dosimetry laboratories to offer calibration services for other quantities and parameters measured by XMMs. Traceable calibration of this equipment will provide additional confidence for quality control of clinical X-ray systems.

The work proposed will provide the European countries with a well-consolidated methodology for accurate calibration and verification of X-ray imaging dosimeters. Considering the large number of XMMs in clinical use, the results of this work will have a significant impact in medical X-ray dosimetry. The European metrology community will profit from this project, by acquiring improved knowledge in the field of X-ray dosimeter calibration, by increasing its influence when responding to an expanding demand related to the appropriate measurement of patient exposure and strengthened collaboration with the industry.

The entire traceability chain from primary and secondary standards until the end-user is covered and reviewed together. The planned and established European Metrology Networks can also provide valuable support for the dialogue between different stakeholders.

Outcomes for relevant standards

The research results provide relevant data for the updates of existing IEC standards such as IEC 61267, IEC 61674, IEC 61676, IEC 62220-1 and International Code of Practice IAEA TRS-457 and their future extensions. Close cooperation with those standardization organizations is emphasized to achieve international impact.

Longer-term economic, social and environmental impacts

The research proposed will have a direct impact on the accuracy, consistency, and comparability of clinical X-ray dosimetry measurements. The proposed procedures will provide the best outcome at all levels to enable a traceability chain and harmonized calibration procedures for dosimeters worldwide. The improved procedures will increase the European influence on the global market. Finally, this will provide a benefit to a large number of patients through a reliable quality assurance of X-ray imaging.

22NRM02 StanBC

Standardisation of Black Carbon aerosol metrics for air quality and climate modelling

Summary of the project

<u>**Overview**</u>

Black carbon (BC) contributes to climate forcing and is an air pollutant impacting health. Equivalent Black Carbon (eBC) mass concentrations are typically measured in real time with light absorption photometers. Being very sensitive to changes in emissions, eBC mass concentration might be regulated in the future as a metric for soot-like combustion by-products. However, neither eBC mass nor the related aerosol light absorption measurements have been standardised, traceability is incomplete and uncertainties are poorly understood. This project will provide and establish new standards for aerosol light absorption coefficient and mass absorption cross-section, whose combination leads to eBC mass concentration. These metrics are not addressed in the EN16909 standard on Elemental Carbon (EC) mass concentration.

<u>**Need**</u>

The quantity of airborne particles loosely described as black carbon has been widely measured by various optical methods since the early 20th century, because instruments for this are relatively simple and robust. Carbonaceous particles continue to receive high levels of attention from the scientific community and policy makers, with the related parameter Elemental Carbon included in the EU Ambient Air Quality Directive, because of their role in both climate change and health effects. The dominant sources have changed over the decades, from domestic and industrial coal burning to vehicle combustion emissions, with more recent contributions from wood and biomass burning.

Black carbon has been identified as an important climate-forcing agent, contributing to warming of the atmosphere. Because black carbon has a much shorter atmospheric lifetime than CO_2, black carbon mitigation strategies could rapidly slow down the rate of climate change. In climate models, the effects of black carbon are accounted for through the metric “aerosol light absorption coefficient”, whereas the BC sources are described by the mass emission rate.

Airborne particles have serious human health effects across Europe and worldwide. Yearly, about 300,000 premature deaths in the EU are attributed to fine particulate matter (PM). Studies of short-term health effects suggest that the metric “black carbon mass concentration” in ambient air is a better indicator of harmful particulate substances from combustion sources than the total undifferentiated PM mass concentration.

The two metrics “aerosol light absorption” (*b*) and “BC mass concentration” (denoted below as *BC*) are directly proportional to each other, and the conversion factor is known as BC mass absorption cross-section (MAC):

$$BC = \frac{b}{\text{MAC}}.$$

Optical absorption measurements are challenging and traceability is hampered by the fact that routine monitors determine the absorption of particulate matter collected on a fibrous filter. The presence of the filter has a large effect, due to internal scattering within the filter, which can increase absorption by a factor of five, and to saturation effects as the filter accumulates material. These effects are currently handled with generic correction factors. Moreover, filter-based monitors treat MAC as a constant, disregarding the fact that it depends on site-dependent aerosol properties. There is therefore a need to replace these generic, built-in correction factors and MAC values with properly determined calibration factors (which strongly depend on various particle properties and the wavelengths of the light source).

Objectives

1. To standardise in-situ reference methods for aerosol light absorption coefficient (extinction minus scattering and photo-thermal interferometry) and develop a robust uncertainty budget estimation as a function of the wavelength and ambient aerosol properties (e.g. single scattering albedo, SSA). Target measurement uncertainties are ≤10% (95% confidence level). To provide clear guidelines to end users about the specifications, limitations and application range of each reference method.

2. To standardise methods for the measurement of the aerosol mass absorption cross-sections (MAC) (i.e. at various wavelengths) based on traceable measurements of light absorption and EC mass. To establish the relationship between BC mass and EC mass (EN 16909:2017) via inter-comparisons.

3. To develop procedures for calibrating filter-based light absorption photometers against the reference methods using a series of well-defined synthetic aerosols generated in the laboratory. The SSA of the synthetic aerosols will span the whole range from <0.5 (highly absorbing) to almost 1 (purely scattering) in order to obtain SSA-dependent calibration factors along with the associated measurement uncertainties (target uncertainties are <15 % for 95% confidence level).

4. To develop a new CEN standard which describes

    a) Traceable reference methods for determining aerosol light absorption coefficients (i.e. at multiple wavelengths) and

    b) Procedures and materials for calibrating filter-based photometers against the reference method(s).

    To this end, a dedicated working group will be initiated within CEN/TC 264 "Air quality". Moreover, to work closely with the CEN/TC 264/ WG35 "Standard Method for Measurement of OC and EC Deposited on Filters" and ISO/TC 146/SC 3 "Air quality: Ambient atmospheres" to ensure that the outputs of the project are aligned with their needs, communicated quickly, and in a form that can be incorporated into the relevant CEN/ISO Standards at the earliest opportunity.

5. To address the Stakeholder needs regarding BC-related metrics laid out in the Review Report of the European Metrology Network (EMN) for Climate and Ocean Observation (see Sections 3.1.4.1 and 3.1.4.2) and establish strong collaboration with the EMN Pollution Monitoring (currently under development). To facilitate the uptake of the technology and measurement methodologies developed in the project by the national and European air quality monitoring networks (e.g. ACTRIS, EMEP, GUAN, NABEL, UK Black Carbon Network, Atmo-France, FMIODATA, Sinica) and instrument manufacturers.

Progress beyond the state of the art and results

The current state-of-the-art is that black carbon measurements are being widely made based on a principle that has been used for many decades, with one of several designs of filter-based instrument, such as multi angle absorption photometers (MAAP), aethalometers and particle absorption photometers. These instruments do not measure BC mass concentration directly; they determine light attenuation as it passes through the filter with the sample, convert it to the absorption coefficient based on several assumptions, and calculate the so-called equivalent BC (eBC) mass concentration with the use of a fixed MAC value.

Thanks to recent developments within the EMPIR Black Carbon (2017-2020) and other EU projects, there are now traceable techniques that measure aerosol light absorption while the particles are airborne, and these of course are not complicated by the effects of the filter. Studies are clarifying the corrections needed to obtain accurate aerosol absorption coefficients and eBC mass concentration from filter-based instruments by inter-comparisons with reference methods but further work is needed. The corrections can be made more valuable by including more detailed information on the particles (e.g. light scattering properties, particle size etc.).

The technical results that are expected from this project are as follows:

1. Standardisation of traceable, primary methods for determining aerosol light absorption coefficients at multiple wavelengths of the light source

The traceability of two different laboratory-based primary methods for determining aerosol light absorption coefficients (i.e. photothermal interferometry PTI and the extinction minus scattering EMS method) will be extended to multiple wavelengths. A calibration procedure for these primary methods will be standardised based on the use of reference materials with well-known and SI-traceable absorption coefficients (gases and aerosols).

2. Standardisation of methods for the determination of the aerosol mass absorption cross-section (MAC)

MAC is not a constant but depends on various BC aerosol properties. The dependency of MAC on particle size and aerosol mixing state will be systematically investigated in the laboratory using reference aerosols. A set of MAC values will be determined to convert aerosol light absorption reported by filter-based absorption photometers into eBC mass concentration.

3. Protocol for the lab-based calibration of filter-based absorption photometers

Calibration of filter-based absorption photometers has only been performed for a small subset of relevant aerosols (i.e. aerosols with low SSA) and is not yet standardised. The calibration procedure will be extended to include more environmentally relevant reference aerosols, covering the whole aerosol SSA range (i.e. from almost 0 up to about 1).

4. New CEN TC 264 standard

Currently, no standard exists on BC-related metrics. The Consortium will initiate a new Working Group (or Subgroup of WG 35) within CEN TC 264 dedicated to the standardisation of aerosol light absorption and eBC mass concentration. The results of this project will feed directly into the new standard.

Outcomes and Impact

The issues of climate change and air pollution are truly international. Moreover, the breadth and depth of the challenges that need to be overcome to provide traceability for BC-related optical and mass concentration measurements require an extensive range of expertise. The scope of this project is therefore beyond the capabilities of a single NMI and a pan-European approach is essential in order to deliver the work.

Normative projects tackling global challenges, such as pollution and its detrimental effects on public health, must achieve wide consensus in order to harmonise procedures in Europe (and worldwide). They rely therefore by nature on the close collaboration between countries and the will to align national regulations. The EPM programme, bringing together NMIs, research institutes, instruments manufacturers and experts from air quality monitoring networks across Europe, is the ideal platform for the work described in this project.

Outcomes for industrial and other user communities

The EMPIR 16ENV02 Black Carbon and 18HLT02 AeroTox projects have greatly contributed to the development and characterisation of novel aerosol instruments (including a soot generator, the oxidation flow reactor known as OCU, and the photo-thermal interferometer PTAAM-2λ). All these are manufactured in Europe and will be employed in the calibration procedure for filter-based absorption photometers either as reference aerosol sources or as reference measurement methods. Moreover, several manufacturers of filter-based absorption photometers are based in the EU. This project will enhance the end users' confidence in these instruments through standardisation, promote sales and help European manufacturers assume a leading role in the global market.

Outcomes for the metrology and scientific communities

The direct impact of the proposed research will be more accurate and more comparable measurements of aerosol light-absorption coefficient and better estimates of eBC mass concentration than in the current status of the widespread aerosol monitoring networks in Europe, through the standardisation of traceable methods for calibrating filter-based absorption photometers.

Indirectly, the impact would be very widespread. In terms of scientific benefits, the improved measurements would fit into EU atmospheric aerosol projects, refining climate change models, and improving the quality of conclusions from cohort health studies looking at the health effects of air pollution. Air quality measures to reduce human exposure to BC such as emission reduction and low emission zones have already been taken. However, traceable BC-related metrics to reliably quantify the success of these measures are not yet available. The results of this project will feed directly into national air quality monitoring networks across Europe. The improved measurement accuracy will also help set up reliable black carbon emission inventories.

Outcomes for relevant standards

Currently, there are no legislated limits for BC for outdoor air concentrations, only the total mass of fine particles is regulated. This is partly due to the fact that there is no well-defined metric for BC mass concentration in ambient air. Ultimately, the project will provide a CEN standard on BC-related metrics and form the basis for future European legislation.

Longer-term economic, social and environmental impacts

In terms of socio-economic benefits, the project output can lead to revised air quality legislation including eBC mass concentration, for which reliable monitoring methods would be available. It will provide a basis for better decision-making on measures designed to reduce BC emissions, both for its global warming impact and its health impact. Ultimately this would have significant benefits both on human health within Europe, contributing to a reduction in the 300,000 premature deaths per year in the EU, and to global environmental sustainability. More specifically, more efficient policies for the reduction in BC emissions will help slow down global warming, thus reducing the melting of glaciers in alpine and arctic regions, mitigating changes in rain patterns and preserving the health of ecosystems.

22NRM03 MetHyTrucks

Metrology to support standardisation of hydrogen fuel sampling for heavy duty hydrogen transport

Summary of the project

<u>Overview</u>

Hydrogen can significantly contribute to reducing emissions from the transportation sector as it is particularly well suited for long-haul heavy-duty (HD) vehicles. The uptake of hydrogen for heavy-duty transport requires further standardisation to support Europe's green energy future. If the development of sampling systems and methods at hydrogen refuelling stations (HRS) for light-duty (LD) vehicles have been addressed in recent projects, there is a lack of technical evidence for heavy-duty transport.

This project will deliver the evidence needed for the standardisation of hydrogen fuel sampling for heavy-duty applications. This includes the development of **dedicated sampling systems** for gaseous species and particulate matter, **methodologies for the validation of sampling methods**, guidelines for the evaluation of sampling representativeness, uncertainty budget and safety in addition to venting protocols. The outputs will be directly fed into ongoing **standardisation development** done in CEN TC 268 and ISO TC 197 technical committees.

