Strategy 2020-2030

Consultative Committee for Electricity and Magnetism (CCEM)

18 May 2021

Contents

1. Executive Summary

A completely updated strategy was prepared in 2020 by the Consultative Committee for Electricity and Magnetism (CCEM). Its intended audience are mainly the members of the CCEM, decision makers at NMIs, members of the CIPM and delegates of the CGPM. The strategy was formally approved by the CCEM in its 2021 meeting and will be periodically updated.

The CCEM strategy presents the future challenges for electrical measurement science originating from the development of emerging technologies like smart electrical grids incorporating renewable energy production, high-frequency communication, electrical vehicles and sensor networks. Fundamental quantum phenomena underpin the extraordinary accuracy that can be achieved with electrical measurements and the development of novel quantum technologies will continue to have a significant impact on electrical metrology. 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.

The CCEM does not operate R&D projects on its own but provides leadership and vision to NMIs and DIs to inform their decisions on measurement science and research activities. It organizes information exchange through scientific presentations and workshops on emerging technologies. The CCEM makes use of its network of member institutes to create impact on global measurement challenges and to promote capacity building. The CCEM has the ambition to extend its interactions beyond its member institutes to other Consultative Committees and by seeking to engage with other international organizations developing foresight exercises.

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. The CCEM seeks actively for ways to further improve the efficiency of comparison organization and CMC review.

The CCEM oversees the work programme of the BIPM electricity laboratories. The comparison services form an integral part of the CCEM comparisons and allow NMIs to uniquely demonstrate their measurement capabilities at the best uncertainty levels. The 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 requires capabilities for measuring electric current over more than 20 orders of magnitude.

In addition, there is a massive 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 consider the dynamic (i.e. not steady-state) behavior of these quantities to match 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 etc.) is placing increased demands on the accurate measurement of an increased range of electrical quantities.

The strategic, global importance of electrical technologies can hardly be overestimated. Accurate and traceable measurement of electrical quantities plays a crucial role in enabling the reliable and quantitative application of these technologies for the benefit of science, industry, the economy, the health sector, and the public good. This can be illustrated with the following examples:

- Electrical energy is playing an increasing role as a medium for energy production, transfer, and end use. The most promising forms of renewable energy, such as wind and photo-voltaic cells, employ electrical technologies. As the smart grid develops, there is a growing need to bring laboratory accuracy on-site, to properly investigate the real-world behavior of this critically strategic infrastructure.
- New and developing communications technologies (e.g. 5G and beyond – 5G/6G) are moving to higher frequencies to increase the communication bandwidth. This is becoming increasingly important as we move to new ways of working as a consequence of Covid-19.
- 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.
- Vanishingly small currents are increasingly important in medical applications (ionizing radiation), the detection of faint light sources, and in molecular identification. This is an area where there is immediate need for greater sensitivity and accuracy.
- Industry 4.0 and the Internet of Things (IoT) are very much built on new and sophisticated electrical technologies, making widespread use of sensors (physical stimuli converted to electrical signals). It is expected that the increasingly sophisticated processing and manipulation of metrological data in these applications will need to employ rigorous digitalization methods.
- 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.

However, it is really the impact of fundamental quantum phenomena that underpins the extraordinary accuracy that can be achieved with 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 to the redefinition of the SI in 2019. But 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 that quantum phenomena will play an increasing role in this area in the following ways:

(i) new and improved applications of these quantum effects to other electrical quantities (such as impedance, power, rf electric fields etc.),

(ii) new kinds of materials (e.g. graphene) and novel devices (e.g. based on spin or charge),

(iii) new quantum techniques to push 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 single quantum objects and entangled property of their quantum states (e.g. quantum computing, quantum sensing). This may well lead to metrological applications and new challenges for electrical measurements.

Whilst the potential and applications of these new possibilities are overwhelming, it should not be forgotten that there is an associated and critical need to rigorously demonstrate traceability; just because nature enables this extraordinary performance of quantum standards, humans and machines can still get it badly wrong – all the more as they are complex! This is particularly important as turn-key systems, encapsulating 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 the support of broader-based, complex, and rigorous technologies. These trends will be well served by the established metrological disciplines that already ensure global consistency of electrical measurements to a very high level of accuracy.

3. Vision and mission

CCEM vision

To be the recognized international focus for electrical metrology, serving the global community by providing a reliable measurement foundation for science, innovation in industry and emerging technologies.

CCEM mission

To foster equivalence and promote harmonization of electrical measurement worldwide, by providing:

- an international forum for coordination of global comparability of electromagnetic measurements and
- collective leadership in progressing the science and the application of electrical metrology.

4. Strategy

The CCEM strategy to implement the CCEM mission and vision has three main elements: progressing the science of electrical measurement, promoting global comparability and improving stakeholder involvement.

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 supports the awareness for emerging technologies through information exchange and the organization of workshops.

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 as a unique international organization and focus of electrical and magnetic metrology.

