# Strategy 2026-2035

# Consultative Committee for Electricity and Magnetism (CCEM)

01 08 2026

# Contents

# 1. Executive Summary

An updated strategy was prepared in 2026 by the Consultative Committee for Electricity and Magnetism (CCEM). Its intended audience is mainly members of the CCEM, decision makers at NMIs, industry stakeholders, members of the CIPM and delegates of the CGPM.

The strategic global importance of electrical technologies can hardly be overstated, particularly in the context of the CIPM Strategy 2030+. The CIPM identified monitoring the global environment, health and life science, food and water safety, energy, and advanced manufacturing as the five main areas in which the need for metrology arises from global challenges. Accurate and traceable measurement of electrical quantities plays a crucial role in enabling advancements in these areas, in particular in the energy transition and the growth of digital infrastructures. A general challenge for the CCEM community is the ubiquitous application of electricity and electrical measurements that leads to a large number of electrical quantities, having wide ranges of values and frequencies ranging from DC far into the GHz range. Novel quantum technologies continue to develop at a remarkable pace, and this will continue to have a significant impact on the future of electrical metrology.

The CCEM does not operate R&D projects on its own but provides leadership and vision to NMIs and DIs with a focus on quantum-based measurement standards and new and existing technologies enabling precision metrology. The CCEM wishes to involve all concerned parties in advancing electromagnetic metrology and sharing expertise efficiently. Therefore, the CCEM will continue to organize workshops and selected technical presentations and webinars in key emerging areas. These knowledge-transfer activities are closely linked to the BIPM Capacity Building & Knowledge Transfer (CBKT) Programme.

The CCEM supports the global comparability of measurements by implementing the CIPM MRA through the organization of key comparisons and coordination of RMO key and supplementary comparisons. It maintains an extensive list of service categories for which CMCs can be submitted. Electricity and Magnetism is the second-largest area after Chemistry in terms of the number of CMC entries in the BIPM Key Comparison Database. Therefore, efficient management remains of strategic importance.

The CCEM actively engages with stakeholders with the goal to better understand stakeholder needs and to increase the impact of CCEM activities addressing them. This engagement will be deepened by collaborating more closely with international standardization bodies and by inviting stakeholders to participate in CCEM events.

The CCEM oversees the work programme of the BIPM electricity laboratories. The BIPM comparison services form an integral part of the CCEM comparisons and allow NMIs to uniquely demonstrate their measurement capabilities at the best uncertainty levels. BIPM has developed special expertise in quantum electrical standards that is exploited in on-site key comparisons at NMIs, which in many cases lead to an improvement of the NMI’s standard. The BIPM calibration services provide traceability to a significant number of NMIs without their own primary realizations.

## 2. Scientific, economic, and social challenges

We live in an increasingly electrical age. At the one extreme we have the development of a sophisticated 'smart' grid for the reliable transmission of a growing quantity of electric power at higher voltages and currents; at the other, we have the manipulation of only a few electrons for novel devices to sustain the inexorable demand for information processing. This demands measurement capabilities spanning more than 20 orders of magnitude in electric current.

In addition, there is a vast parameter space associated with electrical measurements. Not only do we have the possibility to measure quantities such as voltage, current and resistance; these can all be DC as well as AC quantities with frequencies up to 100 GHz and beyond. Furthermore, there is a need to characterize the dynamic (i.e., not steady-state) behavior of these quantities to reflect real-world applications. Indeed, the ongoing and relentless development of new and innovative electrical technologies (e.g., electric vehicles, high-frequency communications, renewable energy sources and applications of quantum technologies) is placing greater demands on the accurate measurement of a broader range of electrical quantities.

The strategic global importance of electrical technologies can hardly be overstated, particularly in the context of the CIPM Strategy 2030+. The CIPM identified five areas in which the need for metrology arises from global challenges: monitoring the global environment, health and life science, food and water safety, energy, and advanced manufacturing. Accurate and traceable measurement of electrical quantities plays a crucial role in enabling the advancements of these areas, since virtually all physical quantities will ultimately be converted to electrical signals. This can be illustrated by the following examples:

