Consultative Committee for Amount of Substance: Metrology in Chemistry and Biology
Gas Analysis Working Group Strategy for Rolling Programme Development
(2025 to 2030 and beyond)

1. EXECUTIVE SUMMARY

The Gas Analysis Working Group (GAWG) provides the framework that supports the global measurement infrastructure for gas analysis. Its scope of activities enables global comparability for measurements of gas composition, isotope ratio, gas/liquid mixtures, particles and aerosols and new measurement technologies. In collaboration with the Regional Metrology Organisations (RMOs), the GAWG responds to the needs of nine sectors: atmospheric monitoring of the environment, air quality monitoring and indoor air, emissions measurement, efficient and safe trading in traditional energy gases, diversification in the supply of energy gases, hydrogen economy, implementation of legal metrology, healthcare and advanced manufacturing.

The GAWG will respond to the evolving needs for metrology raised by the CIPM. This will include **climate change and the environment**, by addressing ever more demanding regulatory limits for pollutants in air and emissions, emerging pollutants, isotope ratio for source apportionment of greenhouse gases and new capabilities in particle metrology. It will also focus on clean growth and decarbonisation of the global economy by enabling the **energy** transition with hydrogen and biomethane metrology. Work in **health and life science**s will provide vital infrastructure for new healthcare diagnostic devices. **Advanced manufacturing** will also feature in the work programme with a focus on underpinning impurities in process gases, airborne molecular contamination in clean rooms and metrology for sustainable food packaging.

The strategic agenda will be realised with a work programme addressing the key scientific challenges to advance the global measurement system. The GAWG has identified seven priority areas for advancing the state of the art in measurement science (new greenhouse gas reference materials for isotope ratio, implementation of regional greenhouse gas scales and traceability to the SI, diversification of the energy gas supply by underpinning biomethane and hydrogen purity measurements, aerosol metrology to improve comparability and address new measurands, measurement capabilities and reference materials to underpin reactive gases, advanced spectroscopy and stimulating innovation by characterising new technologies).

The GAWG will respond to the requirements from industrial, regulatory, government and academic stakeholders. The work programme is driven by national priorities, focusing mostly on government policies and legislation to meet climate commitments and for the protection and sustainability of the environment. There is also substantial focus on supporting industry, such as the specialty gas industry, instrument manufacturers, atmospheric monitoring networks, organisations driving the energy transition towards decarbonisation, healthcare and advanced manufacturing. Standardisation bodies are also a key stakeholder and members of the GAWG will participate in relevant committees and develop documentary standards. The active programme in gas metrology at the BIPM will facilitate the development of collaborative activities with other international organisations with related missions, notably WMO and IAEA.

Promoting global comparability is high on the GAWG agenda with a progressive mission to increase impact and throughput with the same resource. A strategy for a broader application of comparison results will provide evidence for Calibration and Measurement Capabilities (CMCs) with a manageable number of comparisons featuring core capabilities. Broad claim CMCs will create more efficiency and encourage more stakeholder engagement with the Key Comparison DataBase (KCDB). It will also provide more focus on the broad range of analytically challenging components and emerging requirements from stakeholders.

The GAWG has a mission to accelerate the progress of developing NMIs and enhance the interface with the RMOs. Most have an active programme of comparisons linked to GAWG key comparisons and supplementary comparisons, where there is limited global interest. The GAWG will support and interact via satellite comparisons, assessing core capabilities to work with efficiency, while ensuring the needs of all institutes are met. It will also promote knowledge transfer activities including workshops and secondments.

2. SCIENTIFIC, ECONOMIC AND SOCIAL CHALLENGES

Summary of key sectors' reliance on chemical/biological measurement and how they are influencing the future GAWG strategy

The GAWG, in collaboration with the RMOs responds to the needs of nine different sectors. This is achieved by developing studies to assess the international comparability of measurement capabilities and prioritising critical measurement issues. The GAWG also provides a forum to exchange information to advance the state of the art in measurement science, by investigating new and evolving technologies, measurement methods and reference materials. The drivers, impact and key requirements from these sectors are described below. The GAWG aims to engage with other consultative committees on global challenges of mutual interest.

1 Climate - atmospheric monitoring of the environment

The measurement of greenhouse gases is pivotal to understanding changes in the Earth's climate. National and international legislation is aimed at reducing greenhouse gas emissions and requiring their measurement in the atmosphere. Long-term observations based on accurate and stable standards ensure that data meets the requirements of the World Meteorological Organisation's Global Atmosphere Watch (WMO-GAW) Programme compatibility goals and environmental policy makers, as well as academic and regulatory users. The GAWG has made prodigious strides towards meeting these needs with the development of high accuracy, SI traceable, gas reference materials of carbon dioxide, methane, nitrous oxide and carbon monoxide, driving the uncertainties towards the compatibility goals of the WMO GAW Programme.

Volatile Organic Compounds (VOCs) play a key role in the chemical mechanisms that lead to the photochemical generation of ozone and aerosols, which can have harmful effects on ecosystems and human health and control the oxidative capacity of the troposphere. Some halocarbons and other related components also contribute to radiative forcing. The GAWG is enabling National Metrology Institutes (NMIs) and Designated Institutes (DIs) to facilitate the traceable calibration of analytical instrumentation that prevent or reduce these effects on the public and the environment.

Aerosol particles also have an impact on atmospheric science. They have a direct effect on the optical properties of the atmosphere via scattering and absorption of radiation, and an indirect optical effect via cloud formation and their chemical interactions. Aerosol properties are one among of the Essential Climate Variables identified by the Global Carbon Climate Observing System (GCOS) of the WMO, the Intergovernmental Oceanographic Commission of the United Nations Educational, Scientific and Cultural Organization (IOC-UNESCO), the United Nations Environment Programme (UN Environment), and the International Science Council (ISC) and Intergovernmental Panel on Climate Change (IPCC). Many of the relevant measurands such as aerosol particle number concentration, size distribution and composition are largely in common with those in the European Air Quality Directives. Specific issues associated with measuring ambient aerosol particles, as opposed to industrial or vehicle emissions, are the temporal and spatial variability of their concentrations and composition, their typically trace-level concentrations and the large range of particle sources (from the directly-emitted to secondary organic aerosols formed by gas precursors), the high proportion of semi-volatile particles, their hygroscopicity and the possible losses of target analyte during sampling and extraction.

2 Air quality monitoring and indoor air

The combined effects of ambient (outdoor) and household air pollution cause about seven million premature deaths every year. World Health Organisation (WHO) data shows that 9 out of 10 people breathe air containing high levels of pollutants [1].

Accurate measurements of air pollutants such as sulphur dioxide, nitrogen monoxide, nitrogen dioxide, carbon monoxide and benzene are required to fulfil the directives on ambient air quality and clean air (e.g. European directive 2008/50/EC). They are also essential to understand population level exposure, improve air quality models and emission inventories, to discern long-term trends in amount-of-substance fraction (later referred to as amount fraction) and to enforce air quality and vehicle emission legislation. This is essential for the timely evaluation of air pollution mitigation policies, and to improve our understanding of the influence of anthropogenic emissions on the climate system. The GAWG provides the mechanism to underpin these measurements from its comparison programme targeting these components.

Airborne particles in ambient air have traditionally been regulated for human health purposes by the mass concentration of the size fractions such as PM_{10} and $PM_{2.5.}$ However, legislation requires other metrics, such as elemental and organic carbon, total carbon, black carbon, anions and cations, major metals (lead, arsenic, cadmium, mercury, nickel) and more recently, number concentration and size distribution of ultrafine particles (UFP). In recent years, the GAWG has stepped up its programme on aerosol metrology and has coordinated the first key comparison on particle number and charge concentration (CCQM-K150). A more expansive comparison (CCQM-K185) was coordinated in 2024.

Ozone is a principal pollutant associated with photochemical smog. Ground-level ozone concentration is an important air-quality parameter which is monitored and reported world-wide. The reference method for ground-level ozone measurements is based on UV photometry, with replicates of the NIST Standard Reference Photometer (SRP) acting as primary standards for numerous national and international ozone-monitoring networks. The GAWG provides the means to assess the global comparability of ozone measurements with an ongoing key comparison, BIPM.QM-K1, coordinated by the International Bureau of Weights and Measures (BIPM). The GAWG recommended a new and published SI-traceable value and uncertainty for ozone cross-section at 253.65 nm (air) and implementation is almost complete. It will allow ozone to be measured more accurately. Better measurements will result in more efforts toward cleaner air which is better for human and environmental health.

The new Air Quality Directive that was revised and adopted in 2024 (Directive (EU) 2024/2881 of the European Parliament and of the Council of 23 October 2024 [2]) focuses on ambient air quality and cleaner air for Europe. There are more stringent air quality legislation limit values that drives the need for capabilities to underpin lower amount fractions with better accuracy.

3 Emissions measurement and control

There are pressing requirements for atmospheric measurements to deal with sources of air pollution, protecting nature and boosting the economy. This ensures the world can meet the legally binding international targets to reduce emissions of the most damaging air pollutants. It also leads to the development of capability to realise new goals to cut public exposure to pollution.

The National Emission Reduction Commitments Directive sets national emission reduction commitments for Member States and the EU for five important air pollutants: nitrogen oxides (NOx), non-methane volatile organic compounds (NMVOCs), sulphur dioxide (SO_2), ammonia (NH_3) and fine particulate matter (PM2.5). These pollutants contribute to poor air quality, leading to significant negative impacts on human health and the environment [3].

The GAWG provides the global measurement infrastructure to underpin measurements of emissions from industry, agriculture and transport. This is vital to enable industry, regulators and the research community to comply with legislation and reduce emissions of pollutants, such as sulphur dioxide, oxides of nitrogen, hydrogen chloride, ammonia and UFP.

4 Efficient and safe trade in conventional energy gases

Gas distribution network operators are dependent on measurements to calculate the calorific value and the presence of any impurities that may negatively affect home appliances. These measurements also enable nations to demonstrate compliance with technical specifications or regulations.

The GAWG provides the measurement infrastructure to underpin the composition of natural gas which directly impacts the accuracy and quality of gas bills. Hydrocarbon dew points can also be determined, to ensure that condensation of the mixture will not take place in the gas pipeline. The GAWG also provides the framework to underpin the quantification of sulphur-containing odorants, added to natural gas to allow any potentially hazardous leaks to be detected.

5 Diversification in the supply of energy gases

As we strive to deliver a sustainable, low carbon economy, there is an increasing focus on alternative sources of energy. Biomethane which is produced from biogas is already injected into the gas grid in several countries. It may contain impurities such as siloxanes that are not monitored, since they do not fall under any current regulations. These components, if present, could significantly deteriorate performance of home appliances by allowing the build-up of silica following combustion. The GAWG therefore, addresses the requirements from biogas plants to check the quality of their biomethane against documentary standards for biomethane quality (e.g. EN 16723 in Europe).

Liquefied gases such as Liquified Natural Gas (LNG) and liquified Petroleum Gas (LPG) are used to meet peak demand when the normal pipeline infrastructure cannot and simplifies transport from source to destination. On the large scale, this is done when the source and the destination are across an ocean from each other. It can also be used when adequate pipeline capacity is not available. Significant metrology challenges exist to quantify the composition of LNG and LPG for trading. The GAWG addresses these requirements and recently completed the first key comparison on LPG (CCQM-K119).