Improving stakeholder involvement

The CCEM has a large international representation with typically 50 delegates from 30 countries attending the BIPM for the biennial meeting of the committee and its working groups. Our aim is to harness this network to have impact on global measurement challenges and to promote capacity building for electromagnetic measurements in anticipation of future technological requirements. In particular we seek to engage with other international groups and organizations developing technology roadmaps and foresight exercises, with key manufacturing and supply industries, and with countries having developing economies. Through these activities the CCEM aims to enhance the impact of electrical metrology, and the uptake of new developments.

5. Activities to support the strategy

5.1 Progressing electrical measurement science

The CCEM does not conduct R&D projects. New science is taking place at the NMIs and the CCEM has a guiding and coordinating role. The CCEM identifies measurement challenges for NMIs through CCEM strategy documents and work plans of the CCEM Working Groups.

Electrical measurement science can be roughly divided into activities with a more fundamental focus and those related to emerging technologies and societal grand challenges. Key areas in the fundamental research are strongly related to further development and application of quantum standards. Scientific activities in support of emerging technologies, and in relation to societal challenges, are dominated by the wide-ranging aspects of digitalization, including mobile communication, internet of things, smart electrical grids, sensor networks, quantum technologies etc. Measurement challenges in these applied fields are related to extended electrical parameter scales (e.g. higher frequencies), miniaturization, properties of materials and interconnectedness.

The recent (May 2019) revision of the SI introduced revolutionary changes with respect to electrical quantities. The CCEM will continue to enable smooth implementation of the revised SI through high-level guidance (*mise en pratique*). We will monitor the progress to identify any shortcomings, or evolving needs, and produce additional/revised guidance as necessary. The CCEM will work proactively with the electrical measurement community to promote the revised SI and help disseminate its electrical and magnetic quantities effectively and efficiently.

The CCEM will continue organizing workshops and selected technical presentations in key emerging areas, involving acknowledged experts, particularly at the time of CCEM meetings. The focus of these events is likely to shift from more generic to more specific topics such as Josephson waveform metrology, digitalization, sensor network metrology, smart grid metrology, metrology for quantum technologies, electric and magnetic metrology for the nanoscale, etc.

These knowledge transfer activities are closely linked to the BIPM Capacity Building & Knowledge Transfer (CBKT) Programme. This programme aims to increase the effectiveness within the world-wide metrology community of 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 started in support of developing NMIs, e.g. on quantum electrical standards, scaling techniques, and practical realizations of secondary electromagnetic units.

Due to the ubiquitous use of electricity, the CCEM promotes cross-discipline collaborations with other Consultative Committees. One example is the joint task group with the CCRI on low-current measurements for ionizing radiation. Very accurate measurements of low dc current, which may be linked in the future to single electron tunneling, are critical for achieving reliable and accurate standards for ionizing radiation and improving the efficiency of their realization. Other examples are the cooperation with the CCM on the “electronic” kilogram and with the CCU on the redefinition of the ampere.

5.2 Promoting global comparability

The CCEM leads the implementation of the CIPM Mutual Recognition Arrangement (MRA) in Electricity and Magnetism. A particular focus is on working smarter, improving efficiency and leading by example through CCEM input to the review of the CIPM MRA. Electricity and Magnetism is the second largest area after chemistry in terms of the number of CMC entries in the BIPM Key Comparison Database. The CCEM manages this through a number of approaches.

Out of a wide variety of electrical and magnetic quantities, value 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 both in low-frequency and radiofrequency areas, co-sharing piloting responsibilities, etc. This helps overcome challenges such as finding pilots for comparisons.

The CCEM coordinates and reviews regional key comparisons and works with RMO Technical Committees to understand emerging changes in comparison needs. It publishes 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 addressing emerging needs.

Efficient management of CMC reviews in electricity and magnetism includes unique approaches such as sharing inter-RMO reviews of CMCs between RMOs (only one RMO reviews proposed CMCs in a particular service category) and an efficient sampling strategy whereby some CMCs are only reviewed in the inter-RMO review by the CCEM 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 Chair of the CCEM Working Group on RMO Coordination – 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 the present 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 will encourage the development and implementation of a harmonized approach to digital calibration certificates in the CCEM community, working with 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.

5.3 Improving stakeholder involvement

The interaction of the CCEM and its Working Groups is currently largely confined to the biennial meetings at the BIPM and interim satellite meetings held in conjunction with the Conference on Precision and Electromagnetic Measurements (CPEM). Most of the business outside these meetings is concerned with the management of international comparisons and occasional special interest meetings hosted by the Working Groups.

Our ambition is to achieve a greater involvement with international committees and networks involved with the standardization of electrical measurements and the development of roadmaps and other documents articulating the future trends in this area.

To this end, we will invite representatives of these organizations to take part in our regular meetings, for example by giving an invited talk or by joining one of the strategic discussions of the Working Groups. It is anticipated that the increasing use of online methods for technical meetings will make it easier for occasional participants to join without a large time or financial commitment.

We will also seek contributions from Consultative Committees in other technical areas (e.g. from the CCRI for requirements for low-current measurements and the CCM for the use of quantum standards for Kibble balances) as well as key manufacturing and supply industries, accreditation organizations and universities.