Need

With the increasing interest in using hydrogen and fuel cells in medium and heavy-duty applications, the need for dedicated standards for these application increases. Currently the number of buses, trucks and trains in Europe are around 500 units but will increase at a very high pace. At least 60,000 hydrogen driven trucks are expected to be in operation by 2030 which will require a large infrastructure of truck-suitable hydrogen refuelling stations.

Hydrogen-powered vehicles require extremely pure hydrogen with some contaminants reducing performance of the fuel cell already at very low levels. Previous metrology projects have paved the way for the development of the European quality infrastructure for the hydrogen conformity assessment. However, the reliability of a measurement is intrinsically linked to the representativity and reliability of the sampling itself. Poor sampling may lead to potentially damaging a fleet of HD vehicles. Moreover, standardisation is required as HD-HRS network will be shared between operators (e.g., BP, Air Liquide, MotiveFuels), sampling practices should not create a source of discrepancies in quality within the emerging network.

Within ISOTC 197 /WG33, a new standard is being developed to support hydrogen sampling at hydrogen refuelling stations. Sampling is currently not standardised, and only good practice information are available in Annex K of ISO 19880-1. The new draft ISO19880-9 standard is focussing on the sampling for passenger (HRS) due to the lack of technical evidence and available sampling systems for heavy-duty HRS (HD-HS). **The main barrier is the lack of sampling systems adapted for heavy-duty applications**.

New or adapted sampling approaches will need to be trialled in real conditions to assess performance of the sampling approach. Without such dataset and evidence, any standardisation document cannot be progressed. This will require a **standardised protocol** to meaningfully demonstrate sampling systems performance.

An additional challenge is **lack of estimation of the uncertainty budget due to the sampling**, this is needed to assess the total uncertainty budget for the hydrogen quality assessment. This budget is directly linked to the representativeness of the sample collected.

Finally, the sampling of hydrogen at HRS is an operation within an explosive atmosphere area involving safety risks. Therefore, an important aspect to consider is how **to safely perform hydrogen sampling**.

Objectives

The specific objectives of the project are:

1. To develop **reference methods/systems** based on new hardware for interfacing relevant nozzle geometries for hydrogen heavy duty applications. This includes addressing methods for both gaseous and particulate phase. In addition, method comparison with existing methods for sampling for light duty application is documented to demonstrate equivalence or identified bias.
2. To **develop methodologies for validation of sampling systems**. This includes method validation including evidence of impact of physical parameters (e.g., pressure and flow) on sampling representability. Gas sampling validation includes accurate gas contamination and assessment of recovery yield. System is laboratory based for flexibility in fluid physical parameter control and gas composition. To estimate the uncertainty due to the sampling
3. To develop **guidelines for evaluation of uncertainty of sampling, sampling representativeness** including minimum sampling size (**target uncertainties of 10 %)** and sample volume/gravimetric requirements by performing repeated samplings under varying conditions.
4. To support the **safety** standardisation of heavy-duty sampling involving safe sampling of hydrogen: **venting** of hydrogen, **risk assessment** and **training** of stakeholders.

5. **To contribute to the standards development work of the technical committees CEN TC 268 and ISO TC 197** to ensure that the outputs of the project are aligned with their needs, communicated quickly to those developing the standards and to those who should use them, and in a form that can be incorporated into the standards at the earliest opportunity.

<u>Progress beyond the state of the art and results</u>

Methods for sampling hydrogen for quality assessment (gaseous species and particulates) at heavy-duty HRS (Objective 1)

This project will develop new sampling systems or adapt existing sampling systems to HD applications. This is the first necessary step to enable the collection of a representative sample of hydrogen at these emerging stations. Several engineering companies will develop sampling systems to fill the market gap and NMIs will ensure that metrological aspects for the validation of these systems are considered. The new sampling systems will be tested and validated leading to the development of guidance on metrological testing and validation of sampling systems for heavy-duty HRS sampling.

Methodologies to validate the sampling systems to ensure sample representativeness (Objective 2)

This project will develop a protocol to validate sampling systems. The first version will take advantage of all the knowledge that has been gathered during previous projects (16ENG01, 19ENG04, FCH-JU HYDRAITE). The outcome of the project will allow to finalize the protocol using feedback from activities conducted throughout the project. Finally, to enable validation of all the performance parameters of the sampling system, the project will provide recommendation to assess the performance of sampling systems with regards to recovery in an environment where accurate gas contamination can be prepared. This will allow to establish documented evidence which proves that a given sampling method meets the requirements for the intended purpose.

Guidelines for sample representativeness and measurement uncertainties arising from sampling (Objective 3)

The current practice to assess hydrogen purity according to ISO14687 involves the process of taking a sample. Measurement uncertainty is the most important single parameter that describes the quality of measurements The uncertainty associated with the sampling process must inevitably contribute to the uncertainty associated with the reported result. While existing guidance identifies sampling as a possible important contribution to the uncertainty in a result, procedures for estimating the resulting uncertainty are not well developed and further, specific, guidance is required.

Good practice guide for hydrogen venting during sampling exercise (Objective 4)

The sampling of hydrogen fuel at HRS is an operation within an explosive atmosphere (ATEX) area involving safety risks which includes a step of venting. The sampling exercise is not part of the normal procedure at HRS. As HD-HRS operate at high flowrate and downtime operation has to be minimized (to not disturb the refuelling of trucks), safety is a key element for the standardization of sampling. To reduce the risk to an acceptable level, reliable risk assessment methodology is required so that appropriate control measures can be planned and required safety standards can be established.

<u>Outcomes and Impact</u>

Outcomes for industrial and other user communities

The project outputs will enable fit-for-purpose hydrogen sampling services for industries, testing laboratories, research organisations and other end-users. End-users can rely on hydrogen purity assessments which in turn contributes to prevent serious damage to hydrogen-powered trucks and busses and secures and improves the overall European quality infrastructure for the hydrogen conformity assessment. Considering existing fleet of 500 and future fleet of 60000 vehicles, it is critical to ensure that the hydrogen fuel will not reduce vehicle lifetime, increasing cost of ownership significantly and availability of the service for the early adopter communities. Maintaining high level of service is key for successful energy transition towards green energy and lower CO_2 emissions.

The dissemination activities will enable the uptake of the project's outputs by industrial stakeholders including HRS operators, fuel cell electric heady duty vehicles, fleet operators, hydrogen producers, testing laboratories, research institutes and other end-users as well as standardisation committees.

The project outputs contribute to lowering the detrimental impact on the climate and health via extended implementation of hydrogen mobility.

Outcomes for the metrology and scientific communities

The objectives of the project are well aligned with the metrology needs. Sample representativeness has been highlighted as a high priority in the Strategic Agenda [6] produced by the EMN Energy Gases.

Gas metrology and commercial gas analysis laboratories will be able to use suitable sampling strategies at heavy duty refuelling station for ensuring representative samples of hydrogen can be taken and transported to their laboratory.

NMIs having developed traceable and reliable methods for hydrogen quality assessment will be able to expand their services to the sampling of hydrogen at HRS.

Outcomes for relevant standards

The project's outputs will provide direct input to several working groups within TC 197: WG24, WG29, WG27, WG28 and WG33. The project is of very high relevance for ISO/TC197/WG33 "Sampling for fuel quality analysis" as it directly contributes to the development of ISO/WD ISO19880-9. The project has also direct link to EN17124, EN17127, ISO19880-8, ISO19880-1 and ISO14687.

The project will also provide input to the activities of other committees, such as BIPM WGFF, Euramet/Metchem SC-GAS, and national working groups and mirror committees. The project outputs will also be disseminated to the European Metrology Network for Energy Gases as several partners are active members of this EMN.

Longer-term economic, social and environmental impacts

In addition to supporting climate change targets, hydrogen buses and heavy-duty vehicles will improve air quality and provide health benefits as only water is emitted from the tailpipes; this will prevent people from breathing in carbon dioxide and carbon monoxide emissions and reduce the frequency of pollution peaks. As more heavy-duty HRS are built, the number of Fuel Cell Electrical Vehicles (FCEVs) will increase and become more visible to society. But as for any new market, public safety needs to be guarantee and acceptance need to be obtained. These can only be achieved by minimising operational problems which is in turn reached by confidence and assurance that the fuel has the required quality. Performing a representative sampling is of paramount importance for the quality assessment. As enhanced acceptance of FCEVs is achieved, these vehicles will be more and more regarded as normal road vehicles rather than a prototype or small fleet. The societal acceptance of hydrogen fuel is essential to achieve the energy transition toward a greener society. As mentioned in the strategic agenda from the EMN Energy Gases, it is clear that the electricity grid alone cannot support user energy demands. Moreover, diversification by the development of hydrogen technology allows for our society to absorb a shock in a major energy input.

22NRM04 e-TRENY

Metrology support for enhanced energy efficiency in DC transportation systems

Summary of the project

Overview

DC railway and metro systems, supplied by unidirectional substations, show significant waste of energy for their inability to fully recover the energy produced by electric braking. Bidirectional substations and/or storage systems are expected to significantly improve the energy efficiency but presently equipment and procedures lack to determine their real overall efficiency performance as well as the efficiency of their components like power transformers and converters. Following needs expressed by IEC TC9, CLC SC9XC and CLC TC14, this JRP will develop new methodologies for DC transport efficiency determination, that combine accurate on-site measurements with circuit models of the railway electric system.

Need

The transport sector, in particular road vehicles, is responsible for almost **one quarter of Europe's greenhouse gas (GHG) emissions**. The **modal shift to public transport with electric rail** as a backbone (urban rail in urban areas) is a self-evident priority, and the EU policy to support the development of sustainable and smart mobility will lead to a consequent increase of energy consumption by electric rail transport. A major weakness in the efficiency of DC transportation systems is the **limited recovery of the electric energy** generated during the electrical braking of the trains. Estimates show that an amount of 1 GWh per year, about the annual consumption of 365 families, can be wasted in one single commuter line.

This situation is strongly improved by the **introduction of bidirectional power converters and storage systems** that allow for the injection of the braking energy in the upstream AC grid or in the local storage system. However, electric transport operators, supply designers and developer require **standardized methodologies and procedures** that support the substation procurement and allow accurate and reliable evaluation of the **actual efficiency** of power transformers and converters and system energy saving under real operating conditions in order to verify the compliance with the designed efficiency or to quantify the cost/benefit ratio in a more realistic way.

CLC/TR50646 has declared standardization **needs for the traceable determination of efficiency** for different operation modes (traction, regeneration) and the determination of the performance of harmonic compensation on AC and DC side. With the increased efficiency of modern power converters and power transformers, **CLC TC14** has called for on-site determination of their losses under actual operating conditions, requiring **traceable measurements with ultimate accuracy**. Accurate losses determination under real operating conditions requires a new traceability that involves distorted and dynamic conditions.

Objectives

The overall objective of the project is to **support enhanced energy efficiency in DC railway systems**, via new traceable methods for **on-site measurement of the efficiency of substation transformers and converters** and for measurement of the **efficiency increase achieved by the adoption of energy recovery systems such as non-conventional bidirectional substations or energy storage systems** in commercial service.

The specific objectives are:

1. **To provide an overview** on possible configurations for non-conventional DC substations (e.g. bidirectional and/or with storage systems) including evaluation of pros and cons. **To perform a survey** of real installations focusing on the design characteristics and the expected or declared energy savings. To establish a suitable measurement approach and **to design instrumentation** for on-site measurement campaigns.
2. **To develop a metrological infrastructure** for calibration of high voltage (3 kV) and high current (1000 A) DC transducers and measurement systems under dynamic conditions with typical timescales from a few hundreds of milliseconds to a few seconds.
3. **To develop, calibrate and apply on-site** setups and algorithms for the measurement of the energy losses of non-conventional AC/DC substations and the charge-discharge efficiency of electric storage systems with an overall on-site **target uncertainty of 10%** of losses. The setups allow capturing signals from DC to 20 kHz to perform Power Quality and transient event analysis.
4. **To develop, characterise and determine** the accuracy of a hybrid method based on the combination of field measurements and models for the determination of the energy saving provided by the upgraded DC supply system in real operating conditions.
5. **To contribute to standards development** of technical committees CLC TC9X, CLC TC14 and IEC TC9 aligning project outputs to their needs with rapid communication including final users (e.g. DC transportation system operators, manufacturers, designers).

Progress beyond the state of the art and results

Measurement systems for on-site converter efficiency

The in-force standards on power converters for DC railway supply only deal with AC/DC diode-rectifier systems. It is requested there that "If the purchaser requires measurement of the losses this shall be mentioned in the procurement specification. The **admissible tolerance for losses is +10%** of the guaranteed value". The standards give very little information about the accuracy of the measurement chain for losses; detailed information is provided only for 50/60 Hz power component measurements. For losses lower than 3% (efficiency > 97%) the standard proposes a calorimetric approach which is time-consuming and cannot be implemented on-site. The project will go beyond this by in-situ accurate and traceable efficiency determination.

This project will develop a **new traceable measurement infrastructure** able to measure on-site the losses of conversion systems (power transformers, power converters, storage systems) during commercial service in two test cases, metro and tramway line. **Losses of AC/DC, DC/AC DC/DC and power transformers will be determined** with an **overall uncertainty better than 10%** of losses. This uncertainty allows **reliable loss determination** even for losses value lower than 3%. The system will allow to correlate efficiency and signal distortion up to 20 kHz.