- **Climate change and health** sciences each rely on traceable electrical measurements across a wide range of applications, from air-quality and pollution sensing, environmental radiation monitoring, to medical devices, biosignal monitoring, ionizing-radiation dosimetry, and low-light detection. In particular, accurate traceability of very small currents is essential for aerosol sensors, radiation detectors, photodetection, and advanced diagnostic instrumentation.
- **The energy transition** drives a growing demand for electrical metrology across generation, transmission, and end use. The shift toward renewable energy sources such as wind and photovoltaics, combined with the expansion of DC technologies including electric vehicles, DC microgrids, and high voltage DC transmission, is creating a large number of new measurement challenges for our electricity grids, including bringing laboratory-grade accuracy on site.
- **Advanced manufacturing** depends on traceable electrical measurements for precision fabrication, process control, robotics, semiconductor production, high-frequency electronics, and nanoscale characterization. Electrical metrology supports accuracy, interoperability, and quality assurance, while enabling reliable calibration of sensors, instruments, and automated systems across increasingly complex manufacturing environments.
- **Artificial intelligence and digital infrastructure** are creating new challenges and opportunities for electrical metrology. The rapid growth of large data centres needed to train and run AI systems requires accurate measurement of power consumption at

scale, while the increasing integration of AI into measurement systems and instrumentation is reshaping how electrical metrology is practiced.

From a more technical perspective, the following examples are important for addressing the challenges through a horizontal approach and are applicable across all areas:

- New and developing communications technologies (e.g. 5G and beyond) are moving to higher frequencies to increase the communication bandwidth. This is becoming ever more important as we live in an increasingly connected world.
- New parts of the spectrum (e.g., THz) are opening up new technologies and applications, particularly in the areas of security screening, product inspection, material characterization, and disease detection. This part of the spectrum is not well served by existing metrological techniques.
- Industry 4.0 and the Internet of Things (IoT) are built on sophisticated electrical technologies, making widespread use of sensor networks that convert physical stimuli to electrical signals. The increasingly complex processing and manipulation of measurement data in these applications require rigorous digitalization methods, including machine-readable representations of SI units and quantities. The CCEM actively supports this through its work on the SI Digital Framework, enabling electrical metrology data to be seamlessly integrated into automated and interconnected systems.
- As devices become smaller and increasingly complex, it is envisaged that many metrological standards can be integrated (‘NMI on a chip’). In addition, because of the diminishing length scale involved, the electrical characterization of nanostructured devices (on-wafer) is a growing challenge.
- Metrology for quantum technologies can contribute across all areas by providing traceable electromagnetic measurements, quantum-enabled sensors, standards, and calibration methods. CCEM can support this through quantum electrical standards, low-current traceability, high-frequency metrology, and robust measurement frameworks. Because quantum computers and quantum sensors depend critically on electromagnetic components, the CCEM community can also support their supply chains and the development of trustworthy quantum hardware components.

However, it is the impact of fundamental quantum phenomena that underpins the extraordinary accuracy achievable in electrical measurements. It was the success of the Josephson effect (for DC voltage) and the quantum Hall effect (for DC resistance) that paved the way for the redefinition of the SI in 2019. Novel quantum technologies continue to develop at a remarkable pace, and this will continue to have a significant impact on the future of electrical metrology. We can expect quantum phenomena to play an increasing role in this area in the following ways:

(i) new and improved applications of these quantum effects to other electromagnetic quantities (such as DC magnetic fields, impedance, power, RF electromagnetic fields),

(ii) new class of materials (e.g., 2D materials such as graphene) and novel devices (e.g., based on topological insulators, twisted 2D materials, and van der Waals moiré materials),

(iii) new quantum techniques to improve the accuracy of single-particle manipulation (e.g., high-accuracy quantum current standard),

(iv) the impact of the so-called second quantum revolution that exploits the manipulation of individual quantum objects and entangled properties of their quantum states (e.g., quantum computing, quantum sensing). This may well lead to new metrological applications and new challenges for electromagnetic measurements.

Whilst the potential and the number of applications of these new possibilities are immense, it should not be forgotten that there is also a critical need to demonstrate traceability rigorously; although nature enables the extraordinary performance of quantum standards, humans and machines can still get it badly wrong, especially as such systems become more complex. This is particularly important as turn-key systems, incorporating intrinsic standards and capable of extremely high accuracy, are employed more widely for industrial use.

The impact of electrical metrology will undoubtedly change, but the direction of this change seems to be towards supporting broader-based, complex, and rigorous technologies. These trends will be well served by the established metrological disciplines that already ensure global consistency in electrical measurements to a very high level of accuracy.