6 Hydrogen economy

Hydrogen fuel cell electric and battery vehicles are being rolled out in many countries to decarbonise transportation. Fuel cell electric vehicles provide advantages compared to battery vehicles, such as quick refuelling time, longer range and a lower carbon footprint, as battery production typically generates around 20 tonnes of carbon. Hydrogen fuel quality is critical for the development of the hydrogen economy as hydrogen fuel cell vehicles are extremely sensitive to impurities (as low as 4 nmol mol^{-1} for some components). The mission of the GAWG is critical to ensuring equivalence in hydrogen quality testing worldwide. The NMI and DI capabilities will also be able to assess the feasibility to supply fuel cell vehicles directly using hydrogen transported through the existing natural gas grid.

7 Implementation of legal metrology

Implementation of some areas of legal metrology for the regulation and statutory requirements for measuring instruments and the methods of measurement are enabled by gas metrology. Examples include underpinning automotive emissions for vehicle testing and breath alcohol and interfering substances to underpin drink driving, airline and workplace legislation. In the latter example, there is a requirement for traceable reference materials for calibrating evidential breath analysers as specified by the International Organisation of Legal Metrology (OIML) International Recommendation OIML R 126.

The GAWG programme supports these requirements by providing the means to demonstrate global comparability for capabilities to disseminate traceability for ethanol and gases found in automotive emissions (e.g. propane, carbon monoxide, carbon dioxide and oxygen).

8 Healthcare

The detection of medical conditions such as cancer from related biomarkers in exhaled breath is a non-invasive technique with the potential to become a vital tool for screening and diagnosis. A lack of standardisation in breath collection and analysis is a major barrier to adoption into clinical practice. There is need for reproducible breath sampling techniques, new advanced measurement methods and accurate and traceable gas reference materials. The GAWG has a vital role to play in the heath sector by providing a sound platform on which metrology can be used to support the testing of newly developed non-invasive devices for early diagnosis and by serving as a forum to share ideas, foster greater collaboration and act as a mechanism for underpinning scientific advances in metrology for clinical diagnostics.

9 Advanced manufacturing

Gas metrology plays an essential role in underpinning vital processes in advanced manufacturing. This includes enabling measurements of impurities such as water vapour in process gases, quantifying the composition of noble gases, enabling the introduction of safe sustainable packaging for food and monitoring airborne molecular contamination in the form of chemical vapours or aerosols which have an adverse effect on products, processes or instruments. Technological progress is driven by the ability to operate at ever smaller scales and with greater complexity, which in turn increases the demand for lower amount fractions of contaminants (e.g. hydrogen chloride and ammonia). Real-time, online monitoring is critical to ensure that corrective action is taken before contamination impacts on production costs.

Gas metrology also supports one of the biggest challenges for emerging technology based on organic electronics and graphene by assuring the lifetime of the product. These materials are highly sensitive to moisture and oxygen, and metrology to underpin quantitative degradation studies of the active components and performance measurements of encapsulating barrier materials is essential for future success of the technology.

Many advanced manufacturing processes (such as the semiconductor industry) require the use of clean-rooms which must confirm to specifications limiting the concentrations of particles. Reliable measurements of particle number concentration at ultra-low concentrations are required to assess compliance to these specifications.

Meeting the sector needs

The GAWG enables and supports the global metrology infrastructure to meet the needs of these sectors by underpinning measurements of gas composition and airborne particle properties in a range of matrices for industrial, regulatory, government and academic stakeholders. The work programme of the GAWG is driven by its members responding to their own national priorities and covers five key capabilities:

(A) Reference materials, methods and calibrations for composition of components in the gas phase (binary and multi-component mixtures)
(B) Reference materials, methods and calibrations for isotope ratio of components in the gas phase
(C) Reference materials, methods and calibrations for composition of gas/liquid mixtures (e.g. LPG and LNG)
(D) Reference materials, methods and calibrations for particles and aerosols in a gas matrix

(E) New measurement technologies (e.g. advanced spectroscopic techniques for absolute measurements)

To inform the strategy, a survey was prepared and distributed to the membership of the GAWG in 2020. It focused on the strategic priorities of institutes, comparisons and global comparability, CMCs and future requirements. Reponses from 36 institutes were received.

Figure 1 shows the size and future projection of the five capabilities listed above, as indicated by the results of the survey. Figure 1 (a) shows composition capabilities (A) to be most established with 34 out of 36 laboratories reporting a capability. If we consider large and medium capabilities together, the data shows that capabilities in particle and aerosol metrology (D) are the second largest, but substantially less mature than composition (A). Capabilities for gas/liquid mixtures (C) and new measurement technologies (E) are similar in response and report fewer capabilities than for particle and aerosol metrology (D). Isotope ratio (B) is shown to be the least established with only 10 out of the 36 laboratories reporting a capability. This is expected as activities in this field only commenced within the GAWG in the last 2 years.

Figure 1 (b) shows the future projections and the natural life cycle of activities (no capability, planning, start of activities and growth, stabilisation of capability and finally reduction in capability with uptake from stakeholders and other activities taking priority). Substantial growth is still expected in the largest field, composition (A) in addition to the maintenance of services. In capabilities (B-E), where fewer laboratories have activities in 2020, planning has started in a substantial number of laboratories and an increase in programmes is foreseen in all these fields. Figure 1 (b) also shows that for the four less established areas (B-E), NMIs and DIs will be making plans for new activities in their work programmes. Around half of those currently without capability have plans for investment. These findings are reflected in this strategy document which focuses on continuing the work programme on composition, to support the substantial growth expected and enabling development and investment in isotope ratio, particle and aerosol metrology, composition of gas/liquid mixtures and new measurements technologies.

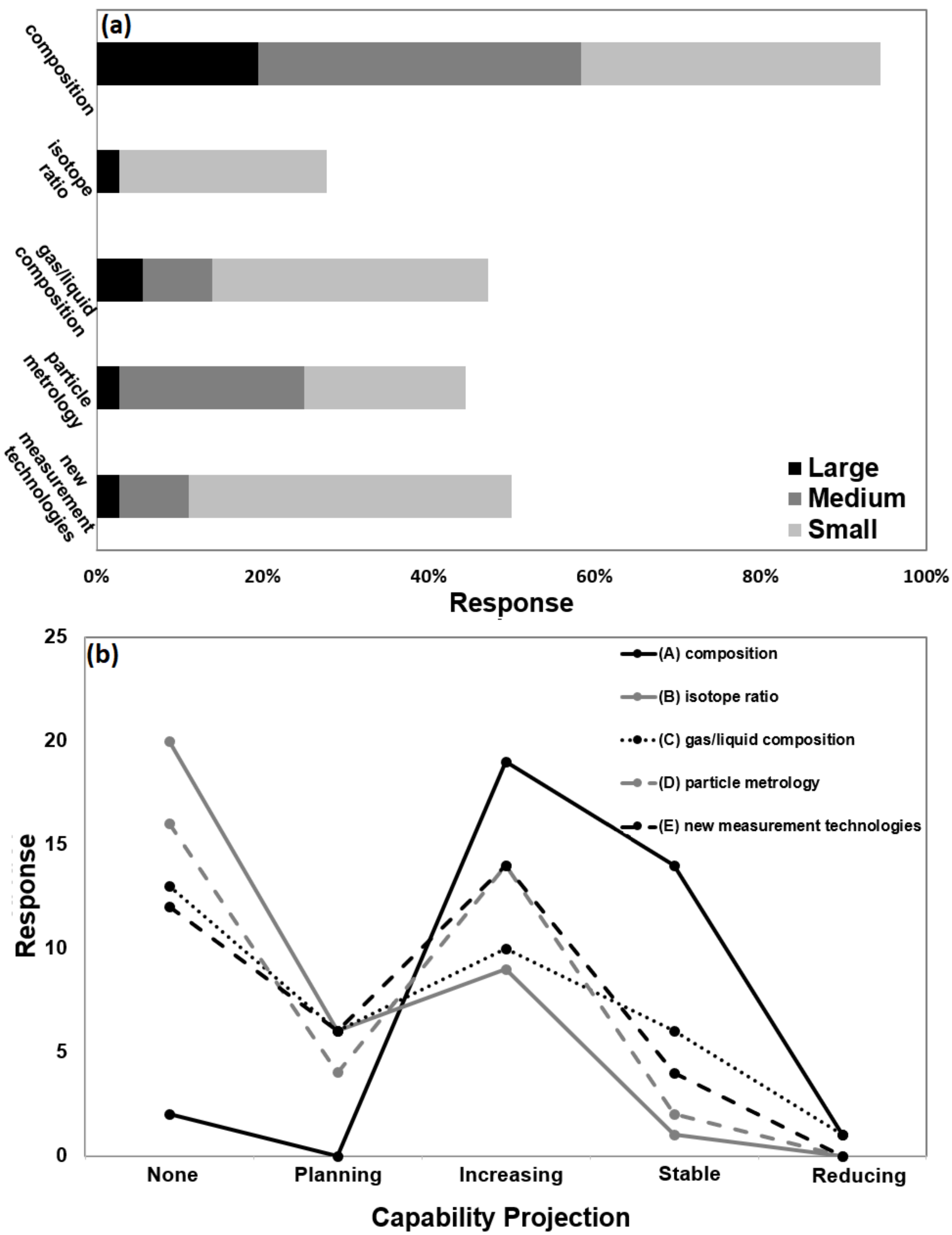


Figure 1 Institute's programme size (a) and future projection (b) against five measurement capabilities, as indicated by the GAWG strategy survey participants.

Figure 2 shows how the capabilities from the 36 institutes that participated in the survey align with each of the sectors described above. From these results, 41 % of capabilities were used to provide traceability to address environment related challenges (climate, air quality, emissions and indoor air), while 24 % were targeted at underpinning requirements for energy (natural gas, alternative fuels and hydrogen). The data also shows how each of the five capability areas are being targeted to address measurement requirements in each sector. Composition (A) is shown to broadly impact across all sectors, with a contribution of around 50 % in each case. Isotope ratio (B) is shown to play a major role in climate with contribution also to air quality and emissions. Gas/liquid mixtures (C) is shown to address the requirements in the natural gas and alternative fuels areas. Particle and aerosol metrology (D) mainly addresses climate, air quality, emissions and indoor air, while new measurement techniques (E) impacts more broadly across all sectors.