Traceability for power measurement under dynamic and low-frequency conditions

Present calibration capabilities (CMCs) for AC power declared by NMIs deal only with static, pure sinusoidal waveforms in the frequency range from 40 Hz to 100 kHz for voltage and current amplitude of hundreds of volt and tens of amperes. No CMCs for DC power CMC are declared in the BIPM database (KCDB) since there were not widespread applications up to now.

In order to guarantee accurate on-site losses and efficiency measurements, the project will develop **new traceability for DC dynamic signals** (voltage and current ramps) with slew rates from 500 A/s to 10 kA/s and from 100 V/s to 10kV/s with amplitudes up to 1200 A and voltage 3 kV. The overall target uncertainty will be 0.01%. Moreover, the project will upgrade the systems developed in the MyRailS 16ENG04 project by providing traceable systems for **AC and DC distorted power measurement even under dynamic conditions**, up to 20 kV 300 A AC and 4 kV 3600 A DC. These systems will emulate the relevant load fluctuation experienced in the transportation systems.

System efficiency determination

System efficiency is presently demonstrated by manufacturers using simulations only, without standardized approach for validation of the simulator in terms of reliability and accuracy. Even standard EN 50641, released in 2020, still lacks coverage of measurement of all quantities necessary for a complete determination of system energy efficiency.

This project will develop and test a **hybrid tool combining a power-flow model of the transportation system with distributed measurements** performed both at substations and on-board trains. The tool will provide the energy saving introduced by non-conventional substations with associated uncertainty and sensitivity estimate, and the goodness of coordination between the voltage control at substations and on-board trains. Information on the optimum number and position of measuring points will also be provided with associated uncertainty.

<u>Outcomes and Impact</u>

The project will positively influence the assessment of the energy efficiency of DC railway systems, in particular those with new bi-directional substations, providing knowledge to power transformer and converter manufacturers, substation designers and installation engineers. The new instrumentation developed in the project will allow unique on-site determination of energy efficiency (at MW level) of power transformers and of AC/DC and DC/DC high-power converters under real operating conditions. The project will provide a methodology for accurate determination of energy saving introduced by non-conventional substations.

Outcomes for industrial and other user communities

The new facilities for on-site AC and DC power measurement will allow the first-ever determination of losses of high-power high-efficiency (> 97%) converters under actual grid conditions and for dynamic load conditions. This will provide unique insight to the DC transport industry into the actual efficiency of railway supply systems in the presence of grid harmonics and other disturbances. Furthermore, a reliable and traceable measurement system for the determination of harmonics/ripple on AC and DC supply systems will impact the verification of the electric pollution introduced by the power converters for the different operating conditions. The experience gathered by the on-site measurements will allow drawing up a **Best Practice Guide** that will simplify (and thus reduce cost thereof) **on-site compliance assessment activities** to the technical requirements of railway transportation systems tenders.

The project will also develop and make available a **hybrid method, combining measurements and power-flow model,** that will allow the determination of the energy saving provided by installation of non-conventional substation(s) in DC railway systems. A clear and accepted definition of parameters which quantify the efficiency improvement is of vital importance in the trade exchange between the manufacturer (or contractor) and infrastructure owner (or operator). An example is **line receptivity**, a parameter that is more and more present in tender technical requirements. The project will provide a clear definition and methodology to estimate receptivity in different operating conditions by a tool that combines measurements with a modeling approach. This will prevent disputes between customers and providers of new DC railway supply systems.

Metrological and methodological tools will be provided to define and measure the conditions for an optimized coordination of the reversible substation and storage system, compensating for deviations from the ideal power exchange among running trains in braking and tractioning conditions, and allowing the removal of the dissipative rheostatic braking system from on-board trains. This will provide major savings to operators of DC railway systems.

To facilitate the uptake of project's outputs there will be considerable **stakeholder engagement** throughout the project (and after its end) with industrial stakeholders including railway, metro, tramway infrastructure managers, railway operators, power converter manufacturers, installation engineers, railway supply system designers. The participation of **industrial partners** in the project and the establishment of a Stakeholder Committee will ensure that the project outcomes are strongly aligned with industrial needs.

Outcomes for the metrology and scientific communities

The developed laboratory facilities and procedures for the characterization of DC and AC broadband voltage/current sensors and power measurement systems used for on-site measurements will be the basis for submission of **new calibration services (CMCs)** under actual grid conditions (i.e., with ripple and harmonics).

The **new metrology knowledge** gained in the development of the new laboratory facilities and in its subsequent use for calibration and verification of the voltage/current sensors and the power measurement systems will be an important metrology outcome of the project. This knowledge will be shared with the metrology community during several meetings of the EURAMET SC Power and Energy, the EMN on Smart Electricity Grids and CPEM conferences. It is expected that the new facilities for calibration of DC voltage and current sensors in the presence of ripple, as well as the new Energy Efficiency Measurement Systems (EEMSs) for on-site efficiency measurements in transport systems will raise significant interest in the metrology community.

The measurement campaigns will result in **unique data on DC railway systems**, with a clear uncertainty characterization, that will be very useful for further research activities in the statistical analysis of power flows and for designers, who can have data which represent the real energy state of the system with information on its variability. The methodology can be applied to different contexts and will allow to develop designs even more tailored on the considered context.

The measurement campaigns will furthermore provide unique **insight into the efficiency of power transformers and converters under actual grid conditions and varying load conditions**. At present, there is hardly any scientific literature on this subject due to the complexity of the required measurements. This project will provide pioneering research in the loss mechanisms of transformers and converters under non-ideal conditions.

The development of new measurement systems and the results of the on-site campaigns will result in a series of **high-quality scientific papers**, showing a significant advance with respect to the state of the art.

Outcomes for relevant standards

The project research outcomes will contribute to the **research priority declared by the IEC TC9 and CENELEC TC9X** on the efficiency determination of power converters installed in railway DC substations and on the accurate determination of the energy saving introduced by non-conventional substations. In particular, input will be provided to IEC TC9 WG50 and CENELEC subcommittee 9XC WG11 on the measurement system and on the procedures for losses and harmonic/ripple determination.

The project research addresses the **need expressed by CENELEC TC14** for research on accurate on-site determination of power transformer and power converter losses under actual distorted conditions. The results of the on-site campaigns in the project and the developed methodology will be promoted within CENELEC TC14 and IEC TC11. During the TC meetings, possible uptake of project results in a new technical specification or report will be discussed and eventually pursued.

Longer-term economic, social and environmental impacts

The new measurement infrastructure for traceable quantification of efficiency and benefits of new substations under actual operating conditions will foster the diffusion of **new energy-efficient technologies** for power conversion in DC railway systems. A reliable methodology to quantify the cost-benefit ratio of new investment devoted to energy saving will positively contribute to decision-making processes on the uptake of these investments. The increase of the braking energy recovered by the system will **contribute to the European policy** for a smart and sustainable European transport system and contribute to climate and environment by CO_2 savings.

22NRM05 MeLiDos

Metrology for wearable light loggers and optical radiation dosimeters

A2 Summary of the project

Overview

Light has a profound impact on humans, and ongoing clinical research is being carried out on the biological and physiological effects of light on sleep, health and wellbeing. Wearable light loggers are lightweight wireless devices that measure the light doses that humans incur over time. though new standardised methods and metrics have been introduced in CIE S026, calibration and characterisation of such dosimeters remains challenging. This metrological gap extends to UV radiation dosimeters. This project will provide guidance on the characterisation and use of wearable light loggers and the data they produce to ensure their reliability for the studies that use them.

Need

Daylight has always been part of human life, regulating physiological activity and cadencing many aspects of society. At the same time, the invention of electric lighting has led to more and more people spending the day indoors and lately, working from home. However, the intensity of artificial light is a fraction of that of daylight and the spectral composition is also different. While the study of sources and lighting can always be done in laboratories or controlled conditions, the direct effects of light on human physiology needs field measurements of the light dose humans receive in real settings.

Moving laboratory equipment being highly impractical, wearable light loggers have been used to assess the light exposure of humans in clinical research, as they can be carried and provide first-hand data about light exposure throughout the day of a subject. However, their compact and lightweight, black-box design introduces a variety of limitations that leads to inaccuracies, inappropriate metrics or non-representative data. How the data is processed depends on a number of parameters for each device, such as the number and type of sensor used, sampling rate, data format and model. There is no current guideline or standard for the characterisation of these devices, leading to highly unreliable data and wasted time due to inappropriate device specifications and/or data processing and interpretation.

In TN002:2014, CIE has identified the need to harmonize photobiological and photometric quantities. With the rapidly evolving field of lighting (future revision of CIE S025, publication of CIE S026, introduction of daylighting by EN 17037 and revision of workplace lighting in EN12464-1) and the spread of wearable devices of all kinds, it is important to keep metrology recommendations and guidelines up to date to ensure reliable studies that underpin future health recommendations and policies.

Objectives

The overall goal of the project is to introduce metrology for light dosimeters, in particular for devices designed to answer the needs raised by CIE S026 with the introduction of the sensitivity of melanopsin, a photo-pigment present in the eye and involved in physiological responses to light but not in the formation of images. More specifically, the project will deliver metrics and procedures, as well as guidelines depending on use cases, in order to lay the groundwork for future normalization efforts.

The specific objectives are:

1. **To develop novel characterisation methods, and propose a set of quality indices for light loggers and UV radiation dosimeters**. The quality indices may be similar to those defined by ISO and CIE for illuminance meters and luminance meters and their measurement should be validated through an interlaboratory comparison.
2. **To develop data analysis methods to verify and increase the quality of data**, and to establish the correlation between different data sets.
3. **To produce recommendations on (meta-)data model and data formats, as well as summary metrics and on the practical use of light loggers,** including device placement, compliance and quality control.
4. **To investigate the performance of new portable devices** able to measure spatially resolved photobiological quantities and to compare them with spatially averaging devices, to determine relevancy depending on use case.
5. **To collaborate with CIE Division 2 and Division 6,** and the users of the standards they develop to ensure that the outputs of the project are aligned with their needs, including the provision of recommendations in a form that can be incorporated into future standards at the earliest opportunity.

Progress beyond the state of the art and results

Characterisation methods for wearable light loggers designed to evaluate Non-Image-Forming (NIF) effects and UV radiation dosimeters (Objective 1):

Though it has been known for over two decades that light has a profound effect on human health and wellbeing, only recently has CIE S 026 defined spectral sensitivity functions, quantities and metrics to quantify the light triggering these effects. The spectral measurement and characterisation of light sources in testing laboratories are usually well understood and the measurement uncertainties are at an acceptable level for current uses. In recent years, various wearable light loggers and UV radiation dosimeters have been developed to enable the measurement of spectrally weighted irradiances and irradiance doses in field experiments, implementing CIE S 026. Because these instruments need to be portable and light weight, their design differs from those typically used in laboratory environments. Traditional methods of providing traceability for example by measuring the spectral responsivity with the narrow band source are thus not suitable. So far, no standardized methods exist to characterise wearable light loggers and UV radiation dosimeters.

This project will build a metrological framework for the characterisation of wearable light loggers, giving methods for their evaluation, validation and traceability. The developed methods will be validated through an intercomparison, contributing to measurement capabilities at NMIs as well as in industry. The project outcomes will be summarised in a publicly available good practice guide (GPG), which will support CIE in the development of standards for the characterisation of wearable light loggers. The overall goal is to provide guidance and methods to stakeholders on how to reliably characterise wearable light loggers.

Good Practice Guide for the utilization of wearable light loggers in the field and the validation of the data

There are multiple applications for wearable light loggers and different devices designed to answer specific applications. There are currently no guidelines or recommendations related to the proper selection and use of wearable light loggers. This project will define a usage landscape based on the applications' needs and provide recommendations on the quality indices and other characteristics that a User should pay attention to while choosing and using wearable light loggers.

The data measured by wearable light loggers can be affected by multiple factors, mostly coming from the wearer's such as compliance, environment and behaviour. It is therefore necessary to include processes and data analysis methods to validate the data. This project will also provide a research-oriented software ecosystem to facilitate data analysis, validation and representation, as well as the cross-comparison between different devices and studies with harmonized data format.

Guidelines and groundwork for the characterisation of future sensors aiming to surpass the inadequacies of currently available devices

The fast development of wearable devices and the spread of their use for aggregating data with constellations of devices or for behavioural studies poses a major challenge for the reliability and traceability of the data generated by these devices. New sensor technologies for wearable light loggers will be investigated in this project in order to ensure the methods and recommendations delivered stay transferrable to new technologies and do not easily become obsolete. In particular, the use of spatially resolved devices will be investigated since they can have additional value even for the study of non-visual effects of light.

Outcomes and Impact

Outcomes for industrial and other user communities

The project will deliver recommendations and guidelines for the characterisation of wearable light loggers, providing industrials or scientists developing wearable light loggers and UV radiation dosimeters with methods to characterise and improve their devices. It will also be a reference to look at when building devices that look at other wavelengths.