## 3. Vision and mission

### CCEM vision

To be the recognized international focus for electrical metrology, ensuring trustworthy and traceable measurements are embedded at the heart of science, industrial innovation and global economy.

### CCEM mission

To foster equivalence and global interoperability, and promote the harmonization of electromagnetic measurements within the SI, by providing:

- an international forum for the coordination of global comparability of electromagnetic measurements and digital dissemination of results, and
- collective leadership in progressing science and seamless integration of electrical metrology in our society.

## 4. Strategy

The CCEM strategy to implement the CCEM mission and vision has three main elements: promoting global comparability, progressing the science of electrical measurement and improving stakeholder involvement. A crucial part of this strategy is realized via the BIPM laboratory program.

**Promoting global comparability**

The CCEM ensures global comparability of electromagnetic measurements by implementing the CIPM MRA in the field of electricity and magnetism:

- Organizing CCEM key comparisons and coordinating RMO key and supplementary comparisons,
- Managing the Calibration and Measurement Capabilities in electricity and magnetism in a novel and efficient way,
- Supporting and enhancing the impact of BIPM in organizing and running BIPM comparisons, in developing and providing leading edge measurement services, and in adding value on electromagnetic metrology as a unique international organization.

**Progressing electrical measurement science**

CCEM provides leadership and vision to national metrology institutes and designated institutes, and beyond, in support of measurement science and research. The particular focus is on quantum standards and new and existing technologies enabling precision metrology. CCEM raises the awareness of emerging technologies through information exchange and the organization of workshops.

**Improving stakeholder involvement**

The CCEM engages with stakeholders with the goal to better understand their needs and increase the impact of CCEM activities addressing them. This engagement will be deepened by collaborating more closely with international standardization bodies, and by inviting stakeholders to participate in CCEM events via invited talks and strategic discussions.

The CCEM promotes cross-disciplinary collaboration with other Consultative Committees and key industries, accreditation bodies, and academia. It furthermore aims to enhance engagement with developing NMIs via capacity building and training workshops addressing their electromagnetic measurement needs.

**BIPM laboratory support**

The BIPM supports the CCEM activities by providing comparison and calibration services for fundamental electrical quantities ensuring global traceability and comparability under the CIPM MRA. Centralized on-site comparisons using dedicated quantum standards and specialized expertise are seen by the CCEM as the most efficient approach.

For NMIs without quantum standards, the BIPM offers bilateral comparisons and calibrations, whose demand has been steadily increasing. Knowledge transfer is promoted through collaborative comparisons, secondees, and training workshops.

# 5. Activities to support the strategy

## 5.1 Promoting global comparability

The CCEM leads the implementation of the CIPM Mutual Recognition Arrangement (MRA) in the field of Electricity and Magnetism. Electricity and Magnetism is the second-largest area after Chemistry in terms of the number of CMC entries in the BIPM Key Comparison Database. Therefore efficient management is of strategic importance. A particular focus is on streamlining processes and demonstrating best practice in the implementation of the CIPM MRA. The CCEM addresses this through several coordinated mechanisms.

Out of a wide variety of electrical and magnetic quantities, value ranges and parameter ranges, the CCEM selects key quantities that are subject to CCEM key comparisons. The CCEM then organizes key comparisons while investigating new, more efficient, timely, and robust comparison schemes such as star-type or hybrid comparisons in both low-frequency and radio-frequency areas, co-sharing piloting responsibilities, etc. These approaches help address persistent challenges, including the identification of pilot laboratories, timeliness, and the resilience of comparison schemes.

The CCEM coordinates and reviews regional key comparisons and works with RMO Technical Committees to understand emerging changes in comparison needs. It publishes and periodically updates guidelines for the organization of comparisons that, in particular, help the RMOs.

The CCEM has established and maintains a service category list for electricity and magnetism, balancing the need to cover a comprehensive range of electrical and magnetic measurements in the technical and scientific community with manageability and responsiveness to emerging needs. Recent additions to the service category list include DC power and energy (to support electric vehicles). Furthermore, new CMC types for linearity and influence coefficients are now available in all applicable categories. Emerging stakeholder needs together with technical developments are expected to lead to other new service categories in the coming decade.