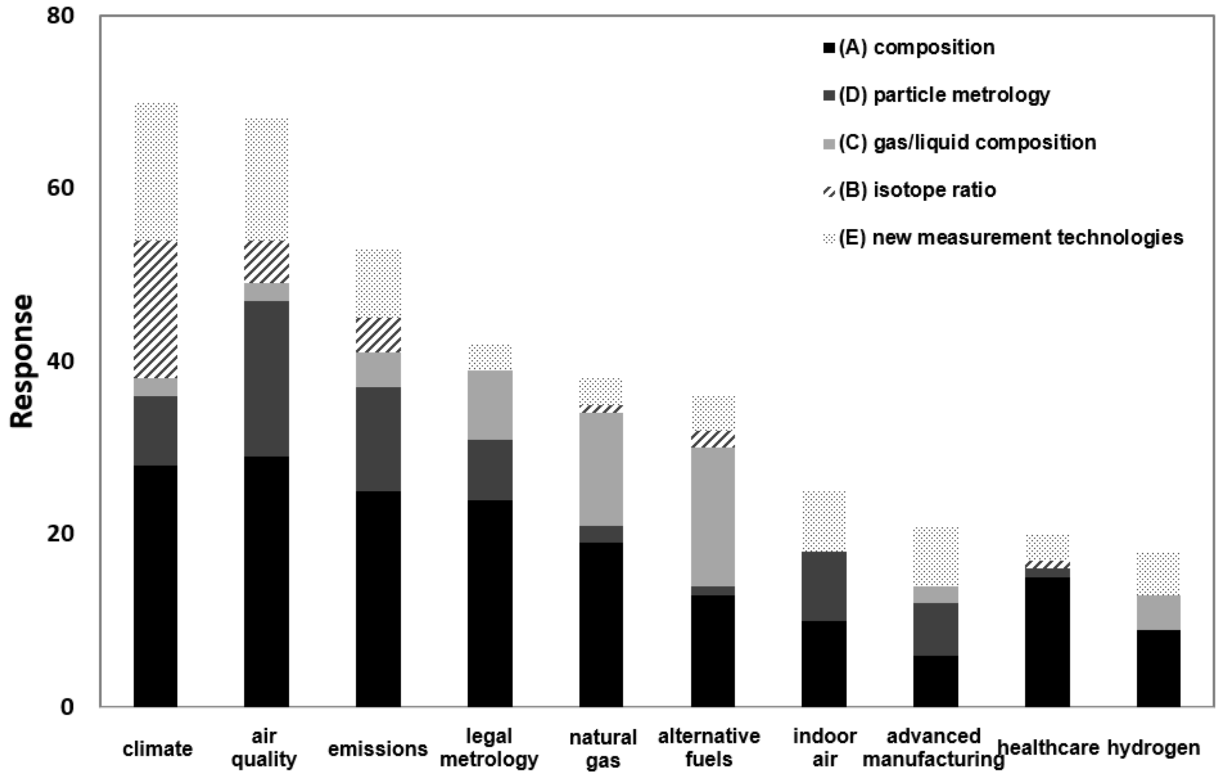


Figure 2 Application of the five measurement capabilities against the sectors described, as indicated by the GAWG strategy survey participants.

In the survey, for each sector, participants were also asked to state whether they had CMCs registered in the KCDB, whether they were intending to submit CMCs or had no plans. Of those that responded with CMCs or intentions to submit claims, the proportion of those planning CMCs were as follows: hydrogen– 87 %, alternative fuels - 63 %, air quality - 55 %, climate - 50 %, advanced manufacturing – 44 %, emissions - 39 %, natural gas - 26 % and legal metrology – 22%. The two sectors with the highest responses were expected, as we embrace the energy transition and capabilities are established to support the hydrogen economy and the diversification of the energy supply. The GAWG work programme will be tailored accordingly to respond to this shift while ensuring maintenance of more mature areas with fewer new CMCs being submitted (e.g. natural gas).

Responding to the future needs

The GAWG is responding to the evolving needs for metrology and the key scientific challenges to advance the global measurement system. Focus will be directed towards understanding complex systems, to enable the effective mitigation of climate change, efficient and alternative energies and the predictive power of medical and human health data. The following trends are driving developments in the GAWG work programme.

Mitigation of climate change and net zero will be a key focus area. Over the past few years, the GAWG has made significant progress in underpinning composition of key greenhouse gases in the atmosphere. These developments have strengthened the relationship with the atmospheric monitoring community. The advancement of commercial spectroscopy and the urgent requirement for better data quality to infer the origin of key greenhouse gases and underpin government emissions inventories, means the development of gas reference materials for isotope ratio is high on the GAWG agenda. This essential work will enable governments to demonstrate the effectiveness of policy and inform future targets for mitigating climate change. The GAWG is addressing the requirement for a new infrastructure to deliver international carbon dioxide reference materials with traceability to the primary VPDB isotope ratio scale, to meet the increasing demand. This will address the demand from the advent of commercial optical spectroscopy and issues in realising the scale which have existed for several decades. An initiative on absolute isotope ratio measurements will put carbon dioxide isotope metrology on an SI basis for the first time, by addressing the issue of mass bias in isotope ratio mass spectrometry from various parameters and resolve a long-standing traceability exception within the CIPM-MRA.

Air quality and protection of the population will be high on the GAWG agenda. Air pollution is a serious health hazard and the major environmental cause of premature death in the developed world. Priorities from national and regional legislation for population protection, air quality and occupational exposure are increasing. There is substantial demand for smaller uncertainties and improved technologies for sensing to ensure sufficient data quality and coverage. The GAWG is responding to the key scientific challenges by addressing the requirement for more stringent and emerging air quality requirements (e.g. nitrogen dioxide, particulates and UFP in indoor and ambient air). WHO stated in their published guidelines in 2021 [4] that UFP are pollutants of "particular interest" and recommended monitoring of UFP. The air quality directive (EU) 2024/2881 [2] has adopted this request. As a result, there is need to enhance measurement and calibration techniques. A major source of nitrogen dioxide in urban regions is from fossil fuel combustion with large contributions from the transport sector, specifically diesel-powered motor vehicles. In Europe, the trend of decreasing nitrogen dioxide over the last past decade has been small due to large increases in diesel vehicle ownership, resulting from government driven tax incentives, in conjunction with emission standards not delivering the expected reductions under real world driving conditions. As a result, there is a focus on portable emissions measurement systems on vehicles for key pollutants from exhaust which will require measurements to validate compliance with regulations. Recent advances in technology have led to selective nitrogen dioxide measurement techniques which require accurate gas reference materials for calibration.

The GAWG will position the world to develop a smart and resilient energy system to enable new clean energy and negative emissions technologies. This will be enabled by an increasing diversity of energy generation technologies and methods to integrate a higher proportion of renewable energy on the energy grid. Enabling the injection of alternative fuels such as hydrogen and biomethane in the gas networks, is a key objective in the future GAWG work programme. Requirements from the energy industry include quality assurance of emerging fuels (e.g. hydrogen and biomethane) and linking physio-chemical properties to composition measurements. Additionally, there is a requirement from grid operators to underpin the introduction of new odorants for a 100% hydrogen network that are compatible with existing and new (polyethylene) pipeline and home appliances. Significant changes in our energy mix will need to be managed including combined gas power and carbon sequestration plants with gas metrology to support purity analysis of carbon capture and storage. Hydrogen fuel for transport will support global efforts towards decarbonisation. As the global vehicle fleet transitions to electric vehicles, particulate emissions from tyres, brakes and road surface wear will dominate tailpipe emissions and pose new measurement challenges to assess toxicity to human health and the environment.

The GAWG will respond to changes in healthcare. A shift towards proactive healthcare with a focus on prevention, personalised medicine and long-term care, as well as embracing upcoming technological advances and the digital revolution. The success of technology based on non-invasive devices for early diagnosis and screening of medical conditions will rely on the identification and calibration of exemplar VOC biomarkers. It will also require standardised methodologies for breath sampling and real-time analysis. This lack of standardisation represents a substantial barrier to the widespread adoption in clinical practice.

The GAWG will enable the next generation of gas reference materials. Miniaturising reference materials and calibration devices will be a key element in the transition from capital to consumable items. The future of gas reference materials will not only improve accessibility for end users to traceability (e.g. reference materials can be purchased in smaller volumes and are more cost effective) but will solve challenges with logistics for field measurement campaigns involving aircraft and long-distance shipping. It will also provide the foundation for improved stability studies as smaller units can be produced and archived more easily. Improved passivation of storage media is critical to enabling NMIs and industry disseminate traceability, with accuracy and long-term stability. A lack of metrology focus, and scientific understanding of the chemistry at the surface is a barrier to innovation and progress towards the next generation of gas reference materials, calibration devices and sampling systems. The applications are far-reaching, and the impact of this research will touch the lives of everyone (e.g. underpinning clean growth by enabling the hydrogen economy with traceability for hydrogen purity). The enhanced stability of reference materials will improve maintenance of existing CMCs.

Moving forward, the GAWG will focus on refining its work programme to meet the needs of the future. This will include addressing ever more demanding regulatory limits for pollutants in air and emissions, emerging pollutants, isotope ratio for source apportionment of greenhouse gases, new capabilities in particle metrology, enabling the energy transition with hydrogen and biomethane metrology, providing the infrastructure for new healthcare devices and advanced manufacturing.

3. VISION AND MISSION

Vision of a world in which all chemical and biological measurements are made at the required level of accuracy to meet the needs of society.

The mission is to advance global comparability of chemical and biological measurement standards and capabilities, enabling member states and associates to make measurements with confidence.

4. STRATEGY

1 To contribute to the resolution of global challenges such as climate change and environmental monitoring, energy supply, food safety, healthcare including infectious disease pandemics, by identifying and prioritising critical measurement issues and developing studies to compare relevant measurement methods and standards.

2 To promote the uptake of metrologically traceable chemical and biological measurements, through workshops and roundtable discussions with key stakeholder organisations, to facilitate interaction, liaison and cooperative agreements, and receive stakeholder advice on priorities to feed into CCQM work programmes.

3 To progress the state of the art of chemical and biological measurement science, by investigating new and evolving technologies, measurement methods and standards and coordinating programmes to assess them.

4 To improve efficiency and efficacy of the global system of comparisons for chemical and biological measurement standards conducted by the CCQM, by continuing the development of strategies for a manageable number of comparisons to cover core capabilities.

5 To continue the evolution of CMCs to meet stakeholders needs, incorporating the use of broad claim CMCs where applicable to cover a broader range of services and considering options to present these in a way that meets stakeholder needs and encourages greater engagement with the CMC database.

6 To support the development of capabilities at NMIs and DIs with emerging activities, by promoting a close working relationship with RMOs including mentoring and support for NMIs and DIs preparing to coordinate comparisons for the first time and promoting knowledge transfer activities including workshops, as well as secondments to other NMIs, DIs and the BIPM.

7 To maintain organisational vitality, regularly review and, if required, update the CCQM structure for it to be able to undertake its mission and best respond to the evolution of global measurement needs, by prioritising where new areas or issues should be addressed within the structure and evolving working group remits as required.

5. ACTIVITIES TO SUPPORT THE STRATEGY

The GAWG is actively engaged in activities to support the strategy of the CCQM (see section 4). Figure 3 shows the results of the survey with the institute's interest in the general objectives of the CCQM and the benefits of participation in the GAWG.