5.4 Work program of the BIPM laboratories

In the field of electricity, 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 providing traceability to the SI for many smaller NMIs, and by allowing larger NMIs to demonstrate the equivalence of their own primary standards and to support their CMCs. The comparison of NMIs' primary electrical quantum standards with the lowest possible uncertainty requires dedicated travelling quantum standards, which are provided by the BIPM. Comparing quantum standards at the highest level of accuracy also requires special expertise, which the BIPM staff has developed as a consequence of its specialization in this task. Providing these comparisons which require specialized equipment and special expertise from one single laboratory, is 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. 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.

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 some cases, for NMIs having acquired quantum standards very recently, these comparisons are 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.

To make optimal use of its quantum standards, the BIPM also provides calibrations, typically for smaller NMIs not possessing primary standards. The long-term availability of these services allows Member States to rely on them for their traceability needs. Since the new Member States typically have only limited metrological capabilities, the number of calibrations has been slowly growing in recent years.

These activities are considered by the CCEM to be an important contribution to its comparison program and a useful and beneficial component of the BIPM work plan, and the usage of these services is continually evaluated as the technology of quantum standards evolves to allow more direct dissemination.

The BIPM makes use of its specialized equipment and expertise for developments on improving the realization of electrical SI units and on providing new services. Examples are extending the present 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 is developing a calculable capacitor as a second standard for impedance, in addition to the quantum Hall effect, to ensure the integrity of the world-wide traceability of this quantity, to consolidate the BIPM measurement capabilities at the highest level and to help curating knowledge in this key technique.

The 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.

6. Annex

6.1 General information (as of 2021)

CC Name:	Consultative Committee on Electricity and Magnetism
CCEM President:	Dr. ir. Gert Rietveld (VSL, Netherlands)
CCEM Exec. Secretary:	Dr. Michael Stock (BIPM)
Date established:	1927
Last meeting:	32nd CCEM in 2021
Number of Members:	26

Number of participants at last meeting: 58 delegates and experts from member NMIs and 7 observers (the meeting was held online)

Periodicity between meetings: 2 years

CCEM Working Groups:

Working group on low-frequency quantities (WGLF)
Chair: Dr. Murray Early (MSL, New Zealand)

Working group on radiofrequency quantities (GT-RF)
Chair: Dr. Markus Zeier (METAS, Switzerland)

Working group on RMO coordination (WGRMO)
Chair: Mr. Lucas di Lillo (INTI, Argentina)

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 the wide frequency range covered by the GT-RF together with finite resources so that efforts must be prioritized. 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 program 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 (May 2021), the following CCEM key comparisons are ongoing:

- CCEM-K3.2018 Inductance at 10 mH and 1 kHz
- CCEM-K5.2017 Active power, 53 Hz, 120 V – 5 A and 240 V – 5 A
- 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
- CCEM.RF-K5.c.CL S-parameters, coaxial lines, PC-3.5 mm connectors, 50 MHz – 33 GHz
- CCEM.RF-K26 Attenuation in PC-3.5 mm connectors
- CCEM.RF-K27.W Power in WR15, 50 – 75 GHz
- Pilot Study dielectric properties of materials (dielectric loss)

The following table gives an overview of the numbers of completed and ongoing comparisons in the RMOs (situation in 2020):

	key comparisons		supplementary comparisons	
	ongoing	completed	ongoing	completed
AFRIMETS	0	0	2	1
APMP	5	9	4	15
COOMET	0	6	10	11
EURAMET	2	21	8	35
GULFMET	0	1	5	5
SIM	0	16	3	14
Total	7	53	32	81

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 190 individual services.

In September 2020, 4392 CMCs from 62 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 in the Excel tables (and the corresponding workload to maintain them) without reducing the amount of information.

6.4 Summary of work accomplished

Organization of CCEM meetings and workshops

Meetings of the CCEM are organized every two years, the last time in 2021. Meetings of its working groups are held in addition in the years in-between, in general at the time of a CPEM conference. At the 2015 and 2017 CCEM meetings, major attention was paid to matters related to fundamental constants and the revision of the SI.

The existing CCEM policy to maintain a strong science focus in its meetings has been strengthened: speakers were invited to make presentations on new developments in electrical metrology. Furthermore, a scientific workshop on “Future challenges in Electrical Metrology” with six invited speakers from NMIs and academic institutes was held on 23 March 2017. A workshop on “Radiofrequency and microwave metrology: recent developments and challenges” with five invited speakers from industry and academic institutes was held on 27 March 2019.

Organization of key comparisons

Since the start of the CIPM MRA, the CCEM has organized 48 key comparisons (including the ongoing BIPM comparisons) and 2 supplementary comparisons. During the same time, the RMOs have organized 60 key comparisons and 113 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 has started. 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. The reason for this policy is the wide frequency range covered by the GT-RF so that efforts must be prioritized. 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.

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 "star-scheme" was successfully applied for the first time in a CCEM comparison. 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. 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 containing these CMCs.

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 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' have been 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.

6.5 Document revision schedule

Every 2 years: updating numbers and dates

Every 4 years: general revision