Efficient management of CMC reviews in electricity and magnetism includes innovative approaches such as sharing inter-RMO reviews of CMCs between RMOs and an efficient sampling strategy. Some CMCs are only reviewed in the inter-RMO review by the WGRMO Chair, based on agreed criteria such as magnitude of change, history of previous reviews, coverage by on-site technical reviews, rotation, and high-level technical judgement. Suggestions on the scope of the review are made by the WGRMO chair—a role that has now been enabled in KCDB2.0. At the same time, each RMO has the right to review any of the submitted CMCs, but in practice almost exclusively chooses to trust fellow reviewers in other RMOs and ultimately approves the entire submission.

The CCEM publishes and periodically updates guidelines on CMC submission that reflect the above practices. The CCEM has introduced the Guidelines on Technical Evidence for the Acceptance of Calibration and Measurement Capabilities in the Context of the CIPM MRA, a document that provides clarification and guidance on the criteria for acceptance of CMCs, thereby reducing ambiguity in CMC reviews. Future discussion will include to what extent a comparison on a certain quantity can be used as technical evidence for a wider range of CMCs.

The CCEM Task Group on Digitalization helps implement the CGPM Resolution "On the global digital transformation and the International System of Units" and decisions taken by the Forum on Metrology and Digitalization (FORUM-MD) in the Electricity and Magnetism area. The CCEM contributes to the work within the FORUM-MD from the perspective of Electricity and Magnetism. The CCEM supports the development of the SI Reference Point and BIPM digital services in the field of Electricity, provides an overview of digitalization issues relevant to the CCEM community and shares good digitalization practices within the CCEM community. The CCEM encourages the development and implementation of a harmonized approach to digital calibration certificates in the CCEM community, working with the BIPM and other Consultative Committees.

Section 5.4 contains information on the specific role and contribution of BIPM in promoting global comparability and supporting the CIPM MRA.

## 5.2 Progressing electrical measurement science

The CCEM plays a guiding and coordinating role in the new advances in electromagnetic metrology that take place at the NMIs and the BIPM. To this end, the CCEM identifies measurement challenges for NMIs through CCEM strategy documents and the work of the CCEM Working Groups.

Electrical measurement science can be broadly divided into activities with a more fundamental focus and those related to emerging technologies and major societal challenges. Key areas of fundamental research are closely linked to the further development and application of quantum standards. Since the revision of the SI in May 2019, electrical SI units can be realized using quantum electrical standards, which are now direct realizations of the SI. The CCEM has enabled the smooth implementation of the revised SI through high-level guidance (*mise en pratique*) and will continue to do so. The CCEM will work proactively with the electrical measurement community to promote the revised SI and support the effective and efficient dissemination of electrical and magnetic quantities. In particular, the CCEM will guide efforts to expand the parameter space accessible by quantum electrical standards, facilitate their use, and make them available to end users beyond the most advanced NMIs. To this end, additional guidance will be produced as necessary, such as the guide on measurements of graphene quantum Hall resistance standards, published in 2026.

Scientific activities in support of emerging technologies, and in relation to societal challenges, are strongly influenced by the broad-ranging aspects of digitalization, including mobile communications, smart electrical grids, on-site measurements, sensor networks, the Internet of Things (IoT), and the metrology required to underpin quantum technologies. Measurement challenges in these applied fields are related to extended electrical parameter ranges (e.g., higher frequencies), miniaturization, material properties, and interconnectedness.

The CCEM wishes to involve all concerned parties in advancing electromagnetic metrology and sharing expertise efficiently. Therefore, the CCEM will continue to organize workshops and selected technical presentations in key emerging areas, involving recognized experts, particularly in connection with CCEM meetings, but also as webinar series. The focus of these events is likely to shift from more general topics to more specific ones, such as waveform metrology, digitalization, sensor network metrology, smart grid metrology, metrology for quantum technologies, electrical and magnetic metrology at the nanoscale.

These knowledge-transfer activities are closely linked to the BIPM Capacity Building & Knowledge Transfer (CBKT) Programme. This programme aims to strengthen effectiveness across the worldwide metrology community, particularly among those Member States and Associates with emerging metrology systems. CCEM experts have already contributed significantly to the BIPM CBKT courses “Leaders of Tomorrow” and “Sound Beginning in the CIPM MRA”. In the coming years, it is envisaged that further CCEM-specific CBKT activities will be initiated in support of developing NMIs, for example on quantum electrical standards, scaling techniques, and practical realizations of secondary electromagnetic units.