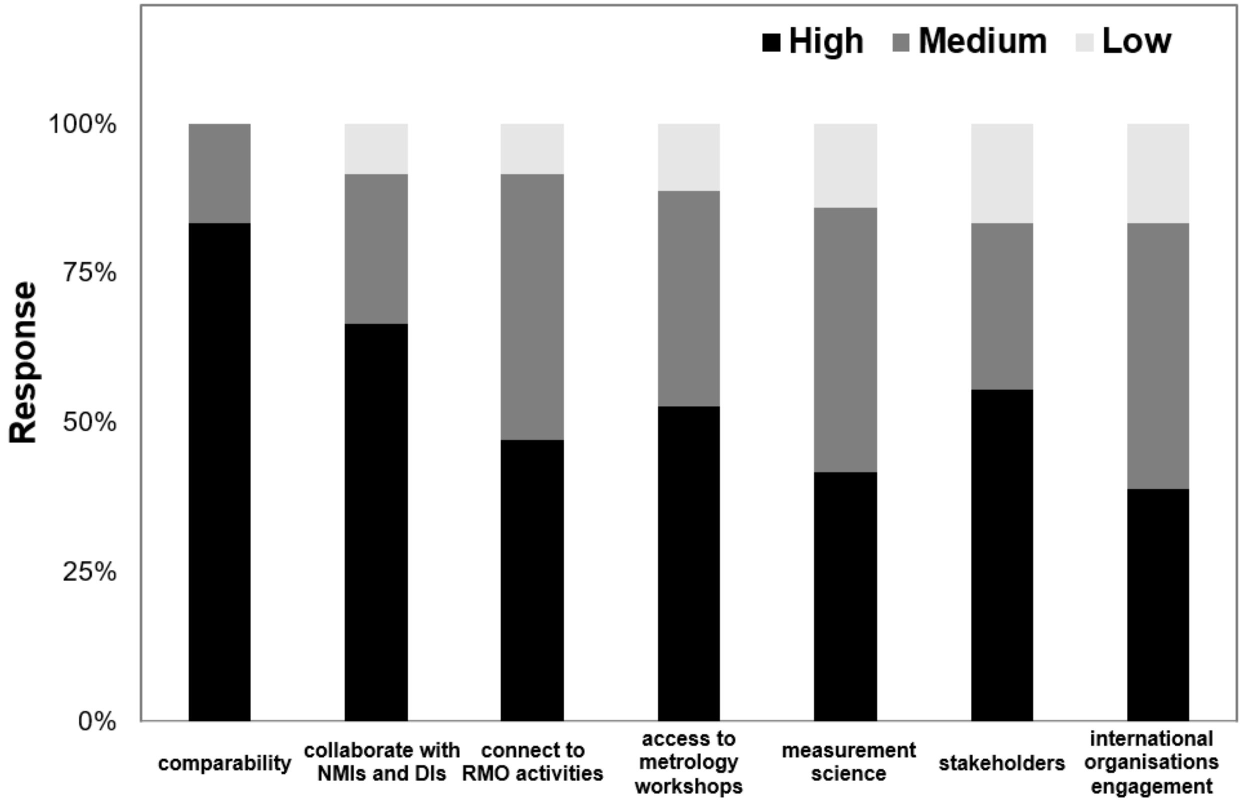


Figure 3 Interest levels in the general objectives of the CCQM and the benefits of participation in the CCQM-GAWG, as indicated by the GAWG strategy survey participants.

The objectives are shown in ranked order based on the high and medium responses to the survey. For all objectives, more than 80 % of the responses were either high or medium, representing strong support from the GAWG membership. The difference between responses to the objectives is subtle. When considering only high responses, enabling and demonstrating measurement comparability is shown to be considered as the highest priority. Collaboration with NMIs and DIs is shown to be the next highest priority followed by meeting the needs of stakeholders, access to metrology workshops, connecting to RMO activities, advancing measurement science and engaging with international organisations (shows the fewest high responses).

The GAWG strategy will respond to this in two ways. Firstly, it will continue its work programme that addresses all these objectives, meeting the requirements of its members and helping to deliver the mission of the CCQM. Secondly, it will focus on ways to refine and tailor its work programme to the members for items in figure 3 that received fewer high responses. Details of the strategy are provided in the sections which follow.

5.1. PROGRESSING METROLOGY SCIENCE

A description of the activities to be undertaken to progress the state of the art of measurement science

The strategic agenda of the GAWG will be realised with a work programme that addresses the key scientific challenges to advance the global measurement system. The GAWG has identified seven priority areas for advancing the state of the art in measurement science in accordance with points 1 and 3 of the CCQM strategy (section 4):

1. Greenhouse gas reference materials for isotope ratio

In collaboration with the Isotope Ratio Working Group (IRWG), the GAWG will play a pivotal role in establishing a robust infrastructure for gas phase reference materials for the isotope ratio of carbon dioxide for source apportionment. This will solve the demand from the advent of commercial optical spectroscopy and issues in realising the VPDB scale which has existed for several decades. This research includes an initiative on absolute isotope ratio measurements to put carbon dioxide isotope metrology on an SI basis for the first time, by addressing the issue of mass bias in Isotope Ratio Mass Spectrometry (IRMS) from various parameters, such as the isotope selectivity of the ionisation process. This science will resolve a long-standing detailed technical problem and traceability exception.

The pilot study CCQM-P204, aimed at evaluating the level of compatibility of laboratories' measurement capabilities to value assign isotope ratios in samples of pure CO_2 gas, expressed as isotope delta values relative to the relevant international scale: δ^{13}(C)VPDB and δ^{18}(O)VPDB-CO_2 was a success. It has provided invaluable insights into the traceability chains and reference standards being employed to currently achieve these measurement results. It provides a foundation for future work.

CCQM-P239 is in progress to assess laboratories' capabilities for carbon and oxygen isotope ratio for carbon dioxide in air. The BIPM laboratories are providing a key resource to initiate these activities, both in terms of sample preparation and centralised measurement facilities to coordinate these comparisons.

2. Implementation of regional greenhouse gas scales and traceability to the SI

The carbon dioxide greenhouse gas scale system, coordinated by the WMO, enables the production and value assignment of standards with a reported consistency between tertiary standards of the order of 0.02 μmol mol^{-1}, approximately a factor of 10 smaller than standards with traceability to the SI. Monitoring greenhouse gas reduction initiatives is expected to require multiple measurement sites for greenhouse gases around the world and an expected increase in demand for reference materials with the internal consistencies that can currently be achieved by the scale approach. Several NMIs are setting up such systems, which will lead to national and regional greenhouse gas scales with scale conversion equations, maintained by CIPM MRA on-going key comparisons.

The GAWG has established a task group which has developed a comparison protocol to enable the mathematical relationship between independently held sets of primary carbon dioxide in air gas reference materials, enabling dissemination on related scales with consistency at the 0.02 μmol mol^{-1} level and an on-going key comparison (BIPM-QM.K5) coordinated by the BIPM will demonstrate the maintenance or divergence of the relationship between scales based on different sets of primary carbon dioxide in air reference materials. The next focus will be methane in air standards, which will require a similar scales approach as applied to carbon dioxide, and an evolution from the CCQM-K82 and CCQM-K82.2023 comparisons that have been coordinated by the BIPM.

3. Diversification of the energy gas supply

The quality of hydrogen fuel is critical for the development of the hydrogen economy. Hydrogen fuel cells in hydrogen vehicles are incredibly sensitive to impurities (as low as 4 nmol mol^{-1} for certain components). If the quality of hydrogen is not monitored it could lead to vehicles failing on the road and would be detrimental to the introduction to market, especially at this early stage. ISO 14687 provides guidance on the required purity of hydrogen (including a maximum threshold for 13 gas impurities and particulate mass concentration). Members of the GAWG are developing accurate analytical methods and reference materials to meet these requirements. The first key comparison on hydrogen purity (CCQM-K164) is complete, assessing current capabilities and sets the scene for further scientific advances.

In addition, advances in measurement science are required to enable biomethane and hydrogen injection into the gas transmission network. Biomethane purity is a priority with international capabilities required for underpinning low-level reactive impurities (e.g. siloxanes). Challenges for hydrogen injection focus on traceability for new odorant components and purity analysis to support decisions on compatibility with existing pipeline materials.

4. Aerosol metrology

Measurements of aerosol particles, such as their optical and chemical properties, particle number concentration, size distribution, shape (morphology) and mass concentrations are well-established and vital for protecting human health and for research on climate change. They underpin and inform air quality legislation, workplace exposure, vehicle emissions (particle number concentrations now part of regulatory requirements) and the characterisation of industrial nanoparticles. Since 2015, the GAWG has provided the means for NMIs and DIs with facilities to demonstrate international comparability and address some of the requirements from stakeholders. Further work is required to improve measurement method uncertainties and comparability of particle size down to 10 nm (and beyond) and number concentration measurements, black carbon mass concentration and the characterisation of regulated components. Development and validation of new portable particle counters for gasoline and aircraft engine exhaust in collaboration with industry would be highly desirable to underpin new European and international legislation for emission control. Also, to develop methods for training and validating machine learning algorithms for particle identification and classification, including tomographic measurements for number concentration of micrometre-sized bioaerosol particles. It is also important to produce stable and well-characterised reference aerosols that simulate the properties of real aerosol particles, such as soot from aircraft and gasoline engines or tyre- and brake-wear particles. There is a requirement to design new aerosol generators which are equivalent to the dynamic gas generation capabilities used by the gas metrology community. Emerging measurands such as particle surface area and lung deposited surface area (LDSA) concentration are known to be a better proxy for the health effects of particles than particle mass or number concentration and further work is also needed to address these measurements.

5. Reactive gases

There is a pressing need for reference materials containing reactive gases such as nitrogen dioxide, hydrogen chloride and ammonia, that meet the needs for underpinning measurements of air quality and for processes in industry (e.g. airborne molecular contamination in clean rooms).

The BIPM laboratories provide an important resource for coordinating comparisons of reactive gases, notably nitrogen dioxide, nitrogen monoxide and ozone, requiring specialised facilities and extended comparison protocols to account for the stability of the components. The BIPM Capacity Building and Knowledge Transfer (CBKT) Programme supports NMIs from countries and economies with emerging metrology systems to engage more effectively in the global metrology infrastructure. Activities are focusing on knowledge transfer of Fourier Transform Infra-Red (FTIR) spectroscopy capabilities and dynamic methods for reactive gases.

Although the GAWG has made steady progress, recent comparisons (e.g. CCQM-K74.2018 and CCQM-K117) demonstrate that the science is still not fully understood and further advances are required to improve equivalence and reduce uncertainties, to meet the needs of stakeholders. Research into the chemistry of the reference mixtures and storage media is essential to making the progress required. CCQM-P172 focussed on assessing the comparability of laboratories' spectroscopic methods for trace gas quantification using nitric acid as a model system, chosen due to its presence in NO_2 gas standards as an impurity. The results provided evidence to support reproducibility of the same FTIR methods (referenced to HITRAN data) employed in different laboratories for the measurement of HNO_3 amount fractions in the 100 to 1000 nmol mol^{-1} range. They also show consistency of two different spectroscopic methods, CRDS and FTIR fitting either individual spectral lines or bands respectively and using references in spectral databases. This work provides the foundation for a new key comparison (BIPM.QM-K6) coordinated by the BIPM, which will provide on-demand access for NMIs developing NO_2 in N_2 standards worldwide starting at amount fractions of 10 µmol mol^{-1}, with requirements to extend this to 1 µmol mol^{-1} and eventually over the range (250-50) nmol mol^{-1}.

Progress has been made for non-methane hydrocarbons in recent years, however challenges remain for a broad range of components (e.g. oxygenated VOCs and terpenes) due to their reactivity. Capabilities for disseminating traceability for oxygenated VOCs in gas mixtures in the nmol mol^{-1} range will be assessed and the stability of these components studied in CCQM-K174. Halocarbons, in particular those that are newly emitted and present in the atmosphere at trace amount fractions (pmol mol^{-1}) require the development of new reference materials and key comparisons to assess their comparability.

Dynamic gas capabilities are often used to underpin measurement of reactive gases. Some are based on permeation with the rate determined with a magnetic suspension balance. A risk has been identified for the continuation of such facilities due to a single supplier of magnetic suspension balances and discontinuation of systems used by NMIs. The GAWG will focus on a solution to ensure the continuation of these capabilities.