The improved quality of studies regarding NIF effects of light will also benefit lighting experts, interior architects and similar professions, who will be able to improve their lighting designs to be more in line with trustful, state of the art research. The best quality light loggers could also be used by these experts, empowering them with new tools to easily monitor the lighting changes throughout a day or with changes in furniture, paint and other interior arrangements.

Outcomes for the metrology and scientific communities

The project will deliver recommendations and guidelines for the characterisation and use of wearable light loggers. This will improve the quality and reliability of the data generated by clinical studies, as well as the robustness of their results and conclusions. They will be able to choose devices which best fit their application as well as get more reliable results from these devices. As the project includes efforts to harmonize data format and analysis methods, as well as a research-oriented software ecosystem, it will also enhance reproducibility and facilitate cross comparisons between studies.

While work on solar UV radiation dosimeters will not be as extensive in this project, it will still benefit scientists by providing them with more reliable tools to measure UV doses in the field and assess its impacts on human health.

The project will also improve the quality of the wearable light loggers that will be designed for and used by the general public. A huge amount of data may become available for scientists this way (open data or under contract), and making this data reliable is again key for the resulting studies.

The metrology benefits are more straightforward, as the project will lay the groundwork for normalization bodies regarding wearable light loggers, with the methods not limited to wearable light loggers for NIF effects of light but also including UV radiation dosimeters.

Outcomes for relevant standards

The results of this project will be used to complement CIE S 026, which defined metrics for NIF effects of light, with recommendations on how to properly measure these metrics, such as device requirements, characterisation and practical use.

The project will also contribute to the implementation of standards in daylighting EN 17037 and workplace lighting in EN12464-1 by improving the reliability of the tools available for building experts to assess their compliance to those standards.

Currently, there is no European standard on solar UV exposure for outdoor workers. This project should contribute to the development of new standards on solar UV exposure, in particular by providing insights for potential Personal Prevention Equipment (PPE) against solar UV radiation.

Longer-term economic, social and environmental impacts

Currently, very little is known about how light exposure affects human health and wellbeing. This project will lead to two different long-term impacts related to the different end users, which in this project designate the users of the data (e.g. scientist, clinical staff or even the wearer themselves).

The introduction of metrology for wearable light loggers will ensure clinical studies have reliable data to better understand the role of lighting in human health and wellbeing. Chronobiologists and sleep specialists in particular will more directly benefit from having reliable tools to study and understand the effect of light exposure on human physiology. The confidence in scientific results mentioned above will hasten the emergence of efficient guidelines and standards for the lighting field as well as health experts. This in turn will improve the livelihood, wellbeing and productivity of the European and other communities for the long term. The same health benefits are expected for the extended work to UV radiation dosimeters. The emerging increase in UV exposure as a result of global warming is expected to increase the number of skin cancer case, as warmer and sunnier days means more time spent exposed to UV radiation. In view of this, characterisation methods and quality indices for the performance of solar UV dosimeters with the aim of optimizing protective measures and effective strategies for skin cancer prevention are of great importance.

Connected devices for monitoring various parameters are already in the hand of the general public (Internet of Things or IoT) but it is not always known what the data means exactly, both among the general public and sometimes, the manufacturer. Recommendations and future standards for the characterisation of light dosimeters, as well as recommendations for the formatting and use of the data, will improve the understanding of the health implications of light exposure by manufacturers, and in turn by the end user.

22NRM06 ADMIT

Characterization of AC and DC MV instrument transformers in extended frequency range up to 150 kHz

Summary of the project

<u>Overview</u>

The goal of this project is to address the standardization needs expressed by the international standardization IEC TC 38 to EURAMET through the CEN STAIR EMPIR Platform. This project will develop traceable measurement methods and procedures for the characterization of Instrument Transformers (IT) used to measure disturbances up to 150 kHz in Medium Voltage (MV) grid. The project partners will closely interact with IEC TC 38 to ensure the incorporation of the project outputs for the revision or new written standards. Metrology community, manufacturers of MV systems and academic will also have a strong benefit from the project results.

<u>Need</u>

Society's increasing use of switching devices (inverters, bulky power electronic converters, active filters, etc.), both as loads as well as part of generators especially for renewable energy sources, has driven consequent proliferation of conducted disturbances on grid voltage and current, also at MV level, up to hundreds of kilohertz, due to the harmonics of the components around the switching frequency. Consequently, standardized methodologies, procedures and infrastructures for calibration, characterization and testing ITs beyond frequencies covered by presently available infrastructures are needed. Characterization of ITs used for MV HFM in AC and DC MV grids is one of the three priority topics submitted by CEN/CENELEC for this call.

Suitable parameters to define the accuracy and the performance requirements of ITs up to 150 kHz are not available. There is an urgent need to standardize procedures to test ITs up to this range of frequency. Indeed standards, which are currently in-force, include requirements only up to 20 kHz and test procedures only for 50/60 Hz. New calibration methods for AC and DC ITs, with high accuracy class, at frequencies up to 150 kHz are needed. High voltage and high current metrological infrastructures, capable to ensure the traceability for this extended range of frequency are missing.

The development of setups to generate realistic test voltages (AC or DC up to 36 kV) and test currents (AC or DC up to 2 kA) will promote new calibration services for electrical industry and to deposit new calibration services for NMIs. Indeed, the achievements of NMIs during previous or ongoing European projects and the present available capabilities and facilities, among all actors combined, do not cover this topic since frequencies higher than 20 kHz and up to 150 kHz represents new issues for the AC electrical networks.

Objectives

The overall objective of this project is to carry out the metrology research necessary to support standardization for the calibration and the characterization of instrument transformers in an extended frequency range up to 150 kHz. The specific objectives are:

1. **To investigate metrological methods and procedures to evaluate the accuracy of instrument transformers** designed to be connected to medium voltage grids. In addition, to identify their performance requirements and to establish suitable parameters for the definition of their accuracies.
2. **To develop the traceable calibration of instrument transformers up to 150 kHz** by developing new reference measuring systems.
3. **To develop the facilities of NMIs and laboratories** to generate AC/DC voltage up to **36 kV** and AC /DC current up to **2 kA** with superimposed spectral content up to **150 kHz**. The aim is to allow NMIs and laboratories, as early and as widely as possible, to **propose new calibration services**.
4. **To contribute to the revision or new written standards** by providing the data, methods, guidelines, and recommendations, which are necessary for the accuracy verification of ITs up to 150 kHz, to technical committees such as **IEC TC 38** "Instrument Transformers".

Progress beyond the state of the art and results

Contribution to the revision or new written standards

Currently there is no specific standard that could serve as a reference guide for the accuracy verification of AC and DC ITs for MV grids, at least from 20 kHz up to 150 kHz. Moreover, the standards issued by the International Electrotechnical Commission (IEC) TC 38 Instrument Transformers do not deal with possible reference instrumentation or uncertainty evaluation. The IEC 61869, part 6, is focused on AC and DC Low Power ITs (LPIT) for MV and High Voltage (HV) grids and gives accuracy requirements at power frequency, and at frequencies up to 20 kHz. However, it does not give indications on measurement methods and test procedures above power frequency. Moreover, the standardization of measurement-asset features, of ITs in particular, is a key requirement for common policies of mitigation of disturbances and efficient control of power networks at a European level. The project will support the standardization by developing methodologies and procedures to characterize and evaluate the accuracy of instrument transformers. It will extend beyond the state of the art by identifying performance requirements and by establishing suitable parameters for the definition of their accuracies at frequencies up to 150 kHz.

Reference measuring systems, traceable test procedures and validated reference setups

Voltage and current traceability for AC and DC ITs in the extended range of frequency up to 150 kHz do not exist yet. High Voltage and high current measuring instruments with large bandwidth exist but they have never been validated for such applications which require high accuracy to assess ITs of 0.1 % class or better. They are usually adopted to measure only the fundamental component (AC 50/60 Hz or DC) or to acquire impulses such as lightning or switching impulses. A statement of uncertainty limits, for accurate IT characterization, must be done for available measuring instruments at NMIs or on the market. Other high voltage and high current accurate measuring systems need to be developed by considering the specificities of grid disturbances and test circuits.

Generation techniques of realistic AC and DC voltage and current waveforms

The facilities of NMIs and testing laboratories to generate AC/DC current and AC/DC voltage with superimposed components up to 150 kHz are very limited. Typically, the best NMI facilities of AC/DC voltage generation for the level of 36 kV do not go beyond 10 kHz. For current generation, the best NMI facilities at 2 kA do not go beyond 9 kHz. We also notice the same on the market, where manufacturers of high voltage and high current sources propose systems less performing than those of NMIs. Validated and stable generators remain an important tool, which are considered as an essential part in the test circuit. The project will make a major step beyond the state of the art by developing novel techniques and generation infrastructures allowing NMIs to offer, as early as possible, new calibration services.

Enhance the achievements of previous and ongoing European projects

Several previous or ongoing projects dealt or are dealing with measurements of high voltage or high current with superimposed components up to several kilohertz (e.g., ENG04 Smart grid, ENG52 Smart Grid II, 16ENG04 MyrailS, 17IND06 Future Grid II, 18NRM05 SupraEMI, 19NRM05 IT4PQ, 20NRM03 DC grids). These EMPIR research projects will benefit from the proposed topic that will extend their outputs and enhance their achievements. In fact, to the best of the partners' knowledge, no NMI has the capability for simultaneous generation of power frequency (DC or AC 50/60 Hz) currents at 2 kA, or voltages at 36 kV, with high superimposed frequency components up to 150 kHz; in the literature either this problem has not yet been solved. The work in this project will certainly enhance the achievements of previous and ongoing European research projects in the field of MV grids measurements. New facilities and capabilities could be duplicated and implemented by all NMIs and testing laboratories. The objective is to grant every actor the possibility to calibrate AC and DC ITs, of 0.1 % class, up to 150 kHz and for voltage up to 36 kV and current up to 2 kA.

Outcomes and Impact

Outcomes for industrial and other user communities

The project has currently 14 stakeholders ranging from Instrument Transformer manufacturers, TSOs and DSOs, measuring instruments manufacturers, HV/MV equipment manufacturers, standard development organisations. These organisations will benefit from the project outputs, which will boost the development of strong return advantage for both AC and DC MV grids. The project will improve high frequency measurements in distribution systems which are highly important for regulators and utilities in all European countries. It will participate to provide a stable, secure and efficient energy supply even if connecting multiple energy sources. The realisation of the necessary metrological infrastructures will represent a benefit for all the actors involved in MV grids.

The European power industry has a leading position in producing and testing ITs with significant experience in both AC and DC types and voltage and current IT types. The traceability developed in this project will allow for a full assessment, reducing then unnecessary safety margin and thereby increasing the operability of manufactured systems. For example, the industry will benefit from traceability methods, characterization methods, testing set-up and generating circuits to assess as early as possible their systems.

Manufacturers of ITs are under pressure, as new development are expected to produce accurate apparatus capable to operate in MV grids at high frequencies. They will benefit directly from the metrological work of the project, for example by exploiting the procedures for characterization, the possible development of accurate standards, the uncertainty calculation and the list of the identified influencing quantities.

Outcomes for the metrology and scientific communities

Metrology and scientific communities will benefit from new measurements capabilities in an area where many achievements have been done, in particular from previous European research projects, but the limits were never pushed so far.

The scientific and technical objectives addressed in this project will be a major step in the metrology community by providing several important additions and extensions to NMI/DI Calibration and Measurement Capabilities (CMCs) related to the calibration of DC voltage, AC voltage, DC current, AC current and up to 150 kHz.

NMIs will improve their knowledge and will be able to perform new traceable measurements on ITs and to offer new calibration services. This proposed research topic improves the metrology for high voltage and other related quantities through new techniques for applying precision measurements and develops competences in a multidisciplinary approach. The proposed objectives will allow a larger number of test laboratories to benefit from research projects in the field of high-voltage / instrument transformer metrology. This will lead to a significant improvement in the overall European metrology capacity

Outcomes for relevant standards

The whole project has been structured in order to answer to specific objectives expressed directly to EURAMET by IEC TC38, Instrument Transformers through the CEN STAIR EMPIR Platform. The project will have then a major impact on TC38 and working groups with new characterization methods.

The project will generate results that will answer to TC38 specific objectives but also they will be very valuable to other standardisation committee such as TC8-SC8A, Grid Integration of Renewable Energy Generation, TC13, Electrical energy measurement and control, TC17, High-voltage switchgear and controlgear, TC22-SC22F, Power electronics for electrical transmission and distribution system", TC77, Electromagnetic compatibility, TC85, Measuring equipment for electrical and electromagnetic quantities, TC95, Measuring relays and protection equipment and TC 51, Magnetic components, ferrite and magnetic powder materials.

Longer-term economic, social and environmental impacts

The project aims to improve grid stability and operability, to ensure a sustainable and affordable energy supply for European society. Indeed, high frequency measurements are important due to the proliferation of new generation switching power converters which are connected directly to AC and DC MV grids. Their emissions may interfere with vital grid operations. The primary aim of the project is to ensure that all the ITs connected to MV grids could operate in stable and safe way with the presence of high frequency components. With the research and outputs from this project, high quality testing facilities will give strong support for the European manufacturers to remain leaders in grid innovation. This has a direct impact on the competitiveness of European power industry on the international market.