## 5.3 Progressing stakeholder involvement

The CCEM and its Working Groups engage with stakeholders through a range of forums, including its biennial meetings at the BIPM, satellite meetings held in conjunction with the CPEM[1] conferences, and ongoing series of public webinars. Our objective is to continually deepen this engagement: to improve understanding of stakeholder needs and to strengthen the impact of CCEM activities in addressing them. The CCEM aims to achieve this through greater engagement with international committees and networks involved in the standardization of electrical measurements, as well as in the development of roadmaps and other documents articulating future trends in this area. We plan to invite representatives of such organizations to participate in our special events, for example by delivering invited talks or by joining strategic discussions, and the increasing use of online formats for technical meetings will make it easier for stakeholders to contribute to CCEM activities.

The CCEM promotes cross-disciplinary collaboration beyond its member institutes, both within the BIPM framework and with external organizations. Within the metrology community, the CCEM engages with other Consultative Committees as the need arises. Examples from the past include CCRI (ionising radiation) on small currents, CCM (mass) on Kibble balances and turn-key quantum standards, and CCQM (chemistry) on Li-ion batteries. The CCEM furthermore maintains active engagement with key manufacturing and supply industries, accreditation organizations, and academia. Beyond the metrology community, the CCEM seeks to engage with organizations developing technology roadmaps and foresight exercises. We also aim to strengthen our engagement with developing NMIs, to promote capacity building for electromagnetic measurements in anticipation of future technological requirements.

## 5.4 Work programme of the BIPM laboratories

To support the CCEM activities in progressing measurement science and promoting global comparability of electrical measurement values, the BIPM provides comparison and calibration services to NMIs of Member States for the most fundamental electrical quantities: voltage, resistance, and capacitance. This range of services underpins the infrastructure of the CIPM MRA by allowing larger NMIs to demonstrate the equivalence of their own primary standards and to support their CMCs and by providing traceability to the SI for many smaller NMIs. The comparison of NMIs’ primary electrical quantum standards on-site with the lowest possible

[1] CPEM: Conference on Precision Electromagnetic Measurements, international biennial conference series on electromagnetic measurements at the highest accuracy level.

uncertainty requires dedicated travelling quantum standards, which are provided by the BIPM. Comparing quantum standards at the highest level of accuracy in varying laboratory environments also requires special expertise, which the BIPM staff has developed as a consequence of its specialization in this task. In many cases, the cooperative work of the BIPM and local staff during an on-site comparison leads to an improvement of the NMI's standard and has an aspect of knowledge transfer.

The CCEM considers providing these comparisons, requiring specialized equipment and special expertise, from one single laboratory to be by far the most efficient and effective way of organizing these comparisons. The BIPM's commitment to the long-term maintenance of these facilities allows these comparisons to be offered to NMIs on an ongoing basis and guarantees Member States the continuous accessibility to traceable realizations of the three most fundamental electrical quantities.

The BIPM comparison programme specifically consists of on-site comparisons of Josephson voltage standards (JVSs) and quantum Hall resistance (QHR) standards and three comparisons using conventional standards for voltage, resistance, and capacitance. Following needs expressed by the CCEM members, the BIPM has extended the comparison of JVSs in 2025 from DC measurements at 1 V and 10 V to AC measurements at 0.75 V and 7 V (RMS) up to 1 kHz. The comparison of QHR standards includes the calibration of a 100 Ω resistor against the QHR and resistance scaling from 100 Ω to 1 Ω and to 10 kΩ. In 2025, for the first time, a graphene QHR standard of a participant was included in the comparison measurements, which confirmed the suitability of this type of standard for most demanding uncertainty requirements. Typically, two on-site comparisons of JVSs and two comparisons of QHR standards are arranged per year.

For NMIs which do not possess quantum standards, the BIPM organizes ongoing bilateral comparisons using Zener voltage standards and conventional resistance and capacitance standards. In cases where NMIs have acquired quantum standards very recently, these comparisons are arranged as a first step before an on-site comparison.

The BIPM also acts as the pilot laboratory for large-scale CCEM comparisons in the fields of its expertise, for the last time in 2018 with a comparison of capacitance standards. The BIPM participates in RMO comparisons to link them to the related BIPM comparisons, most recently in 2025, when the BIPM acted as the central linking laboratory for three subgroups of participants of a EURAMET capacitance comparison.

To make optimal use of its quantum standards and the related measurement equipment, the BIPM also provides calibrations, typically for smaller and developing NMIs not possessing primary standards. The long-term availability of these services allows Member States to rely on them for their traceability needs, also in case problems arise with the quantum standards at their NMI. Due to expanding needs for traceability by Member States, the number of calibrations has been slowly growing in recent years, with on average 80 calibrations per year during 2022-2025, compared to 60 calibrations per year 10 years earlier.