6. Advanced spectroscopy

Traditional gravimetry and manometric approaches for generating gas reference materials can be compromised by consumable reference materials and lack of measurement sensitivity, selectivity, dynamic response and remote capability. A future focus for the GAWG will be for its members to develop optical methods scaled by invariant spectroscopic properties of molecules and atoms to measure amount fraction and isotopic abundance of gas mixtures with quantifiable systematic and statistical uncertainties required for SI traceability. This will be achieved by measuring the absorption of electromagnetic radiation corresponding to distinct wavelength-specific transitions between two assigned quantum states of the analyte. It will include diverse experimental approaches to identify origins of potential systematic biases. The GAWG will seek to collectively leverage complementary independent state-of-the-art optical techniques for consistent and accurate determination of spectroscopic constants. These techniques and value-assigned spectroscopic constants will provide experimental benchmarks for theoretical calculations and enable amount fraction measurements.

A task group was established to tackle these issues. A pilot study (CCQM-P229) on absolute line intensities of selected $^{12}C^{16}O$ transitions has been completed. It is the first of its kind and involves distinct primary measurements of amount fraction based on linear absorption spectroscopy. Participants each chose a specific spectroscopic technique and measured the overlapping sets of rotation-vibration transitions within the 3-0 vibrational band of the $^{12}C^{16}O$ isotopologue of carbon monoxide. The pilot study investigated the systematic biases between the different experimental techniques and made direct comparisons with theory. It demonstrated the feasibility of making exceptionally accurate determinations of molecular line intensities (< 1‰ relative uncertainty level) through coordinated experiments that leveraged complementary and independent primary measurements from participating laboratories. This work discussed serves as a reference case to which experimentalists using a variety of independent spectroscopic methods can compare their results and establish confidence in their assigned measurement uncertainties. Extension to other bands of carbon monoxide as well as other molecular bands that are amenable to line-by-line analysis should make possible continued advances in primary spectroscopic measurements of amount fraction, partial pressure, temperature, and isotopologue ratios.

7. New technologies

The work programme of the GAWG will align with step changes in technology to provide the measurement infrastructure to stimulate and support innovation. Analytical verification is an essential step in the primary realisation of the mole for the components addressed in the scope of the GAWG activities. Advances in measurement techniques and instrumentation are therefore fundamental to NMIs and DIs developing and improving capability. They will be studied and characterised as a by-product of key comparisons.

5.2. IMPROVING STAKEHOLDER INVOLVEMENT

A description of the activities to be undertaken to improve stakeholder involvement

The work programme of the GAWG is aligned with point 2 of the CCQM strategy (section 4) and driven by its members and the RMOs, responding to the requirements from industrial, regulatory, government and academic stakeholders for world-wide comparability of measurements of gas composition and isotope ratio and airborne particle properties in a range of matrices. The work programme of individual NMIs and DIs is driven by national priorities, focusing mostly on government policies and legislation to meet climate commitments and for the protection and sustainability of the environment. There is also substantial focus on supporting industry, such as the specialty gas industry, instrument manufacturers, atmospheric monitoring networks, organisations driving the energy transition towards decarbonisation, healthcare and advanced manufacturing. Standardisation bodies are a key stakeholder and members of the GAWG participate in the relevant committees and develop documentary standards under ISO, CEN and ASTM. The active programme in gas metrology at the BIPM is facilitating the development of collaborative activities with other international organisations with related missions, notably WMO and IAEA.

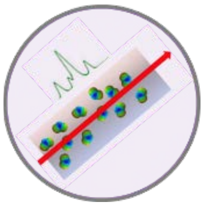
Key stakeholders and activities to be undertaken to extend engagement with these communities are described below. Mechanisms available to the GAWG to further stakeholder engagement, ordered in an increasing level of formal engagement include:

- Workshops focusing on stakeholder needs;
- NMIs and DIs that are members of GAWG transferring information to and from stakeholder communities;
- Establishment of GAWG task groups including input and involvement of stakeholder communities;
- Participation of expert stakeholder laboratories in CCQM pilot studies;
- BIPM liaisons to stakeholder organisations;
- Agreements between BIPM and stakeholder organisations enabling liaison status to CCQM and participation in the CIPM MRA and the GAWG

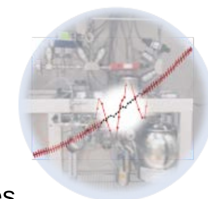
GAWG task groups

GAWG task groups are established to achieve a defined task with terms of reference. The membership usually requires expert laboratories and stakeholders. They provide a unique forum to ensure the CCQM delivers impact and meets the need of stakeholders.

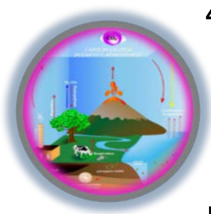
1. Ozone Cross-Section Change Management to develop a plan and timetable to allow a globally coordinated and universal implementation of the new consensus value of ozone absorption cross-section at 254 nm, CCQM.O3.2019 (J T Hodges *et al.*, Metrologia, 56 034001, (2019)).



2. Advanced Spectroscopy to develop and validate accurate spectroscopic measurements of analyte number density and isotopic abundance to provide fit-for-purpose alternatives to traditional mass and manometric-based measurement techniques, which can be limited by the availability of consumable reference materials, sensitivity, portability, selectivity and dynamic response.

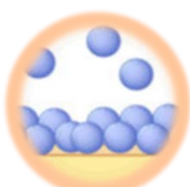


3. Greenhouse Gas Scale Comparisons to meet the future demand for gas reference materials that are traceable to the WMO scale, because of the requirement for multiple measurement sites for greenhouse gases around the world for evaluating a robust economic system based on their mitigation.



4. Isotope Ratio Metrology to build on current research advances, formalise the collaboration between NMIs and expert laboratories and provide a measurement infrastructure to underpin global measurements of source apportionment that will have enduring value.

5. Aerosol Metrology to engage with stakeholders to identify the metrology gaps, provide a framework to demonstrate capability required to meet future legislative and end user requirements and harmonise the use of terminology in the aerosol metrology community.



6. Passivation Chemistry for new knowledge and models related to adsorption and reactions of components in high pressure gas cylinders and innovative cylinder passivation chemistries for gas reference materials with enhanced stability

Climate – atmospheric monitoring community

The WMO-GAW programme coordinates a global network of stations monitoring the composition of the atmosphere. These stations focus on the long-term measurement of components that are responsible for climate change. The WMO signed a Memorandum of Understanding (MoU) with the BIPM in 2002, and the CIPM-MRA in 2010, providing a mechanism for its Central Calibration Laboratories (CCLs) for the major greenhouse gases to participate in the CIPM-MRA and the GAWG. In the intervening period, the GAWG has developed a close collaboration with the WMO GAW and plays an important supporting role in its infrastructure. NMIs and DIs active in the GAWG now provide support for the World Calibration Centres (WCCs) and CCLs for carbon dioxide, methane, nitrous oxide, monoterpenes, nitrogen oxides, dimethyl sulphide, carbon monoxide, ten halocarbons and ten non-methane hydrocarbons that lead to the formation of tropospheric ozone. Experts from the GAWG also participate in the new WMO GAW Expert Team on Measurement Quality, set up to bridge the QA/QC efforts in the different observation networks within the WMO GAW programme.

The International Atomic Energy Agency (IAEA) signed an MoU with the BIPM in 2002, and the CIPM-MRA in 2010, and is a liaison organisation of the CCQM and participates in the GAWG. The IAEA has responsibility for providing stable isotope reference materials for elements such as carbon, nitrogen, oxygen and hydrogen. The IAEA and BIPM laboratories co-coordinated a GAWG pilot study in 2020 (CCQM-P204) on isotope ratio measurements of carbon dioxide in the gas phase, the basis for atmospheric source apportionment measurements of carbon dioxide for national greenhouse gas inventories using commercial spectroscopy. NMI experts active in GAWG and the BIPM contribute regularly to the WMO-IAEA stakeholder meetings on Greenhouse Gases and Measurement Techniques (GGMT). The involvement of IAEA in GAWG and the newly formed IRWG activities follows on from issues raised in the following workshops:

- BIPM-IAEA Workshop on Carbon Dioxide and Methane Stable Isotope Gas Standards (VSL, 2013)
- BIPM Workshop on Global to Urban Scale Carbon Measurements (BIPM, 2015)
- Developments in Isotope Ratio Measurements for Gas Analysis (METAS, 2019)
- BIPM-WMO Metrology for Climate Action Workshop (Virtual, 2022)
- CCQM-GAWG Workshop on Carbon Dioxide and Methane Stable Isotope Ratio Measurements (LATU, 2023)
- 1st Stakeholder meeting of the CIPM Sectorial Task Group on Climate Change and Environment (BIPM, 2024).

Activities to be undertaken to improve stakeholder involvement in the forthcoming period include:

- In response to the recommendations from the BIPM-WMO Metrology for Climate Action Workshop, the establishment of a GAWG task group on passivation chemistry to enhance the stability of the measurement system for global atmospheric composition observations. This will address a long-standing issue of poorly understood and controlled chemical and physical processes involving the target component in compressed gas reference materials. These generally take place on the internal surface of the valve and cylinder and if uncharacterised, substantially impact the accuracy and stability of the measurement system over time.
- Continued coordination of key comparisons and pilot studies to underpin SI traceability and reference systems for greenhouse gases and provide opportunity for expert stakeholder laboratory participation;
- Experts form the NMIs, DIs and the BIPM active in GAWG continuing to interact and participate in WMO-GAW, IAEA expert meetings and WMO-IAEA GGMT activities.
- Knowledge transfer opportunities to help stakeholders better understand and utilise key aspects of metrology and improve engagement with NMIs (e.g. traceability and uncertainty propagation).

Air Quality monitoring community

Since 2015, the GAWG has organised several workshops with stakeholders from the air quality monitoring community to understand their requirements for accurate and traceable measurements including:

- Particle Metrology (BIPM, 2015)
- Standards and Measurements for Clean Air (IPQ, 2016)
- Accurate Monitoring of Surface Ozone (virtual meeting hosted by the BIPM, 2020)

The GAWG also has several members that are connected with regional Air Quality bodies, e.g. the Air Quality Reference Laboratories (AQUILA) which provides a forum for the discussion of issues associated with the comparability of measurements of ambient air quality within the European Union and is representative of similar organisations in other regions. The GAWG comparison, BIPM.QM-K1, SRPs for surface ozone, is referenced in the WMO-GAW quality guidelines for surface ozone measurement.

In the last 4 years the GAWG achieved the following:

- Completed the first key comparison on particle number and charge concentration (CCQM-K150);
- Recommended a new and published SI-traceable value and uncertainty for ozone cross-section at 253.65 nm (air), for implementation.
- Involvement in a CCQM workshop on particle metrology (virtual meeting hosted by the BIPM, 2022) which resulted in establishing a new GAWG task group on aerosol metrology to address the emerging requirements.

Activities to be undertaken to improve stakeholder involvement in the forthcoming period include:

- Continuation of the GAWG task group on ozone cross section implementation, to manage the change process for the ozone cross section value, with membership to include all stakeholder communities.
- GAWG task group on aerosol metrology to identify the metrology gaps, provide a framework to demonstrate capability required to meet future legislative and end user requirements.
- Identify new key comparisons and pilot studies to underpin SI traceability and reference systems for particle and aerosol metrology and provide opportunity for expert stakeholder laboratory participation and harmonise the use of terminology in the aerosol metrology community.
- Repeat key comparisons with lower concentration levels to meet the recommended values of the WHO guidelines (2021) that are adopted by legislation [2].