Many more instrument transformers are needed to reliably meet the increasing demand for renewable electricity around Europe and the world. The installed global stock is expected to increase by a compounded annual growth rate of 3.7 % more than doubling the number of instrument transformers until 2040. ITs performance has a major impact on electricity use to give the non-stop operation of the equipment over its 25-years service life. Better performance translates into reduced load on the electricity system, lower electricity bills and greater reliability.

Using more efficient and accurate ITs can lead to nearly 5 % of global electricity consumption. By 2040, annual electricity savings of over than 750 TWh are possible saving more than 450 million tonnes of greenhouse gas emissions. With the techniques developed in this project, it would be possible to assess ITs to operate efficiently and accurately under high-frequency grid disturbance. These techniques will be available for everybody (utilities, industries, users, TCs) to take the appropriate actions to prevent undesirable events and to calculate the energy consumption precisely and saving then hundreds of terawatthour.

22NRM07 GuideRadPROS

Harmonisation, update and implementation of standards related to radiation protection dosimeters for photon radiation

Summary of the project

Overview

The recent update of the basic standard for photon reference radiation fields in radiation protection, ISO 4037, in conjunction with the new radiation protection quantities introduced in ICRU Report 95, presented significant challenges to calibration laboratories and industry. Serious deficiencies that need to be solved became apparent during the initial implementation. This project will provide protocols and guidance to metrology institutes, standardization bodies and regulators for consistent and harmonized approach to radiation protection measurements and calibrations following ISO 4037. Proposals to update ISO 4037 and future needs for type testing and implementation of new quantities will be provided.

Need

Photon dosimeters are almost universally used in all radiation practices, from personal and ambient monitoring to environmental monitoring, emergency response and protection of workers and the public to protect from harmful effects of ionising radiation. The requirement for dose monitoring is set in Council Directive 2013/59/Euratom.

Most commonly these dosimeters measure ambient dose equivalent, directional dose equivalent, or personal dose equivalent. The dosimeters are calibrated according to ISO 4037 standard, which describes the requirements and procedures to establish photon reference fields. In 2019, all 4 parts of ISO 4037 were updated, with many changes. The new requirements result in high costs and manpower to establish the reference fields. Therefore, to avoid excessive costs and workload, especially smaller and emerging metrology institutes and calibration laboratories need guidance for implementation of the standard, also to avoid the risk that they cannot implement the standard at all. In addition, there are insufficient data in new ISO 4037 standards regarding ^{241}Am reference fields, high voltage measurements and the uncertainty estimates. Furthermore, harmonized procedures for traceable spectrometry are absent and improved quality assurance is expected by increasing confidence on direct determination of dose conversion coefficients.

Currently, there are many IEC standards for photon dosimeters, and there are situations where two standards lead to conflicting requirements for the same type of dosimeter. There are also standardization gaps, due to recent developments in measurement technology. Moreover, gaps related to upcoming and new technologies are foreseen. The standards must be harmonized, and future standardization needs must be analysed.

Finally, ICRU report 95 (2020) proposed new operational quantities to replace the current quantities. This will require a complete revision of the type test standards and characterization study of existing dosimeters to see whether, depending on the dosimeter technology, software and/or design modifications are necessary.

Objectives

The goal is to support standardisation in photon-based radiation protection dosimetry, related to ISO 4037 standard series, IEC standards and the upcoming changes due to new operational quantities of ICRU Report 95.

1. To develop harmonized approach to X-ray spectrometry in concordance with ISO 4037, evaluate the discrepancies between measured and calculated HVL of X-ray spectra and to produce data to update requirements for reference X-ray fields. To produce data for ^{241}Am reference fields to be included in this standard and evaluate methods to determine X-ray tube HV (WP1).
2. To develop cost effective procedures and guidance for the calibration of dosemeters and determination their response as a function of photon energy to enable smaller metrology institutes and other calibration laboratories to implement ISO 4037. To provide training to emerging metrology institutes and produce e-learning materials (WP2).
3. To produce guidance on validated procedures for harmonized type testing based on IEC standards with valid metrological solutions for situations where requirements in existing standards deviate and standardisation gaps exist (WP3).
4. To assess future standardization needs related to new and upcoming technologies and to produce a guidance document for the implementation of the new operational quantities of ICRU 95 into standards and regulations based on the results of Objectives 1, 2 and 3, and to disseminate this to policymakers, regulators, metrology networks, standardisation bodies and laboratories (WP4).
5. To collaborate with ISO and IEC and the users of their dosimetry standards (including the EMN on radiation protection and IAEA) to ensure that project outputs align with their needs. Produce guidance on the implementation of new operational quantities of ICRU 95 into standards and regulations and recommendations for incorporation of this information into future standards. To disseminate project outcomes for inclusion into ISO 4037 (WP5).

Progress beyond the state of the art and results

Harmonized approach to X-ray spectrometry and implementation of ISO 4037

Support will be given to calibration facilities to build up their spectrometry methods by guidance documents on characterising spectrometers and unfolding the spectra to implement ISO 4037. Data will be produced to include ^{241}Am in the future version of the standard.

Training on requirements of ISO 4037 and calibration in reference fields

For the first time, hand-on training and e-learning material will be produced to support calibration laboratories to implement ISO 4037 and to apply changes due to new quantities ICRU 95 in calibration fields.

Validated procedures for harmonized type testing standards

The need for harmonization of existing standards and the need to close standardization gaps will be addressed. An analysis of the standards will be performed and an overview of inconsistencies and a recommendation for harmonization will be provided to IEC. A document will be prepared to help manufacturers identify relevant legal requirements in different countries.

Assess future standardization needs and produce guidance to implement new quantities into the standards

An overview of the state-of-the-art and upcoming technologies in dosimetry will be obtained. The limitations of these technologies with respect to the requirements from the standard will be evaluated and the potential needs for new or updated standards considering the new technologies will be identified. Special attention will also go to the practical implementation of computational dosimetry and spectrodosimeters. Finally, the impact of ICRU 95 to ISO 4037 and IEC standards will be evaluated and reported.

Outcomes and Impact

Outcomes for industrial and other user communities

The revision of the ISO 4037 standards and the adoption of the ICRU 95 operational quantities have an impact on radiation beam quality and the value of the conversion coefficients from air kerma to dose equivalents, respectively. The new operational quantities require changes in the characteristics of the measuring equipment. These changes will have consequences for all industrial stakeholders, including calibration laboratories, equipment manufacturers, dosimetry services and users of ionizing radiation in industry, research and medical applications where radiation protection measurements are needed.

The changes made to ISO standards and especially the adoption of the spectrometric characterization of radiation beams impact the traceability of calibration beams to national references and the accuracy of calibrations. The latter can be drastically improved allowing a more precise and comparable characterization of the measuring devices. Together with harmonized IEC standards this leads to the revision of the type tests carried out before the devices are put on the market.

This project will assess the consequences of the adoption of operational quantities, proposed in the ICRU 95 report, on radiation protection measurements and inform the manufacturers who will then be able to anticipate the changes due to the adoption of these quantities, by planning the recalibration or replacement or adaptation of existing measuring devices. Then, the possible transition from the present to the new operational quantities may be carried out in the most harmonious way possible.

These modifications could require adaptations to the devices, either in the data processing algorithms, or in the physical design of the detectors, or both, to remain in compliance with the type test acceptance criteria. Adaptation of these criteria may be necessary in coordination with the improved measurement accuracy discussed above.

Outcomes for the metrology and scientific communities

The implementation and harmonization of the spectrometry measurements will ensure reliable validation and calculation of laboratory-specific conversion coefficients. The guidance developed within this project will lead to comparable procedures and therefore increase the confidence in metrology and testing. Spectrometry can provide new research data, which is currently available only to a few institutes, and thus help proliferation of scientific knowledge and research. With spectrometric capabilities, institutes can develop new radiation fields for upcoming applications, needed to metrologically support changes in technology and regulation.

The evaluation of the impact of the new ICRU 95 quantities on the photon reference field standards will allow for an informed realization of calibration fields in the metrology institutes and calibration laboratories.

Outcomes for relevant standards

The project will contribute to the implementation and future updates of ISO 4037 standards series and IEC standards that set requirements for radiation protection dosemeters by providing relevant data, guidance documents and validated limits. Moreover, the implementation of the newly proposed operational quantities of ICRU 95 will have an impact on some of the limits given by ISO 4037-1 for matched and characterized reference field and on the radiation doses recorded by the dosemeters.

This will affect the personal doses that are monitored nowadays in compliance with Council Directive 2013/59/Euratom and will have an effect on the dose limits and the future update of this Basic Safety Standard.

Longer-term economic, social and environmental impacts

Stronger confidence in radiation protection dosimetry, both via the promotion of the implementation of the ISO 4037 standard series, and via the assessment of the impact of the new operational quantities defined in ICRU 95 on every day's measurements in radiation protection, has the clear potential of making radiation protection dosimetry practises even better than at present day, allowing also smaller NMI to provided reference field following reliably the standard. It provides an advantage to European-based dosimeter producers over the global market.

Through the objectives of this project, procedures will be brought to maturity so that the implementation of the ISO 4037:2019 both at NMI/DIs and through European national networks of accredited dosimetry calibration laboratories will be facilitated and, therefore, requests of instrument calibrations could be satisfied within Europe.

With the adoption of the ISO 4037:2019 standard series throughout Europe, and with the related CMCs and services that can derive from them, the European citizen would find him/herself in a context of measurement confidence and reliability, the basis on which citizen security can hinge on.

More reliable tested instrumentation in radiation protection dosimetry, possibly supported by the well-informed technical adoption of the new operational quantities defined in ICRU 95 report, could also lead to a stronger European industry and an increased wealth that this can bring.

22RPT01 TracInd BVK-H

Traceability for indentation measurements in Brinell-Vickers-Knoop hardness

Summary of the project

<u>Overview</u>

Hardness is an important material property and it is determined by measuring indentation size realized on the material surface in Brinell, Vickers and Knoop scales. The proposed project aims at investigating the indentation measurement phenomena and providing a better defined, more consistent, unified and reliable measurement and traceability methodology to overcome the inconsistency between the NMIs and lower levels of indentation (hardness) measurements as well as inter-NMIs problem. The project outcomes will be used in the next generation hardness definition, instrumentation and standardization to improve accuracy of testing material in all engineering fields; aerospace, automotive, health, industry and research-development studies.

<u>Need</u>

Material is used in all construction, design and engineering areas. Better design and production requires deep knowledge about the material used. This can be done by making tests on different types of material. By having known critical mechanical properties of material, hazardous and dangerous accidents can be prevented, low cost production can be achieved, healthy and more comfortable products can be produced. This makes it really important to establish accurate, reliable and consistent reference standards at NMIs and a link to the lowest level test in a workshop through continuous traceability chain. Brinell, Vickers and Knoop hardness methods are three of the most important ones used for testing metallic materials and determination of hardness in these scales is made by measurement of the size of an indentation residual on the surface of the material. There are many types of indentation measurement systems and methodologies. The indentation size measurement is completely dependent on the image magnification and processing instrument, operator and software if any, and there is a significant inconsistency between the NMIs, NMI level systems - testing laboratory ones and between the testing laboratories due to lack of well-defined methodology and specifications of the indentation measured and used instruments, i.e. optical microscopes with different Numerical Apertures (NAs) [11], [12], [13] and software where applicable give different measurement results. This was proved in the CIPM Brinell Key Comparison, CCM.H-K2, in 2005 [12] at NMIs level. In the testing laboratory level the situation is much more obvious and the indentation measurement traceability propagation of the reference value to the testing laboratories is not achieved due to the variety of simple devices used for testing without controlling all parameters. In this project it is aimed to overcome this critical problem and constitute consistent, unified, reliable and traceable hardness (here indentation) measurement from the NMI level to testing laboratories.

Objectives

The overall objective of this project is to constitute better defined indentation measurement and traceability methodology to overcome the longstanding inconsistent measurement results between Brinell, Vickers and Knoop hardness measuring instruments in Europe as well as the other regions in the world, starting from the NMI level to the calibration and testing laboratories with thousands instruments. The specific objectives are as follows.

1. To develop a methodology for each of Brinell, Vickers and Knoop (BVK) hardness indentation measurements providing a better defined indentations and their measurement methodology according to ISO hardness standards [1], [2], [3], [4], [5], [6], [7], [8], [9] with more clarification to achieve unification in Europe as well as other regions.
2. To develop long-term stable reference indentations (artefacts) for all possible size and type of indents for assurance of traceability propagation from the NMI level to calibration and testing laboratories and assurance of compliance in inter-NMIs level in BVK hardness scales.
3. To develop a methodology to unify propagation of traceable and consistent indentation measurements from the NMI level to the user one. To find a correlation between the NMIs and testing laboratories' type of machines and constitute a methodology for propagation of traceability for production of consistent hardness instruments to serve to Europe industry.
4. To constitute a list recommendations related to design of hardness instruments (for indentation measuring parts) and present to the hardness instruments producers to provide consistent indentation measurement in the coming generation hardness standardizing / calibration / testing machines.
5. To develop an algorithm with a special software to be used for automatic indentation measurements and analyse the specification of indentations that can be measured automatically to increase automatization in measurement and decrease the operator effect in measurement results in European countries and in turn as well as others.