The CCEM considers these BIPM activities an essential contribution to its comparison programme and an important component of the BIPM work plan. The usage of these services is continually evaluated at CCEM meetings as the technology of quantum standards and the needs of NMIs evolve. With the growing number of Member States and the more widespread use of quantum standards at NMIs, a moderate continued increase of requests for calibrations and comparisons can be expected in the coming years.

The CCEM appreciates and encourages the BIPM laboratories to use its specialized equipment and expertise to improve the realization of electrical SI units and to provide new services. Examples are the recent extension of the on-site comparison of DC Josephson voltage standards to AC signals, developing an AC quantum Hall standard for impedance and exploring the use of graphene samples for the quantum Hall effect.

The BIPM electricity laboratories support the BIPM Kibble balance for the realization of the kilogram, which requires a Josephson voltage standard and a quantum Hall resistance standard to reach its target uncertainty.

On several occasions, the electricity laboratories have invited secondees to help building the BIPM capabilities for future services and to provide knowledge transfer. For the work programme 2028-2031 it is planned to organize a joint CCEM-BIPM workshop as a knowledge transfer activity on practical aspects of the operation of electrical quantum standards and related instrumentation.

# 6. Annex

## 6.1 General information (as of 2026)

CC Name: Consultative Committee for Electricity and Magnetism

CCEM President: Prof. dr. ir. Gert Rietveld (VSL, Netherlands)

CCEM Exec. Secretary: Dr. Michael Stock (BIPM)

Date established: 1927

Last meeting: 34th CCEM in 2025, held in hybrid format

Number of Members: 27

Number of Observers: 2

Number of participants at last meeting: 64 from member institutes, 4 from observers

Periodicity between meetings: 2 years

CCEM Working Groups:

Working group on low-frequency quantities (WGLF)
Chair: Dr. Ghislain Granger (NRC, Canada)

Working group on radiofrequency quantities (GT-RF)
Chair: Dr. Jae-Yong Kwon (KRISS, Rep. of Korea)

Working group on RMO coordination (WGRMO)
Chair: Dr. Damir Ilić (FER, Croatia)

CCEM Task Groups:

Task group on graphene QHR standards
Chair: Dr. Albert Rigosi (NIST, USA)

Task group on digitalization
Chair: Dr. Ilya Budovsky (NMIA, Australia)

Task groups only exist for the limited time required to achieve their specific objective.

## 6.2 Key and supplementary comparisons and pilot studies

In the field of low-frequency quantities, the WGLF has identified seven key quantities for which key comparisons are organized: voltage, resistance, capacitance, inductance, power, voltage ratios, and ac/dc difference. Generally, the WGLF plans to repeat each of the existing key comparisons at a periodicity of ten to fifteen years with some minor modifications to the parameters of each comparison.

In the field of radiofrequency quantities, the GT-RF has identified seven key quantities: power, S-parameters, noise, attenuation, voltage, EM field strength, and antenna parameters. The GT-RF does not repeat key comparisons on a regular basis. The reason is that the wide frequency range covered by the GT-RF together with finite resources require prioritization of the efforts. A higher priority has been assigned to performing comparisons in frequency bands that have not yet been covered, rather than repeating earlier comparisons at previously covered frequencies, unless there are good reasons for doing so. This prioritization, along with the large number of separate frequency bands, results in there being little opportunity for repeating key comparisons on a regular basis.

The CCEM key comparison programme is completed by a set of five ongoing BIPM comparisons. Of these, the comparisons of quantum Hall resistance standards and Josephson voltage standards are organized as on-site comparisons at the site of the participating NMI.

In the field of electricity and magnetism, supplementary comparisons are only organized by the RMOs, not by the CCEM (with two exceptions from 2002). From time to time, the CCEM initiates pilot studies in fields which are not yet mature enough for a key comparison.