ISO and its Technical Committees

ISO technical committees develop written consensus standards, many of which describe or are related to chemical analytical measurement, including the analysis of gases. The standards are developed by experts from national member bodies of ISO, active in working groups of the technical committees. Nomination to participate as an expert in a technical committee or working group is via the national standards body. Several NMIs/DIs have their own staff as members of ISO technical committees and working groups in this way. In addition, the BIPM can apply to be a liaison organisation to relevant technical committees and working groups. The BIPM currently has this status with a small number of ISO technical committees / working groups which deal with mission critical work items and written standards, for example: ISO/TC 334 (ISO 17034 with relevance to the CIPM MRA); ISO TC12 (ISO 80000 series on Quantities and Units with relevance to the SI brochure); ISO TC 146 (Surface Ozone Standards). In addition, ISO/TC 334 is a liaison organisation of the CCQM.

A number of NMIs and NMI experts that participate in the GAWG are also active within ISO technical committees and working groups and contribute to the writing of standards on measurement techniques and analytes/measurands that are also the focus of GAWG activities, studies and comparisons. The participation of individual NMIs in ISO technical committees and working groups already provides a direct mechanism to ensure best practice in metrology is introduced into ISO standards. However, not all NMIs, and sometimes, only a few NMI experts, are active in ISO work, whereas there is a substantial interest in learning of these activities. In addition, ISO technical committees and working groups provide an extended network of organisations and parties that are often interested in the work of NMIs and could help in programme formulation and dissemination of information.

A specific involvement of GAWG members with ISO technical committees and working groups would be expected to achieve 1) knowledge transfer to NMIs and DIs on the latest information on standards development of interest to them; 2) facilitate the organisation of joint workshops between CCQM working groups and ISO technical committees on areas of mutual interest, reaching a broader group of stakeholders; and 3) ensure ISO written standards take into account the latest developments in metrology and reference measurement methods and metrological traceability.

Maintaining a permanent agenda item at the GAWG meeting to cover ISO TC work items/standards of interest, will provide:

1) an opportunity for NMIs and DIs to report on relevant ISO TC work items/standards they are contributing to;

2) consideration of current work items that may be mission critical and require additional input or specific liaison to be established;

3) prospects to organise joint events (e.g. webinars or workshops) with ISO technical committees. In 2017, the GAWG organised a workshop on experience with applying ISO/TC 158 international standards to gas analysis activities at NMIs and DIs.

ISO TCs with work items of current potential interest have been identified as:

- TC 158 (Analysis of Gases)
- TC 24/SC4 (Particle Characterisation)
- TC 146 (Air Quality) and in particular updates of ISO 13964:1998 Air quality — Determination of ozone in ambient air — Ultraviolet photometric method
- TC 197 (Hydrogen Technologies)
- TC 207/SC7 (Greenhouse gas management and related activities)
- TC 193 (Natural Gas)
- TC 334 (Reference Materials)

Specialty Gas Industry

Many GAWG members serve the specialty gas industry by providing traceability for a broad range of components. Interaction occurs via the individual NMIs and DIs offering services as well as conferences (e.g. Gas Analysis Symposium organised by the Collège Français de Métrologie) and metrology research programmes (e.g. the EURAMET European Partnership on Metrology (EPM)). The EPM programme provides a direct mechanism for linking organisations that participate in the GAWG with key industrial stakeholders. The programme funds NMIs and DIs as well as industry to partner and develop capabilities to address key challenges in environment, energy, health and industry. Organisations outside EURAMET can participate as collaborators. There are specific activities which ensure the outputs from the projects are communicated to the GAWG. This enhances the links with industry and informs the work programme to address these.

Activities to be undertaken to improve stakeholder involvement in the forthcoming period include:

- Involvement in the GAS Analysis 2026 symposium and future events. The symposium is attended mainly by the metrology community and specialty gas industry and provides an ideal platform for engagement. At the next event, a special session focused on metrology will showcase developments in measurement science achieved by the member institutes of the GAWG).
- NMI interactions with stakeholders via research programmes such as EPM (relevant examples are listed in section 5.4).

Academic Community

NMIs and DIs interact with the academic community via the EPM programme (e.g. a collaboration was formed with the University of Groningen for developing traceable reference materials for carbon dioxide isotope ratio under a project on Metrology for Stable Isotope Reference Materials).

Activities to be undertaken to improve stakeholder involvement in the forthcoming period include:

- Task group on advanced spectroscopy
- Task group on isotope ratio metrology
- Task group on aerosol metrology
- Task group on passivation chemistry
- NMI interactions with stakeholders via research programmes such as EPM (relevant examples of projects are listed in section 5.4).

To address other emerging requirements, the GAWG will aim to engage with key communities such those involved in the hydrogen economy, diversification of the energy supply and in monitoring emissions from vehicles.

5.3. PROMOTING GLOBAL COMPARABILITY

A description of the activities to be undertaken to promote global comparability including support of the CIPM MRA

Promoting global comparability is considered by the membership of the GAWG as the highest priority (figure 3). The wealth of information generated from 48 GAWG key comparisons, has informed a strategy (GAWG-19-41), for a broader application of the results, to provide evidence for the CMC review process. This strategy involves a selected number of components, matrices and amount fraction ranges (see table 1), for which several institutes have consistently demonstrated equivalence since the CCQM-GAWG was established. Track A key comparisons feature these components and are designed to test the core skills and competencies required in gravimetric preparation, analytical verification and purity analysis of gas reference materials. This aligns with point 4 of the CCQM strategy (section 4).

Components and matrix	Amount fraction range
CO, CO_2, O_2, CH_4, C_2H_6 or C_3H_8 in N_2 or air	10 µmol mol^{-1} – 500 mmol mol^{-1}
CO, CO_2, C_3H_8 and O_2 in N_2	10 µmol mol^{-1} – 500 mmol mol^{-1}
SO_2 in N_2 or air	100 µmol mol^{-1} – 500 mmol mol^{-1}

Table 1 Components and amount fraction ranges to assess core competences

CMCs for all components in table 1 are supported by the pooled uncertainty from the past three Track A comparisons, that involve a selected component and are operated approximately once every three years. This approach ensures that laboratories can maintain existing capabilities with fewer key comparisons. It also allows for focusing more resource for tackling components with a significant analytical challenge and emerging requirements, where additional work is required to meet the uncertainties driven by stakeholders. These are referred to as Track C comparisons. Track D includes all other studies (studies that are stand-alone or run in parallel to key comparisons) not intended to lead to CMCs or to support CMC claims in the KCDB, but to either progress measurement science or knowledge transfer.

The GAWG will continue to include a statement of How Far The Light Shines (HFTLS) in all key comparison reports to clarify what CMCs can be supported by participation without further evidence. This statement will be used in the review of CMCs. Such statements shall consider the relevance of the demonstrated competence for other ranges for the component(s) and matrix being subject of the key comparison, other components in the same matrix, other matrices with the same component(s), purity analysis and other competences. The statement includes a method for extrapolating the stated uncertainty in the key comparison to other amount fractions, matrices and components as appropriate. To support the CMC review, key comparison reports are accompanied by a guidance document specifying the CMCs that are supported without further evidence. Track A key comparisons can also be used to directly support CMCs for the specific component in the matrix or matrices stated in the HFTLS in the key comparison report. This use is similar as that for the Track C key comparisons. This is called the “default scheme” for underpinning CMCs.

Technology changes in gas analysis, laboratories’ funding models and staff at NMIs and DIs may impact core capabilities. Therefore, NMIs and DIs can adopt the broad claims scheme provided they meet the following four criteria:

1 Shall participate in at least three key comparisons in Track A organised by the GAWG (the same criterion applies to any new NMI or DI). This includes RMO linked comparisons.
2 Shall continue to participate in at least one key comparison in Track A every three years, when available through the GAWG. This includes RMO linked key comparisons. In some cases, the GAWG may not organise a suitable key comparison every 3 years.
3 Shall establish a link between CMCs and performance in Track A key comparisons in accordance with GAWG/09-07. A quantitative link like the one proposed by Maurice Cox (GAWG/09-07) is essential for an efficient process.
4 Shall have a quality system in accordance with ISO/IEC 17025 or ISO 17034 and a measurement capability that covers all CMCs.

If an NMI ceases to meet these criteria, it shall resubmit all CMCs for Track A within established HFTLS statements under the default scheme in the upcoming cycle for submitting CMCs. NMIs that do not meet these criteria shall use the default scheme. For ozone key comparison (BIPM-QM.K1), each NMI is expected to participate at least every eight years.

Figure 4 illustrates the importance of the three types of comparison to the membership of the GAWG. Track A comparisons are shown to be of the highest importance to the survey participants. This is expected as these comparisons support core capabilities and support a broad range of claims with a relatively small number of comparisons. Track C comparisons follow closely in the responses received. Again, this is expected as these comparisons are in place for technically challenging reference materials and calibrations that cannot be supported by Track A. These comparisons usually address emerging requirements and result in new products and services. Support for pilot studies (Track D) is shown to be much lower as often new technical areas to GAWG are operated under Track C, due to the pressing requirement to demonstrate capabilities for service provision. Also, the response may be attributed to fewer GAWG members being able to participate in Track D comparisons, as the measurement science is at a very early stage. However, for those that show interest and can participate, the results of these pilot studies are essential to the GAWG and its strategy, as they define the future direction. If successful capabilities can be demonstrated, these will move to becoming Track C and then potentially Track A comparisons.

The importance of Track A comparisons is further illustrated, from the response on the uptake of the broad claims scheme. Most institutes are either using the Track A scheme (41.7 %) or have plans for its implementation (44.4 %). The GAWG guidance for reducing the number of CMCs in the KCDB by applying broader scope CMCs is in alignment with point 5 of the CCQM strategy (section 4). It is being implemented

(36.1 % of institutes that responded stated they are considering grouping single measurand CMCs into a broader scope CMC in the KCBD). However, 63.9 % of institutes that responded were against this initiative, so more work is required to understand the motivations and provide the guidance and communication to increase the uptake.