Progress beyond the state of the art and results

Development of methodology for Brinell-Vickers-Knoop indentation measurement:

Indentation measurement is generally realized with optical measurement devices such as optical microscope and two perpendicular diameters for Brinell, two diagonal length of Vickers and one diagonal length of Knoop indentation are measured. After an inconsistent result was found in indentation measurement in the CIPM Brinell Key Comparison, CCM.H-K2, in 2005 [12] at NMIs level the reason was investigated and it was found that a significant effect is caused by the lenses with different numerical apertures (NAs). Then now it is advised to use NAs ≥0.4 and the measurements are continued with providing traceability via a certified stage micrometer (line scale) without a definition for the border of indentations in all three scales (BVK).

This project will provide first a definition to the border of indentation for a circular shaped indent in Brinell scales for different size and shapes (sink-in vs pile-up), how to define the corners of a square shaped indent in Vickers and an equilateral indent in Knoop scales for different shapes (hard and soft). Then, for recognizing the borders and corners the relevant specification will be investigated and determined. At the end of successful implementation of this research project we will be aware of what we are measuring and where we are looking for to measure.

Development Brinell-Vickers-Knoop reference indentations:

The traceability in indentation measurement is constituted by calibration of the IMSs via a certified stage micrometer and a reference indentation on the hardness reference blocks, but these indentations are certified only by the NMI or calibration laboratory certifying the hardness block with their own IMS. The traceability in 2D (via stage micrometer) is easy to manage because the border is more obvious and the imaging system and operator (as well as the software, if any) effect is much less. But in the real indentation measurement the system performances change and the imaging instruments changes sharply the indentation measurement results.

This project will provide us a set of long-term stable reference indentations for all scales and all possible hardness levels that are creating different indentations developed and agreed on first by the participant NMIs. Then such set of indentations, as a kind of transfer standard, will be used for assurance of measurements according to the aforementioned methodology in the NMIs and to propagate the traceability from the NMI level to the user level. They will be as separate artefacts.

Development of traceability chain from NMI to user level:

During the production of hardness testing machines unfortunately there is no such a traceability or correlation between the highest measurement systems and the simpler ones used in industry. Just a traceability requirement by the relevant ISO hardness standards (as well as ASTM) and in many times these systems gives a very significant deviations due to lack of definition and traceability.

This work will provide us a methodology to unify propagation of traceable and consistent indentation measurements from the NMI level systems to calibration and testing ones. The majority of testing and calibration machines producers will be recommended to design their systems such that comply with the higher level systems. A list of recommendations will be constituted and given to the producers for consistent indentation measurement systems for the coming generation hardness standardizing / calibration / testing machines. A document will be constituted to be recommended to the testing machine producers for future productions.

Automatization of indentation measurements:

Indentation measurements used for measurement of indentation at NMIs level are mainly manual ones beside semi-automatic ones where automatization enables us to measure seize of indents in one direction of the Brinell, Vickers and Knoop indents and for the other direction you are supposed to turn the indentation by 90º angle to make the second diameter or diagonal length measurement. This is done only for one indentation and recently there are few trials to start of measurement of more than one indentation by specifying the location on indents manually by the operator after their realization. In the manual measurement systems the border of indentations is decided by the operator and there might be significant inconsistency between the operators' measurements.

This project will provide us the possibility to revise the indentation measurement system present at TUBITAK where its software and mechanical components will be improved. The system is motorized in four dimensions; X, Y, Z, and R (rotation). In the new state, after the relevant revisions, first, locations of indents will be selected through the software and marked by the indentation measurement system (IMS) automatically, then the indents will be realized by the machines used for realization of indentation and then, again the block will be placed in the IMS in its first position where the indentation locations were marked and indentation measurements will be realized automatically. This will be done for indentations that give us the possibility to realize edge detection with image processing (all types of indentations may not be suitable for such application). The indentations will be analysed and the indentations that can be measured automatically will be determined. There will be automatic calibration of the systems itself in X and Y_directions as well.

Outcomes and Impact

Outcomes for industrial and other user communities:

This project aims to provide reliable hardness test at the industry in all sectors wherever hardness testing is used by providing a better defined hardness (indentation) measurement methodology and by providing sets of reference indentations agreed upon by the NMIs to provide traceability in BVK hardness scales. More importantly a methodology for traceability from the NMI level to the end user will be investigated and a list of recommendations for the hardness instrument producers will be created. It means there will be a new generation instrumentation for BVK hardness measurement with more consistency between the higher level machines (the references constituting the source of traceability in hardness as measurement variable) and industrial ones at the user level. Briefly speaking, the outcomes of the project have a great impact on hardness instruments producers and in turn have impact on all industrial sectors using hardness testing machines from accuracy, consistency and reliability point of view.

Outcomes for the metrology and scientific communities:

The problem constituting the main core of this project start from the scientific part of this issue; the source of the traceability in hardness measurement variable, that is the definition of indentation and its measurement methodology. The investigation planned in this project is already starting at this stage and the first outcome will be the scientific approach to indentation phenomena, indentation definition, measurement methodology and constitution of a uniform measurement method. Clearer definition of the measurement variable will result in more uniform of measurement possibility. This will bring in more accurate and consistent measurement results that will cause better CMCs (calibration and measurement capability) at the NMIs. The NMIs main mission is the realization of scientific metrology that will affect all national measurement systems of the countries in Europe and other parts of the world.

Outcomes for relevant standards:

Once the scientific approach is completed and the indent and its measurement methodology is constituted, then for propagation of this uniformity of measurement it will be proposed to standardization bodies like ISO (and after ASTM). With this regard, ISO 6506-1, ISO 6506-2, ISO 6506-3, ISO 6507-1, ISO 6507-2, ISO 6507-3, ISO 4545-1, ISO 4545-2, ISO 4545-3 are the standards created by and used in Europe. These standards will be will be proposed for revision in line with the outcomes of this project. Also, for non-European standardization body ASTM, ASTM E92, ASTM E384 and ASTM E10 are the standards to be proposed to be revised to clarify indentation measurements in line with the project outcome.

Longer-term economic, social and environmental impacts:

There are huge scientific, technological and industrial activities in European countries. In all of these areas material testing, more specifically hardness testing, is very widely used material properties measurement method.

In Europe the quality assurance of the Brinell, Vickers and Knoop Hardness tests are provided through ISO Hardness standards [1], [2], [3], [4], [5], [6], [7], [8], [9]. Beside lack of uniformity in hardness measurements, manual measurements causes much time, manpower and money loss in testing and calibration laboratories at high scale of money every year. There are many technological productions in European countries and in these productions there are many parts of the products used. Overuse of material in engineering processes due to lack of knowledge about the materials used in production will be another reason for loos of money every year. Europe is also exporting all these industrial products and high technology systems and the same thing may happen in all over the world in more global respect. We should always keep in mind that there are thousands of hardness testing machines used every day in production lines of factories, research institutes, universities, etc. in Europe and in other parts of the world importing testing machines from European producers. Usage of these machines is increasing due to the quality requirements to increase the quality and usage of the accurate products. But there is something missing, that is, the indentation measurement systems in Brinell, Vickers and Knoop Hardness scales are not consistent even within Europe. This may cause trade problems between European producers and non-European clients which may results in huge economical damage.

Developments in science, technology and industry always affect quality of life, comfort of people and beside their work life their social life is developing. Industrial development always need improvement in scientific and industrial metrology. Any development in measurement science will directly affect social life of people. Mentioning about the heavy industry like nuclear power, aviation, fast transportation, medical, space, surgery, pipelines, etc., a product or part of a system mismatching the requested properties might cause irreversible hazardous phenomena in the homeowner of high technology, Europe. High technology means high risk and requests care much more than the other developing or underdevelopment areas.

At the end of this project a methodology will be developed to constitute uniformity in hardness indentation measurements to be used at NMIs level as well as testing laboratories. The result of this research will provide a better approach to testing machine producers and develop hardness instruments with indentation measurement facility with a better accuracy for the next generation testing machines. There will be a consensus between the NMIs and will support the ISO for standardization in this respect. It will facilitate calibration of hardness reference blocks by better indentation measurements and for at least high quality hardness blocks and it will be possible make automatic indentation measurement of the entire surface. This will prevent European testing machine users from waste of time and manpower. It will save civilization from possible damages due to mismatching products or parts usage. European producers being the biggest producers of hardness blocks and testing machines will benefit from the outcomes of this project for more reliable hardness tester production. It will help more precise and accurate measurements in scientific and research studies in Europe. This benefit is first directly related to European producers, universities, institutions due to its being the homeowner of science, technology and production, and second to the other parts of the world as well due to globalization.

22RPT02 *True*8DIGIT

Towards a true 8-digit digitiser

Summary of the project

Overview

This project addresses the development of a digitiser based on state-of-the-art ADCs, operating from DC to 100 kHz, meeting the demands for linearity, noise, and overall accuracy of high-level measurement applications that cannot be met using currently available digitisers. In this project research on the key techniques and technologies needed to underpin a follow-up full-scale project will be performed. An important aim is to provide research capacity building opportunities for developing NMIs/DIs on the design and characterisation of electronic measuring devices needed for a wide variety of interdisciplinary metrological challenges. This will enable these NMIs to join future full-scale projects.

Need

In 2016, the global analogue-to-digital converters market was valued at $2.3 billion and is projected to double in value by 2027 growing at a CAGR of 6.7 % from 2019 to 2027 [1]. Dual-slope and ΔΣ ADCs share approximately 5 % and 20 % of the market, respectively. While high accuracy ADCs have traditionally found applications in the instrumentation and research arenas, they are rapidly and aggressively entering the medical [2] (MRI, digital radiography, CT, ultrasonography), industrial [3] and consumer [4] (audio) markets.

Analogue to digital conversion is arguably the most widely used measurement technology worldwide, employed in almost all communication, smart (IoT) sensors, measuring devices and instrumentation regardless of the application area, up to redefined SI unit realisations. This is due to ADCs ability to provide the most straightforward conversion of analogue information obtained by sensors and transducers to its digital representation, which can then be further integrated into our increasingly digital world. The applications of digitisers often call for state-of-the-art capabilities across all performance parameters and there exist numerous examples in literature of attempts to optimize the performance of the best commercially available digitizing solutions [5].

This project will extend the state-of-the-art in digitiser performance by using mixed technologies, mixed ADC architectures, powerful post-processing, and metrology class measurements to validate performance during all development steps. This will avoid the design compromises required for a full function digital multimeter on the one hand, and the fabrication challenges of an integrated circuit ADC on the other (such as power or size limitations, components price, chip area etc.). Such a development is a complex undertaking; therefore, this project proposes a two-step approach, (i) a capacity building project and (ii) a following full-scale JRP (in 2025 IEM call) to develop a functional metrology grade digitiser with a performance exceeding the current state-of-the-art.

Objectives

The core objective is to perform research underpinning the development of a state-of-the-are digitiser, whose performance exceeds that of currently available DMMs, digitisers or ADCs. The specific objectives are

1. To **identify possible novel metrology grade ADC architectures** for the DC to 100 kHz frequency band and develop comprehensive digital models covering integrating ADC (IADC), Sigma-Delta (ΔΣ) and possible novel/mixed designs and including first and second order error mechanisms. This includes comparing the limitations of the ADC architectures and identifying approaches to mitigate and/or compensate non-ideal behaviour by means of simulations.
2. To **assess possible designs for custom amplifiers** (composite operational amplifiers) for integrator and front-end digitiser circuitry with zero drift, extremely high gain, low noise and error below 1 ppm, and to develop the metrological tools to evaluate their performance. Additionally, to **identify metrological methods for characterisation of linear components** for their stability,

tracking and nonlinear behaviour down to and below -120 dB THD (resistors, capacitors) and electronic switches for their injection currents and transients' stability.

3. To **design and develop an ultra-quiet and stable low noise power supply**, supplied from the mains but with negligible line interference noise, and applicable for all voltage and current spans needed by the metrology grade ADC architectures identified in objective 1.
4. To **develop a precision (< 50 ps jitter) timing solution for the ADC architectures** identified in objective 1, with a galvanically isolated external trigger, lock-in and internal clock frequency output, and to develop the metrological tools to evaluate its performance.
5. To f**acilitate the take up and long-term operation of the capabilities, technology and measurement infrastructure** developed in the project by the measurement supply chain (NMIs/DIs, calibration and testing laboratories), and end users (e.g., electrical power generators, manufacturers of medical imaging devices, ADC and DMM manufacturers). The approach should be discussed within the consortium and with other EURAMET NMIs/DIs, EURAMET TCs or EMNs, to ensure that a coordinated and optimised approach to the development of traceability in this field is developed for Europe as a whole.