At present (July 2026), the following CCEM key comparisons are ongoing:

- CCEM-K6.a/K9 AC/DC voltage transfer at 3 V, 10 Hz – 1 MHz and 500 V – 1000 V, 10 Hz – 100 kHz
- CCEM-K6.c AC/DC voltage transfer at 3 V, 500 kHz – 100 MHz
- CCEM-K13 Power harmonics at 53 Hz with three waveforms
- CCEM-K12.2025 AC-DC current, 10 mA, 5A to 100 kHz
- CCEM-K3.X Inductance at 10 mH and 1 kHz
- CCEM-K14 High voltage ratio
- CCEM.RF-K5.d.CL S-parameters in 2.4 mm coaxial line up to 50 GHz
- CCEM.RF-K29.W RF power from 75 GHz to 110 GHz in rectangular waveguide

The following table gives an overview of the numbers of completed and ongoing comparisons in the RMOs (situation in July 2026, without comparisons before 1999, approved for provisional equivalence):

| | key comparisons | | supplementary comparisons | |
|---|---|---|---|---|
| | ongoing | completed | ongoing | completed |
| AFRIMETS | 0 | 0 | 2 | 4 |
| APMP | 2 | 12 | 4 | 17 |
| COOMET | 0 | 7 | 5 | 20 |
| EURAMET | 7 | 22 | 1 | 47 |
| GULFMET | 1 | 1 | 3 | 11 |
| SIM | 0 | 16 | 2 | 16 |
| Total | 10 | 58 | 17 | 115 |

## 6.3 Calibration and measurement capabilities (CMCs)

The field of electricity and magnetism covers a wide range of calibration and measurement services. This includes services in both the low and high-frequency fields, spanning 12 main categories: DC voltage, DC resistance, DC current, impedance, AC voltage, AC current, AC power, high voltage and current, other DC and low frequency measurements, electric and magnetic fields, radiofrequency measurements and measurements on materials. The list is subdivided in 48 subcategories and 191 individual services. The list of services is reviewed at each meeting of the CCEM and is updated as required by developments in the field. A recent example is the addition of DC power and energy, as well as the possibility to declare linearity CMCs for all applicable categories.

In July 2026, 4692 CMCs from 67 countries were recorded in the KCDB. Many of these CMCs correspond to matrices which include measurement capabilities at several values within a range, sometimes depending on an additional measurement parameter. The introduction of matrices has led to a very significant reduction of individual CMC lines (and the corresponding workload to maintain them) without reducing the amount of information.

## 6.4 Summary of work accomplished

**Organization of CCEM meetings, workshops and webinars**

Meetings of the CCEM are organized every two years, the last time in 2025. Meetings of its working groups are held occasionally in the years in-between, in general at the time of a CPEM conference. Since 2023, the BIPM provides the possibility to attend the CCEM and working group meetings online.

The existing CCEM policy is to maintain a strong science focus in its meetings: speakers were invited to make presentations on new developments in electrical metrology. Furthermore, a scientific workshop on “Metrology for future electricity grids” with nine invited speakers from NMIs and academic institutes was held on 5 March 2025.

A series of CCEM webinars was launched in 2022. Six webinars were organized by early 2026, covering themes from quantum metrology, RF metrology, power metrology, and electro-chemical measurements. The webinar presentations are recorded and available from the BIPM YouTube channel “The BIPM”.

**Organization of key comparisons**

Since the start of the CIPM MRA, the CCEM has organized 45 key comparisons and 2 supplementary comparisons. During the same time, the RMOs have organized 68 key comparisons and 132 supplementary comparisons.

As demonstrated by the wide range of CMC categories, the field of electricity and magnetism deals with a large number of quantities, some of which are measured over a wide range and depend on parameters. To keep the efforts in organizing comparisons manageable, the CCEM has selected a set of seven key quantities for the low frequency field and the same number for the radiofrequency field. These are the most fundamental quantities from which most of the others can be derived.

In the field of low frequency, the first round of key comparisons is finished and the second round is progressing. Generally, the plan for the WGLF is to repeat each of the existing key comparisons every ten to fifteen years, sometimes with some minor modifications to the parameters of each comparison. The comparisons are planned strategically, taking the needs and the available resources into account.

The GT-RF typically does not repeat key comparisons on a regular basis. A higher priority has been assigned to performing comparisons in frequency bands that have not yet been covered.

In response to the difficulty of finding volunteers to organize comparisons, for the most recent comparisons the organization is shared between different NMIs. Each NMI is responsible for one task as writing the technical protocol, characterizing the travelling standards, analyzing the results, and writing the report. This new approach made possible the organization of new comparisons by reducing the burden on one particular NMI or individual.