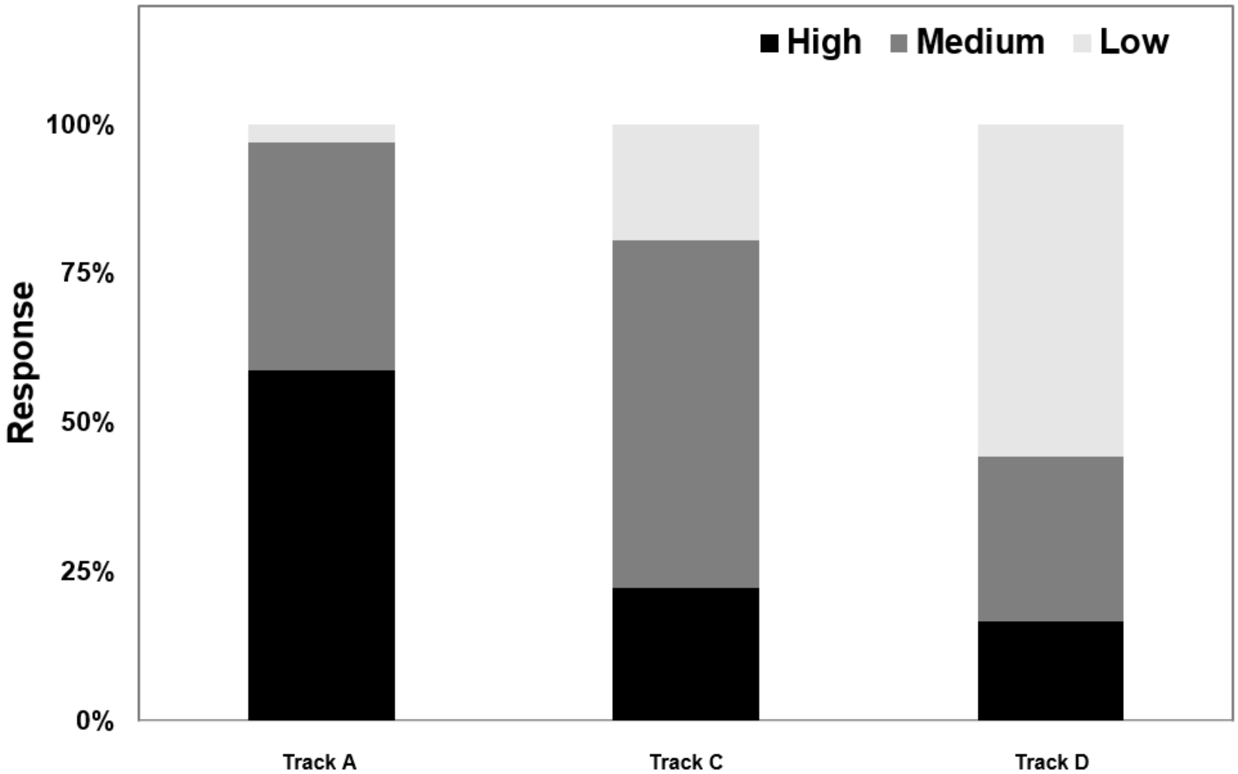


Figure 4 Interest levels in each comparison type, as indicated by the GAWG strategy survey participants.

Figure 5 shows a bar chart of the coordinating laboratories for all GAWG key comparisons and pilot studies that have been completed. It shows that the majority have been coordinated by a handful of organisations. The BIPM laboratories provide an important resource for the coordination of GAWG comparisons, in particular, for greenhouse gases and air quality gases, making use of centralised facilities to analyse and compare reference materials with minimised analytical uncertainties. A task group on future key comparisons has been effective in championing greater diversity in the coordinating laboratories and providing more opportunity to developing NMIs. The future strategic plan now includes key comparisons with three coordinators which have previously led 1 key comparison or fewer. This aligns with point 6 of the CCQM strategy (section 4). A series of guidance documents have been written to support NMIs with less experience in coordinating key comparisons. These include a guidance document for coordinating laboratories designing model 1 and model 2 key comparisons (GAWG-24-01) and a guidance document on operating CCQM-GAWG key comparisons (GAWG-20-02). A strategic goal for the GAWG is to focus more on capacity building and knowledge transfer activities. A future task group will be considered to provide strategic support (e.g. roadmaps and practical assistance) for NMIs planning to start gas metrology programmes and a collective approach towards mentoring for new key comparison coordinators.

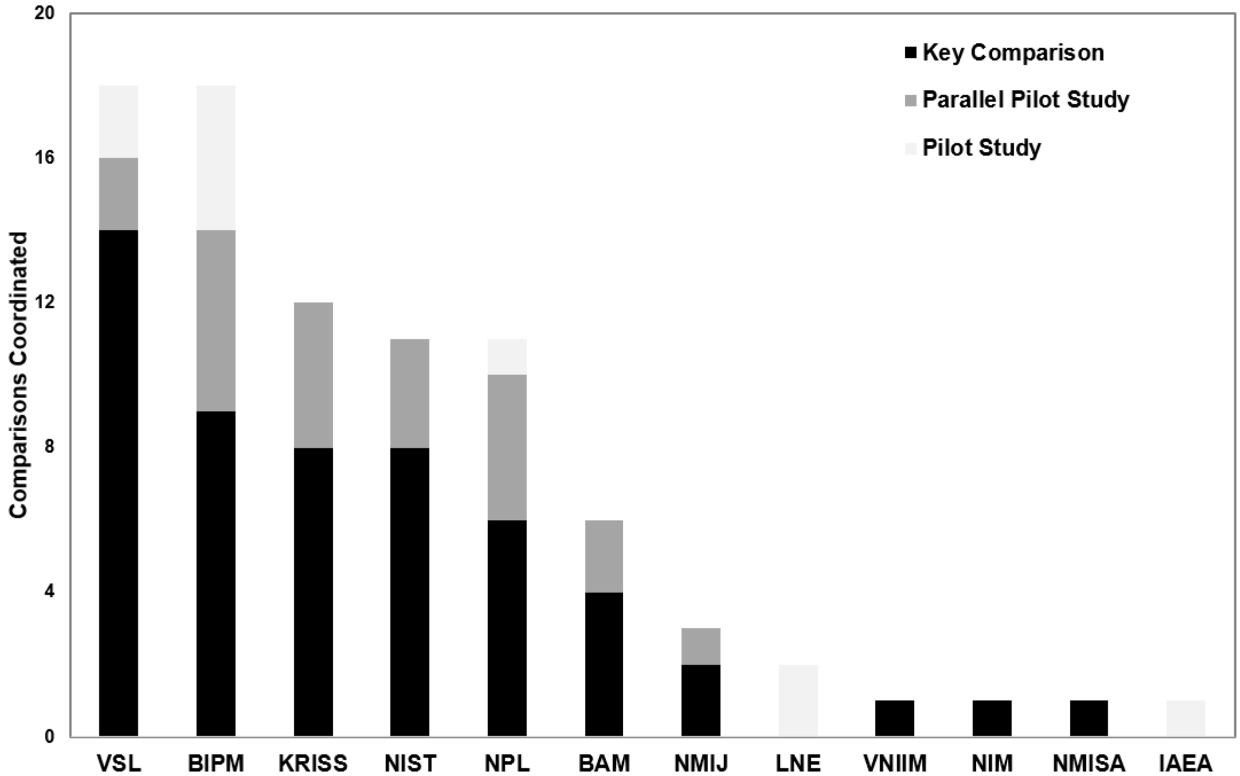


Figure 5 Bar chart showing coordinators of published key comparisons, pilot studies and parallel pilot studies.

Figure 6 shows a plan for future key comparisons and pilot studies. Track A comparisons are planned with an interval of 3 years. A cycle is set up so that all core components feature in a Track A comparison before a repeat is organised. This is to ensure coverage across all components and to accommodate laboratories that are not participating in the broad claims scheme.

The ten-year programme of GAWG comparisons foresees 36 key comparisons and pilot studies in this time period, with 4 core comparisons (Track A), meeting the strategic requirement to have one every 3 years, 6 on-demand comparisons, 23 analytical challenge (Track C) comparisons, and 3 pilot studies (Track D). The number of Track C comparisons reflects the broad range of reference materials and services from NMIs that cannot be underpinned by core comparisons alone. The plan accommodates the trends observed in figures 1 and 2, supporting members developing and increasing capabilities in the areas shown and includes the key sectors of greenhouse gases, air quality, emission gases, natural gas, breath alcohol and advanced manufacturing. The market sectors which has shown the largest projected increase in capabilities (e.g. hydrogen purity and alternative fuels) are also included. The CCQM-GAWG is also planning for the inclusion of comparisons to assess the capabilities for underpinning methane stable isotope ratio measurements for atmospheric studies in light of the growing demand in the field.

The future comparison strategy relies on utilising the specialist comparison facilities of the BIPM Laboratories, for greenhouse gases (amount fraction and isotope ratio) and reactive gases. In addition, the BIPM uniquely provides on-demand comparisons, for ozone, carbon dioxide (amount fraction and isotope ratio) and nitrogen dioxide, providing flexibility for NMI needs in this rapidly developing field. The on-demand key comparison BIPM.QM-K1, established in 2007, provides the means to assess the global comparability of ozone measurements. The on-demand comparison for carbon dioxide in air reference materials, BIPM.QM-K2, provides unique access to a Track A comparison, as well as a specialised facility for comparisons of the highest accuracy greenhouse gas reference materials. In collaboration with the IRWG, an on-demand comparison coordinated by the BIPM, BIPM.QM-K3, will provide comparisons of pure carbon dioxide at any value across the range -1 ‰ to -45 ‰ vs VPDB, with metrological traceability provided by an IRMS carbonate reference system. The range of the BIPM's comparison sample preparation facility is extendable and will also be available to support efforts at progressing measurement science and developing SI traceable calibration hierarchies for carbon dioxide isotope ratio measurements. Comparisons on isotope ratios of carbon dioxide in air will be supported by the on-demand comparison, BIPM.QM-K4, using an IRMS reference system with cryogenic extraction of carbon dioxide from air and with metrological traceability provided by a carbonate reference system maintained at the BIPM. BIPM-QM.K5 will support the development of regional CO_2 scales traceable to the global primary scale providing better access to traceability and a more robust measurement system. It will demonstrate the maintenance or divergence of the relationship between scales based on different sets of primary carbon dioxide in air reference materials. Support for methane in air scales will be supported by on-demand comparisons coordinated by the BIPM, building on the expertise developed form the work on CO_2 and the experience gained from the coordination of CCQM-K82.2023. BIPM.QM-K6, will provide on-demand access for NMIs developing NO_2 in N_2 standards worldwide starting at amount fractions of 10 µmol mol^{-1}, and extending this to 1 µmol mol^{-1} and eventually over the range (250-50) nmol mol^{-1}.

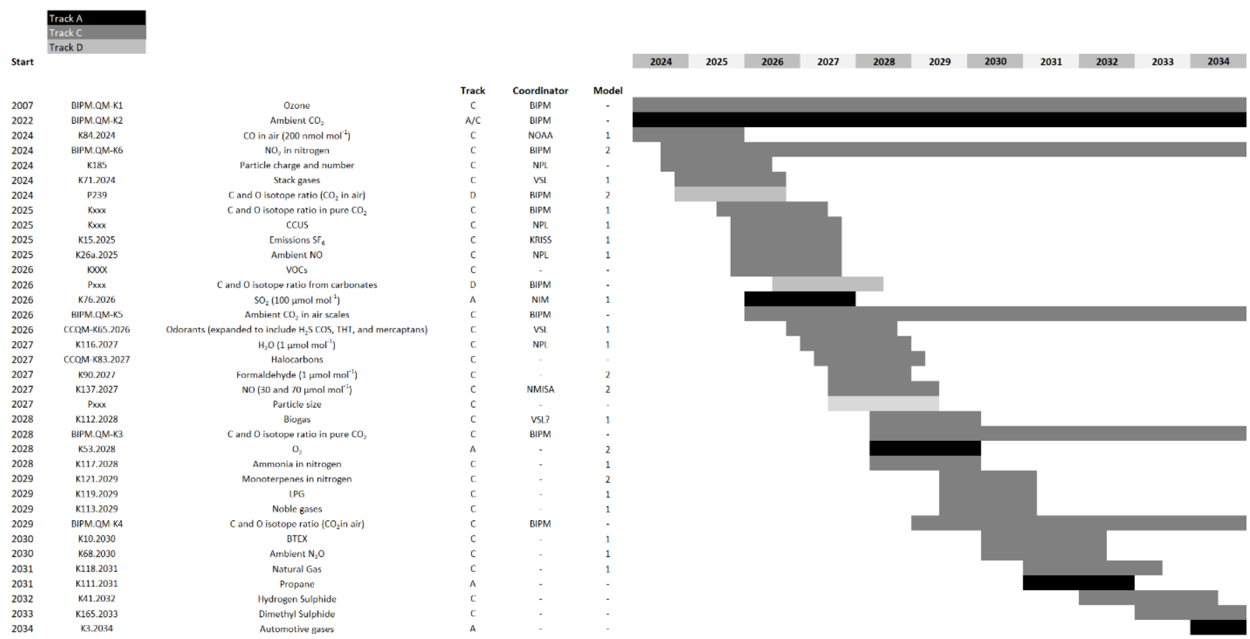


Figure 6 GAWG plan for future key comparisons and pilot studies

The GAWG recognises the importance of ensuring that the information provided by its members participating in key comparisons is consistent and complete. The GAWG will focus on developing protocols and procedures to support this and to encourage participants to produce at the level of quality required. In collaboration with the Organic Analysis Working Group (OAWG), the GAWG will develop policies on the application of performance in key comparisons to support capabilities for purity analysis. It will also set out the criteria for demonstrating a purity analysis capability required for disseminating reference materials and calibration for underpinning amount fraction.