Progress beyond the state of the art and results

Novel metrology grade ADC architectures

For high accuracy sampling measurements, a limited number of high-end digital multimeters and commercial digitisers are currently available in the market. However, their performance limits progress in precision low frequency applications.

This project will deliver key solutions and proofs of concept that will be used in the follow-up project to develop a fully operational digitiser with improved linearity, dynamic range and accuracy. Development of new hybrid topologies with different ADC architectures will be supplemented with a parallel SAR architecture and the use of an ultra-pure sine wave or multi-tone sources to improve digitiser linearity in AC regime.

Characterisation of composite operational amplifiers, linear components and switches

A key component in both IADC and ΣΔ ADC is the operational amplifier (OPA) which performs integration via a feedback capacitor. Single commercial OPAs do not meet the requirements for use as in a state-of-the-art IADC integrator or for zero-drift front-end design.

This project will deliver new topologies for composite operational amplifiers (COPAs) and build prototypes with superior performance to demonstrate that the current performance limitations of integrating and ΣΔ ADCs can be overcome. Measurement techniques will be developed to characterise prototypes of COPAs. A different design of COPA will be delivered for a front-end circuitry with the lowest possible 1/f noise down to mHz and with high linearity and stability to cater for signal frequencies up to 100 kHz.

A precision ADC relies critically on selected linear components and switches that define its performance. However, characterisation of potential imperfections that are known in theory is lacking due to the considerable metrological challenge involved.

This project will deliver measurement techniques to characterise nonlinear behaviour of capacitors and resistors of different construction types and materials to the level required by the demanding objectives in this project. Switches will be tested for correct timing and charge injection repeatability and stability. Test beds will be constructed to isolate unwanted influences. Results will be used to update the models and determine their effect on the modelled ADC performance.

Ultra-quiet, stable and line interference free power supply

Power line interference, once introduced in the instrumentation is practically impossible to eliminate and consequently impacts on precision sampling measurements. Available DC-DC supplies today with multiple isolations between input and output can achieve lower leakage currents than transformer-based power supplies, but are limited in achievable output currents. Hence, the most demanding measurements require the use of batteries as a power source despite the limitation of their restricted operating duration.

This project will develop a novel solution with insignificant line related interferences while allowing continuous operation. Potential malfunction identification and protection will be incorporated to protect sensitive loads.

Precision timing solution for ADC architectures

Accurate timing is essential in IADC and ΔΣ ADC designs, while perfect synchronisation is required for precision sampling measurements. Currently, no IADC or ΔΣ digitisers provide for true synchronisation.

This project will deliver a timing solution including low jitter multiple external triggers, lock-in and synchronisation with 100 MHz clock system frequency and galvanic isolation.

<u>Outcomes and Impact</u>

The outcome of this project targets three pillars: (i) to provide necessary proof-of-concept on key solutions to underpin a follow-up project in 2025 IEM call (WP1 and WP2); (ii) to provide solutions directly applicable to precision instrumentation (WP2, WP3 and WP4); and (iii) to build research capacity in the developing NMIs/DIs that participate thus enabling them to join the following full-scale project and any other related project with their acquired research capabilities.

Outcomes for industrial and other user communities

Industrial end users and stakeholders will directly benefit from project outputs, such as advanced instrumentation with interference-free power supplies, cost effective selection of passive components for sensor/transducers and instrumentation, as well as precision isolated timing solutions for synchronised measurement systems. The project will provide key techniques and develop technologies to improve available state-of-the-art digitiser performance. An improved dynamic range would benefit seismology and geophysical surveying, where seismic sensors already provide a signal with such high dynamic range that even existing high-resolution digitisers present a bottleneck in the acquisition system.

This project will directly liaise with industrial stakeholders via the formation of a stakeholder committee. This group will include representatives from instrument and DAQ manufacturers, test and calibration service providers, chip manufacturers and research institutes, and will help the project's results to directly impact such representatives.

This project will also produce and publish two reports for end-users:

- Report on characterisation of non-linear effects in resistors and capacitors and stability of residual effects in switches.
- Report on characterisation of timing and synchronisation solution

The project's outcomes will be disseminated to instrument and DAQ manufacturers and calibration laboratories by organising at least one international workshop aimed at collaborators and stakeholders, where key developed solutions will be presented, targeted to precision digitising, their wider applicability and impact to precision instrumentation and measurements.

Outcomes for the metrology and scientific communities

The project will improve and extend electrical sampling metrology for signals from DC to frequencies beyond the audio range, leading to innovation in the development and improvement of the precision measuring systems and instrumentation. The project's outcomes will provide the basis for improvements in realisation of new SI units, and applications requiring precise synchronisation and amplitude/phase accuracy at or below the 1 ppm level such as power and energy measurement, smart grid and power quality reference instrumentation calibrations, impedance bridges, AC Josephson, as well as in other measurement fields such as accurate readouts for highly stable temperature sensors. This will have a significant impact on calibration laboratories and their customers.

In the area of digitization and instrumentation, knowledge transfer from experienced NMIs to those less experienced on how to benefit from digitisation and how to design precision measurement systems will be highly beneficial.

The scientific community will benefit from improved readout from sensors, especially from intrinsically low-noise devices like superconducting magnetometers, particle accelerator beam instrumentation, digital integrators for detecting coil-based magnetic measurements and quench detection in superconducting magnets. Such applications are often driven by highly specific requirements that cannot be summarised, but they all call for a best achievable linearity and stability in the final data conversion stage.

Major scientific impact will be provided through the publication of project results in scientific journals and presentations at key conferences. The project will disseminate all key results directly via relevant EURAMET technical committees and further to accredited calibration laboratories and scientific community via conference presentations, scientific publications, web page and appropriate social media outlets.

Outcomes for relevant standards

The project will investigate new test methods required for testing ADC performance beyond current state-of-the-art for linearity and stability. This will impact IEEE standard 1241 and we will communicate directly with IEEE committee TC10 as this is responsible for all IEEE ADC and DAC related standards. Dynamic performance testing will be developed through the use of ultra-pure sine wave and multi-tone sources. This will be relevant for IEC 60748-4-3, which covers dynamic criteria for analogue-to-digital converters. We will liaise with IEC TC47 SC47A as this is the committee responsible for maintenance of this standard. This is also relevant to work being undertaken in IEC TC85 WG22.

Longer-term economic, social and environmental impacts

The technological society in which we live depends, to a large extent, on our ability to measure phenomena in the physical world. To do this we need a sensor which converts the measured quantity into a measurable analogue signal and a digitiser which converts this signal into a number.

The majority of the processing of analogue signals now takes place in the digital domain. The improved digitisers envisaged in this and the associated follow-on project will, in time, filter down to everyday applications such as medical diagnostics, energy conservation, security and internet of things.

Improvements in the precision, speed and accuracy of digitisers over the years have allowed us to measure a wider range of quantities with ever greater sensitivity, with consequent benefits in fields such as manufacturing, medical diagnostics, smart electrical grids, energy conservation and environmental protection. Nonetheless, there is still a wide variety of signals, for example, in the fields of power quality, geophysics, acoustics, whose accurate measurement lies beyond the capability of even the best digitisers that are currently available. Improvements in ADCs, which provide the core element for digitisers, continue to be made. These advances can be exploited to produce metrology-grade digitisers whose performance surpasses those of existing devices. To do this, every functional element of the digitiser, the signal conditioning block, the ADC itself, the power supply and the timing circuitry, must be optimized.

This project supports the long-term transition of EU toward digital transformation. The use of next-generation digitisers is a prerequisite for improved instrumentation and data acquisition systems, which are embedded in manufacturing for process control and quality assurance. Digital instrumentation is becoming standard in the power grid, where this project's outcomes in accuracy and timing will provide for an improved detection and localisation of critical events. New improved instrumentation is needed where the measurement of difficult-to-measure phenomena is necessary to make progress in the field.

22RPT03 MultiFixRad

Improving the realisation of the kelvin by multiple fixed point radiation thermometry

Summary of the project

Overview

The project will aid 6 European national metrology institutes (JV, RISE, DFM, CMI, SMU, and UL) in establishing their own primary reference scales for thermometry, using the method of radiometric interpolation between fixed points with an established thermodynamic temperature. The improved high-temperature measurement standards will respond to industrial needs in the countries and enable participation in development projects for fundamental thermometry at high temperature, and at the highest scientific level.

Need

The emerging institutes in this project (JV, RISE, DFM, CMI, SMU and UL) are all intermediate level NMIs in Europe, but they currently lack a realisation of high temperature primary standards. After the recent redefinition of the kelvin one of the most promising primary reference standards for high temperature is to interpolate between high temperature fixed points whose transition temperature have been established with high accuracy, using a radiation thermometer as the interpolation device. However, the method has not yet been tried on a large scale outside the major NMIs. An important pillar of the metrological community is the ability to compare results across different institutions and countries, but this requires that a certain number of institutes are capable of realising the quantity to be compared. This project aims to endow the emerging NMIs with primary thermometry capabilities, and hence help the European metrology community to improve its robustness, but at the same time avoid a fragmented and uncoordinated capacity building. The consortium will create nascent regional centres of excellence in the field, by coordinating the activity in the Scandinavian and central European regions, respectively.

However, the project also responds to emerging industrial needs. The participant NMIs represent countries with substantial production, processing and manufacturing industry with expressed needs for better high temperature standards. Examples include the metallurgical industry, manufacturing of building materials and H_2 production.

Objectives

- To transfer knowledge to emerging NMIs on the theoretical and experimental aspects of using ITS-90 and high-temperature fixed points for radiation thermometry. The emphasis lies on extrapolation from a single fixed point and the associated characterisation of the interpolating instrument (linearity, spectral responsivity, size-of-source). This incorporates progress accomplished in EMRP project SIB01 InK and EMPIR projects 15SIB05 InK 2 and 18SIB02 Real-K.
- To construct a set of medium- to high-temperature fixed points for radiation thermometry adapted to the technical means of emerging NMIs. This includes assessment of the quality of the cells and experimental determination of the optimal thermal conditions for their implementation.
- To realise the MeP-K through the application of the multi fixed point scheme using a variety of radiation thermometers and temperature ranges in accordance with the needs of emerging NMIs, and to compare several realisations to the ITS-90. The target uncertainty of the realisations is 0.6 K at 1800 K and 1 K at 2300 K.
- To perform an interlaboratory comparison linked to key comparison CCT-K10 to underpin improved calibration and measurement capabilities (CMCs) for participant laboratories in the field of radiation thermometry.
- To facilitate the take up and long-term operation of the capabilities, technology and measurement infrastructure developed in the project by the measurement supply chain (NMIs/DIs, calibration and testing laboratories), standards developing organisations (e.g. CIPM CCT, EURAMET TC-T), and end users (e.g. metal forming, building insulation, and steam reforming). The consortium is well represented in the CCT and TC-T and will consult with the organisations where needed.

Progress beyond the state of the art and results

Knowledge transfer on the theoretical and experimental aspects of using ITS-90 and high-temperature fixed points.

Above the freezing point of Ag the ITS-90 [1] is defined by extrapolating the Planck radiation from a blackbody at either the Ag, Au or Cu fixed points. While many laboratories perform a sort of scale dissemination this way, few have the capabilities to carry out a thorough and careful characterisation of the pyrometer used in the extrapolation. Among other things it is very important to carefully control the linearity, spectral response and size-of-source (SSE) sensitivity. The first objective will leverage LNE and TUBITAKs extensive experience and competence to train personnel from the emerging institutes (JV, CMI, SMU, RISE, DFM and UL) in the relevant aspects of high temperature pyrometry.

Construction of medium and high-temperature fixed point cells.

High temperature fixed points are non-trivial to construct, characterise and use. Some of them are prone to damage, which means that a laboratory must expect to regularly replace or characterise their cells. Again, the competence, experience and skills of LNE and TUBITAK will aid the emerging institutes in acquiring the necessary capacity to maintain such cells in-house in the long run. To try to build this capacity without support is likely to take many years: within the project this process is shortened dramatically.

To realise the new MeP-K through a multi-fixed point scheme.

The current scale realisation at the participants is either based on thermocouple calibration in fixed points from the intermediate range from 660 °C and up, or radiometric extrapolation in line with ITS-90 at relatively high uncertainty. None of the emerging institutes have a primary realisation of temperature according to the revised MeP-K. This objective will equip the laboratories with the experience, skills and knowledge to implement a temperature scale using interpolation between 3 or more high-temperature fixed points. Within the project the consortium will also explore an interpolation scale for intermediate temperatures, which aims to rival thermocouples from 660 °C and up. As part of this activity new measurements will be carried out on the aluminium and silver points, using the extrapolation technique of ITS-90 to scale the radiometric measurements down from the Cu point.

To perform an interlaboratory comparison with linkage to CCT-K10.

The emerging institutes will all benefit from a link to the K10 key comparison, as this will help document their measurement capability at the end of the project and allow them to register updated and improved CMC values in the Key Comparison database.

Outcomes and Impact

Outcomes for industrial and other user communities

There is a growing need and interest in all the emerging countries for improved standards at high temperatures. The new capabilities established in this project will aid regional accredited laboratories and industrial stakeholders. The project will demonstrate early uptake in the industry by performing three dissemination trials in industrial environments.