To overcome the problem of the long duration of some comparisons, if the travelling standard(s) need to be measured sequentially by a large number of participants, in 2018 the "collapsing star scheme" was successfully applied for the first time in a CCEM comparison by the BIPM. In this scheme, each participant provides the travelling standards for their own participation, which are then compared at the pilot laboratory at the same time. It is foreseen to apply this scheme to other CCEM comparisons in the future, when a sufficient number of standards is available. The collapsing star scheme is currently used in CCEM.RF-K5.d.CL, comparison of S-parameters. This new approach reduces the overall time for a comparison significantly.

The CCEM has published a guidance document for the planning, organization, conducting, and reporting of key, supplementary, and pilot comparisons.

**Streamlining the CMC review**

In 2012, the KCDB held more than 7000 CMCs in electricity and magnetism, the largest number from any field, reflecting the width of the field covered by electromagnetic metrology. The NMIs' Excel tables had at that stage become very big and difficult to manipulate. Stimulated by the CCEM WGRMO, in the subsequent five years NMIs have consistently introduced matrices in the presentation of their CMCs, reducing the number of CMC entries in the EM area by almost 40 % to less than 4400 in November 2018, without loss of information. This has resulted in a significant decrease in the maintenance efforts of the CCEM CMCs, at the same time providing better CMC overviews to the users of the KCDB.

During the same period, the CCEM WGRMO has optimized the CMC review process. Instead of having all other RMOs reviewing the complete CMC set of the submitting RMO, the review of these CMCs is now divided over the RMOs. In addition, some relatively straightforward CMCs may only be reviewed by the WGRMO chair and not selected for further inter-RMO review. The rigor of the inter-RMO review process is still guaranteed, as any RMO is free to review any CMC not assigned to them by the WGRMO chair for review.

The CCEM has published a guidance document for the submission of CMCs in the field of electricity and magnetism. The CCEM has also published the "CCEM Guidelines on technical evidence for the acceptance of CMCs in the context of the CIPM MRA". This document aims to provide clarification to the criteria for acceptance of CMCs contained in the document CIPM MRA-G-13 "Calibration and Measurement Capabilities in the context of the CIPM MRA". The list of service categories for which CMCs can be submitted has been updated on several occasions.

**Enabling the revision of the SI**

At the CCEM meetings in the years before 2018, major attention was paid to matters related to fundamental constants and the revision of the SI. The CCEM WG on "electrical methods to monitor the stability of the kilogram" reviewed the worldwide state-of-the-art in Kibble balances and their measurement results for the Planck constant. This working group furthermore organized regular meetings of scientists working on Kibble balance experiments, to which representatives of the Avogadro community were invited, for in-depth discussions of technical matters between the scientists working on these experiments.

The CCEM WG on "proposed modifications to the SI" published two important documents. First of all, a *mise en pratique* was developed for the base SI electrical unit, the ampere, and for derived electrical units in the revised SI. Secondly, since the introduction of the revised SI introduced a small step change in voltage and resistance measurements and related derived quantities, CCEM Guidelines for Implementation of the 'Revised SI' were prepared to support the electrical stakeholder community in handling this step change.

Having accomplished their objectives, both working groups were closed following the revision of the SI at the 2019 meeting of the CCEM.

**Review of the implementation and operation of the CIPM MRA**

The CCEM made a major contribution to the review of the implementation and operation of the CIPM MRA in 2015 and 2016. The CCEM triggered the development of the KCDB 2.0 by pointing out as early as 2011 that the transformation of the KCDB into a true database and the development of an improved user-interface would be necessary. This had been taken up as one of the recommendations following the review of the CIPM MRA. The CCEM triggered some of the other recommendations by example, e.g,. the efficient sampling approach to the CMC review process and the sharing of roles in organizing key comparisons.

**Publishing a guidance document on the use of graphene for QHR standards**

The Task Group on graphene reviewed the existing guidelines for GaAs devices, the experimental results for graphene QHR standards and published a "Companion Guide to the Revised Technical Guidelines for Reliable DC Measurements of the Quantized Hall Resistance for Graphene-Based Devices" with the objective of formal acceptance of graphene as primary standard.

**Supporting the development of the SI Digital Framework**

The CCEM Task Group on Digitalization, CCEM TG-DIG, has interrogated the KCDB and compiled a list of all quantities that are used in each CMC service category. The consistency of this list with the information provided in the preproduction server of the SI Digital Framework was verified.

## 6.5 Document revision schedule

Every 2 years: updating numbers and dates

Every 4 years: general revision