Outcomes for the metrology and scientific communities

The direct outcome of this project will be to assist six laboratories to set up a primary temperature scale in line with the revised MeP-K that followed the redefinition of the kelvin in 2019 [2]. In particular the partners will implement the interpolation scheme, where precise radiometers are used as interpolation devices that are calibrated using three or more fixed points. This will help disseminate a more precise high temperature scale in Europe.

An important aim with this project is to foster regional collaboration and specialisation within EURAMET. The consortium consists of European NMIs that conveniently cluster in two regions, the Scandinavian and central European regions. This enables the consortium to create centres of excellence to cover regions beyond countries.

The emerging institutes will build expertise, laboratory resources and knowledge to enable participation in future main calls in the EPM programme, in particular Industry, IEM and Fundamental calls. The strategic outlook of CCT for 2020s [9] calls for further development and dissemination of primary thermometry techniques, and this project will enable the emerging institutes to contribute in this work.

Outcomes for relevant standards

The new MeP-K acknowledges the interpolation scheme as a primary thermometry method, but it has not yet been implemented beyond the largest NMIs. The work here will provide valuable experience in a real world example implementation, which will be summarised in a best practice guide written by partners in the project. The experience from this work is expected to inform the CCT on relevant aspects of the new MeP-K.

Longer-term economic, social and environmental impacts

There are a number of industrial processes with high importance for the green transition that involve processing steps at high temperature, which are widely employed in the countries represented in the consortium. Examples range from the manufacturing of solar cells, steam reforming for H_2 production, to manufacturing building insulation materials. High temperature measurement is also important in combustion processes, such as ICE engines, waste incineration or power plants. Improved high temperature standards is the basis for optimising these processes, which in turn may improve product quality, enhance efficiency and reduce the resource footprint of the processes.

22RPT04 RFMicrowave2

Development of RF and microwave metrology capability II

Summary of the project

<u>Overview</u>

This project aims to develop the metrology of fundamental quantities in RF&MW area in NMIs and DIs with emerging capabilities. The project is specifically aimed at institutes which want to decrease the measurement uncertainty and/or extend the CMC capabilities in response to their industrial and economic needs with the aim of involvement in future calls of the EURAMET EPM programme. The objectives of the project will be achieved through small research projects proposed by beneficiary institutes and their local industries with the aim to build a robust and sound approach for measurement of RF&MW quantities and measurement uncertainty evaluation.

<u>Need</u>

Currently, new technologies in the fields of health care, security, traffic management, environmental monitoring, advanced industrial production, quality testing and communications require novel measurement methods and devices. The frequencies, complexity of systems and data rates are still increasing which brings new challenges to the underpinning metrology. The necessary progress in RF to THz metrology on the European level is only achievable through effective cooperation between European NMIs, DIs and their stakeholders. There are several crucial fields, such as measurement of RF power and related quantities (e.g., attenuation), electromagnetic field intensity and antenna parameters measurements which influence the measurement capability and traceability in many other areas. The efficient cooperation of NMIs/DIs will later allow them to cooperate more effectively in future EPM programme calls, where it is currently problematic for emerging NMIs to participate because they lack the necessary expertise in basic RF&MW and EMC metrology. A unified approach to measurement uncertainty evaluation is needed to compare the results of inter-laboratory comparisons and claim uncertainties for commercial calibration services.

The range of complex measurements required in both the time-and-frequency domains will continue to grow to meet the needs of the fast technological progress in many areas. In addition to establishing traceability and reducing the uncertainty of existing quantities, there is a need to address measurement and metrology challenges that are currently not supported by leading and experienced NMIs. In some cases, CMCs do not yet exist in the KCDB for particular quantities because their traceability to basic SI units is very complex. Such challenges are identified by TCEM SC RF&MW, CCEM, CEN/CENELEC and others and include new nano-devices, on-wafer measurements, nonlinear VNA measurements, performance evaluation of alternative EMC test methods, efficient antenna calibration algorithms, high-speed differential measurements and signal integrity, over-the-air measurements in wireless communications and many others.

<u>Objectives</u>

The overall objective of the project is to improve the European measurement and research capability for RF&MW metrology and to strengthen the potential for future cooperation among European NMIs, DIs and their stakeholders.

The specific objectives of the project are:

- To develop traceable targeted RF and MW metrology capability for RF/MW power, attenuation and reflection/return loss in the frequency range up to at least 18 GHz in institutes with less experience. The development will be tailored to the defined industrial and economic needs of participating institutes.
- To develop measurement and calibration capabilities for antenna parameter measurements in the fields covering communications and electromagnetic compatibility (EMC) in the frequency

range up to at least 18 GHz in institutes with less experience. The target parameter will be the antenna factor.

- To develop measurement and calibration capabilities for electromagnetic field intensity measurement in the frequency range up to at least 30 MHz in institutes with less experience. The target parameters will be the electric/magnetic field intensity.
- To develop a unified approach to measurement uncertainty evaluation that will reflect the state-of-the-art methods currently being developed in the framework of other European research projects. The approach will cover full uncertainty evaluation for all developed metrology capabilities from the first three objectives.
- To facilitate the take-up and long-term operation of the capabilities, technology and measurement infrastructure for RF & MW and EMC measurements developed in the project, by the measurement supply chain (NMIs/DIs, calibration and testing laboratories), and end users (e.g., industry, instrument manufacturers, regulators). The approach will be discussed within the consortium and with other EURAMET NMIs/DIs, e.g., via EURAMET TC-EM and MATHMET EMN, to ensure that a coordinated and optimised approach to the development of traceability in this field is developed for Europe as a whole.

Progress beyond the state of the art and results

This proposal follows up on the EMPIR project 15RPT01 RFMicrowave [1] which ran from 2016 to 2019. In this project, less experienced NMIs/DIs gained considerable expertise from top-level institutes by means of seminars, training and interlaboratory comparisons. Particular NMIs were then able to develop better measurement capabilities and offer advanced calibration services to their stakeholders and they also established personal networks which paved the way for future research cooperation. This project will be focused on topics not addressed in the 15RPT01 and will go beyond the state-of-the-art in several areas:

- Advanced RF power measurement techniques - The RF power traceability at the primary level is provided using a calorimeter, which is only available in several developed NMIs. Moreover, it is only available for power sensors with a thermal conversion principle. Other secondary-level techniques are used, such as utilizing a VNA for the measurement of the the calibration factor of power sensors. At the conclusion of the project, emerging NMIs will be able to provide more advanced calibration services for their industrial stakeholders that are mostly interested in secondary-level traceability. Another commonly measured quantity is RF attenuation which requires associated standards and calibration services to ensure traceability. The primary level attenuation measurements require calculable standards, such as a complicated below-cutoff waveguide system limited to MHz frequencies. More affordable techniques, such as use of a calibrated spectrum analyzer, will enable NMIs to offer calibration of RF attenuation at even GHz frequencies.
- Antenna measurements - They are very demanding with respect to knowledge of the underlying principles of electromagnetic field theory, measurement equipment and laboratory facilities. Although calibration of basic quantities such as antenna gain is well established in more experienced NMIs at frequencies up to tens of GHz using conducted tests (i.e., the antenna is generally connected to the analyzer using a cable), currently there are great challenges in the area of 5G communications for measurement of quantities over the air, i.e., without use of cables. Gaining more experience with basic antenna measurements and calibration of antennas for EMC applications in this project will allow participants to offer advanced calibration services for their stakeholders, take part in advanced research projects (e.g., in the EPM programme) and interlaboratory comparisons for granting accreditation and CMC entries in the KCDB database.
- Electromagnetic field measurements - Similar to antenna measurements, electromagnetic field measurements are very demanding and require considerable experience. Low-frequency electric and magnetic field generation and measurements are available in some emerging NMIs up to frequencies of tens of kHz, however, measurements at MHz or even GHz frequencies are currently offered only in more experienced European NMIs. As the outcome of the project, several emerging NMIs will be able to build their own simple realizations of electromagnetic field intensity (parallel plate capacitor, Helmholtz coils, TEM cell) or utilize commercial solutions (fully anechoic chamber). They will be better prepared for their customers' needs and future EPM calls related to integrated European metrology (2025) and health.

Outcomes and Impact

At the end of this project, participating NMIs, will gain the necessary knowledge and skills to provide new or enhanced RF&MW services for their stakeholders. To ensure this, the participation of each partner in the project has been designed according to their and their stakeholders' particular needs. In addition, an individual strategy for each partner for long-term operation of capacity development, including regulatory support, research collaborations, quality schemes and accreditation will also be produced.

Outcomes for industrial and other user communities

The enhanced measurement capabilities in particular NMIs and DIs will help to better engage with local industries and government bodies. In particular, accredited calibration laboratories that get the traceability from NMIs and DIs as the ISO 17025 requirement. National accreditation bodies and national legal metrology institutes may benefit from the broader expertise of the NMIs/DIs staff and involve them as technical assessors or experts during accreditation assessments. EMC test laboratories across Europe will benefit from enhanced capabilities of NMIs and DIs in antenna measurements and electromagnetic field measurements. Public best practice guides on antenna measurements and electromagnetic field measurements will be available for stakeholders via the project website. On-going interaction with stakeholders will be achieved through the project website and the partners will also engage with target end-user communities via the project's workshops, meetings with technical working groups, as well as presenting the project's results at metrology conferences and in scientific publications and trade journals.

Outcomes for the metrology and scientific communities

The project will establish new calibration services in particular NMIs and DIs (e.g., measurement of the calibration factor using a VNA, measurement of high attenuation, calibration services for antennas, measurement of electromagnetic field intensity). Both small institutes that wish to develop new competences and also larger ones aiming to improve/broaden their capabilities will benefit from the project outputs. The project outputs including results of interlaboratory comparisons will be beneficial for extending accreditation scopes of NMIs in the future and for supporting and establishing new CMC entries in the KCDB database. Some project participants have many CMC entries in the KCDB in the field of RF&MW, whereas some participants have no CMC entries yet.

The individual strategies for each partner for the short and long-term developments of their research capability in microwave metrology will be discussed within the consortium and in the meetings with EURAMET TC-EM SC-RF&MW. These strategies will particularly focus on regulatory support, research collaborations with the members of the European research community, quality schemes and accreditation of the NMIs. Project partners will share their strategy and target with their beneficiary organisations, such as accredited calibration and test laboratories, accreditation and conformity assessment bodies, via internal meetings and workshops.

Outcomes for relevant standards

This project does not directly aim to influence existing international standards or contribute to the development of new ones, although efforts will be made to be in contact with standardisation bodies and share the results of the project with them. The project will support active participation in committees such as the EURAMET TC-EM SC-RF&MW or MATHMET EMN. Partners that are members of local standardisation working groups will inform those groups about the progress of the project regularly. Stakeholders from outside the EURAMET community will be contacted (WELMEC, CEN/CENELEC, UNIDO, ISO) to learn about their own needs and how could the project, even indirectly, support them (for example through staff training in view of technical expertise for regulation and conformity assessment).

Longer-term economic, social and environmental impacts

Less experienced European NMIs and DIs will increase their technical expertise so that they will be able to better fulfil requirements of their local stakeholders. Mutual cooperation of project participants will create new personal connections and strengthen existing ones, so that the joint research efforts among European countries will be more efficient. The less experienced institutes will be better prepared for challenging future project calls within the EPM programme together with leading European NMIs, such as the 2025 Health and Integrated European metrology call and the 2026 Fundamental and Industry call.

Automated RF power measurement with measurement uncertainty calculation will significantly speed up the calibration process and thus save money for accredited calibration laboratories and their customers. Better RF&MW capability in NMIs and DIs may, in the long-term, help to harmonise RF&MW metrology and EMC tests which will help European producers and manufacturers of automotive, consumer electronics, digital and communication equipment etc. to compete in the global market. The calibration methods for antennas and field probes will indirectly enable electronic device manufacturers to more readily obtain conformity with related standards; helping to reduce the costs associated with conformity assessment.

More reliable measurements of RF power, antenna parameters and electromagnetic field intensity will be beneficial for energy savings and the protection of citizens against non-ionising radiation from telecommunication base stations, that are very densely distributed in the forthcoming 5G networks, especially in city environments. The 5G base stations work with high power levels and use complicated multi-beam antenna systems to cover large areas with a quality signal. The ability to measure RF power and antenna parameters reliably may allow designing the communication systems with a smaller power margin and thus more energy efficient. The 5G base stations' radiation became source of public concern, also identified as a potential health risk by the ICNIRP. Reliable measurement of electromagnetic field intensity in the vicinity of base stations (e.g., using the code-selective method) will allow potential violations of the recommended radiation levels to be identified.

The project's results will have an indirect social impact through the improved quality and safety of electronic devices. In addition, electromagnetic interference (EMI) radiated from incompatible devices can be considered as environmental pollution and can have environmental consequences that are comparable to vehicle exhaust emissions or wastewater discharge. The environmental consequences can also cause disturbance to machines and, exposure of the population to high electric and magnetic fields.