The GAWG has established principles for when a key comparison is archived and no longer available to support CMCs. A key comparison shall be archived when a replacement is published or when a period of 15 years has elapsed since the publication of the report. A gap analysis has identified a small number of components where the results from the replacement comparison will not be available after 15 years since the publication of the original comparison. These will be monitored and dealt with on a case-by-case basis. The results from the gap analysis is shown in figure 7. The key comparisons have been divided into the different sectors. The track A comparisons are shown at the top of the figure. Grey indicates key comparisons which have been archived. Blue and green are active key comparisons representing track A and C respectively. Magenta shows the upcoming key comparisons which have not yet been published. The start of these bars is an estimated publication date. The yellow shaded region shows the period of the strategic plan (2025-2034). The analysis highlights that for odorants, SF_6, and ambient NO and SO_2, the results of the replacement comparisons will not be available 15 years after the results of the original comparison was published.

For improvements in efficiency, the GAWG will consider the application of AI to the maintenance of review of CMCs in the KCDB.

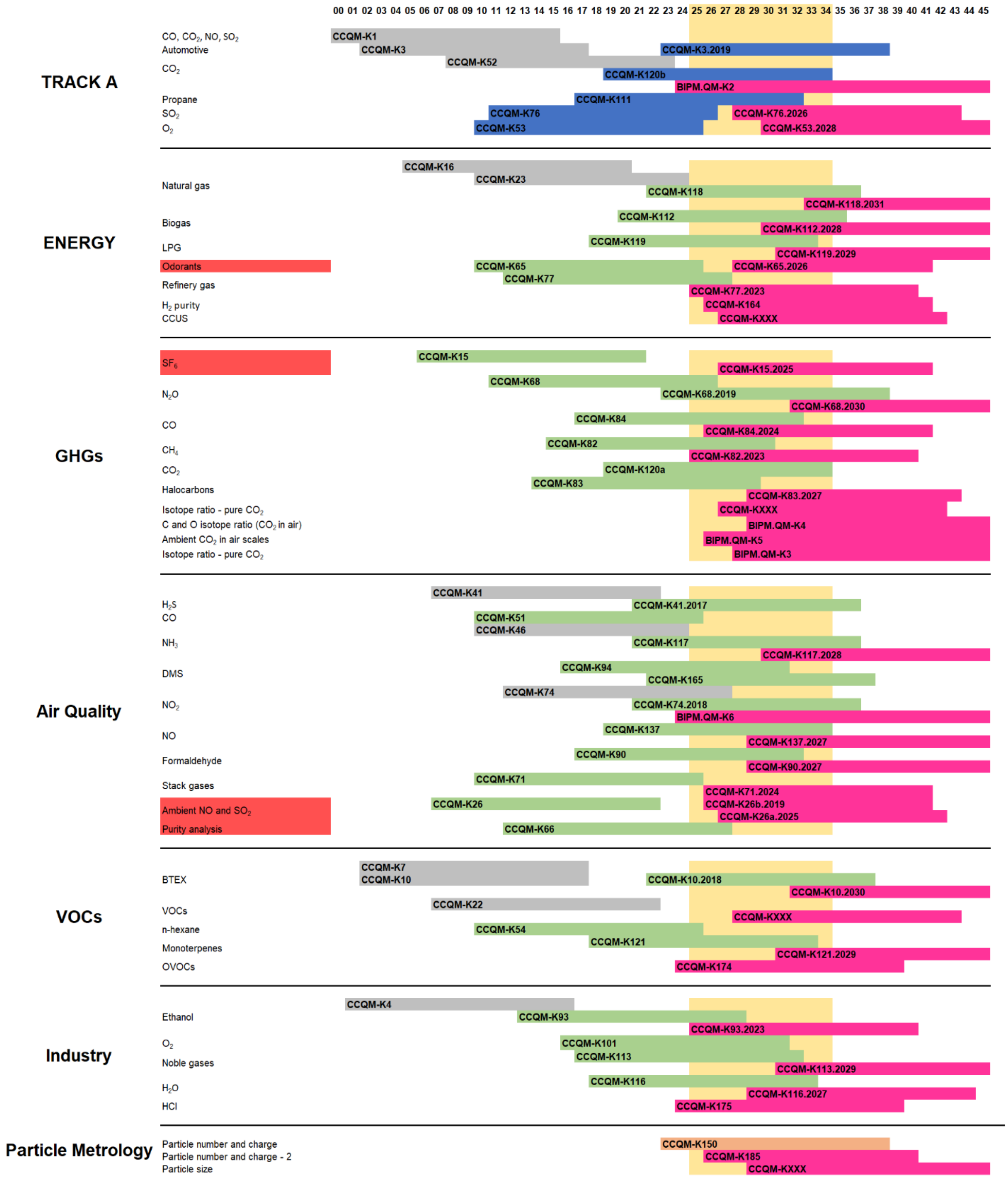


Figure 7 Gap analysis to inform future key comparisons

5.4. INTERACTION WITH RMO ACTIVITIES

A summary of RMO activities and their influence on CCQM WG Strategy and vice-versa

Support for emerging NMIs is provided from RMO activities. Most RMOs (COOMET, SIM, APMP and EURAMET) have an active programme of comparisons linked to GAWG key comparisons and supplementary comparisons, specific to the RMO, where there is limited global interest. The GAWG supports and interacts with RMOs via satellite Track A comparisons, to work with efficiency while ensuring the needs of all metrology institutes are met. It is anticipated that in future the active number of RMOs in the field of gas analysis will increase to include AFRIMETS and GULFMET.

RMO Metrology Programme for Innovation and Research

In EURAMET, the EPM programme coordinates research projects to address grand challenges, while supporting and developing the SI system of measurement units. There is an increased focus on innovation activities to target the needs of industry and accelerate the uptake of research outputs. The programme's capacity-building projects aim to bridge the gap between EU member states with emerging measurement systems and those with more developed capabilities. The programme enables European NMIs and DIs, industrial organisations and academia to collaborate on a wide variety of joint research projects within specified fields.

The programme is leading to the development of new measurement capabilities and the requirement to demonstrate the international equivalence of these is shaping the programme of key comparisons developed within the GAWG, in addition to the activities in the RMOs. The following research projects involve the GAWG:

- Metrology for European emissions verification on methane isotopes (Green Deal Call, 2022-2025)
- Metrology for the hydrogen supply chain (Green Deal Call, 2022-2025)
- Metrology Support for Carbon Capture Utilisation and Storage (Green Deal Call, 2022-2025)
- On farm quantification of ammonia and greenhouse gas emissions from livestock production (Green Deal Call, 2022-2025)
- Standardisation of black carbon aerosol metrics for air quality and climate modelling (Normative call, 2023-2026)
- Metrology for comparable and trustworthy greenhouse gas remote sensing datasets (Green Deal Call, 2025-2028)
- Metrology for hydrogen vehicles 3 (Green Deal Call, 2025-2028)
- Metrology for harmonisation of field isotope ratio measurements (Green Deal Call, 2025-2028)

The vision of EURAMET and its members is to ensure Europe has a world class metrology capability, based on high-quality scientific research and an effective and inclusive infrastructure, that meets the rapidly advancing needs of end users. European Metrology Networks (EMNs) have been established to help realise this aim and will analyse and address the metrology needs in a coordinated approach. The EMNs aim to create and disseminate knowledge, gain international leadership and recognition, and build collaboration across the measurement science community. Of the twelve EMNs that have been established, three (Climate and Ocean Observation, Pollution Monitoring and Energy Gases) are supported by the activities of the GAWG.

In SIM, Metrology for Sustainable Energy Technologies and the Environment (M4SET) project is focused on the importance of ozone measurement traceability and air-quality control standards. The project objective is to strengthen technical capacities in quality control for air quality monitoring networks in Latin

American cities and to aim for better ozone measurement traceability in cities in the region. The project includes webinars to guide the implementation process and address training needs, and comparisons using a transfer standard calibrated with the NIST SRP and subsequently calibrated against the primary SRP standard of the Air Quality Laboratory (CALAIRE) in Colombia and the National Institute of Ecology and Climate Change (INECC) in Mexico. The calibration of photometers of the participating cities against the CALAIRE and INECC SRPs will be performed.

In AFRIMETS, APMP, COOMET and GULFMET, researchers in NMIs and DIs make efforts to develop measurement capabilities and advance science in the field of gas metrology to support the establishment of national infrastructure of gas reference materials through collaboration with GAWG and NMIs/DIs in other RMOs.

RMO comparisons

To increase coverage of key comparisons organised by the GAWG, RMO comparisons linked to a Track A key comparison can be organised by an RMO for acceptance in the broad claims scheme, if it meets the criteria for linking. For example, CCQM-K111 (propane in nitrogen) Track A key comparison, is intended to underpin core capabilities and to support the broad claims scheme. GAWG organised CCQM-K111 and then linked it with APMP.QM-K111, COOMET.QM-K111, EURAMET.QM-K111 and SIM.QM-K111. GAWG has also organised CCQM-K3.2019 (automotive emission gases), another Track A key comparison which is linked with RMO comparisons in the same way. GAWG will link Track A key comparisons with RMO comparisons efficiently to enable the broad claims strategy. Only two NMIs/DIs in each RMO will participate in the key comparison and then one of these institutes will organise the RMO comparison for linking. In addition, a subsequent bilateral comparison can be organised by an RMO to support CMCs in the default scheme (direct support, instead of the broad claims scheme). RMOs are responsible for organising supplementary comparisons which support measurement capabilities for regional specific interests. Examples include analysis of impurities in pure balance gases in EURAMET, hazardous air pollutants in APMP, C_3-C_5 components in liquefied hydrocarbons in COOMET, and synthetic natural gas composition in SIM.

Workshops and focus groups

Several RMOs organise specific workshops or focus groups to address key regional sector challenges. In APMP, TCQM gas analysis experts have organised workshops annually since 2003, to exchange scientific knowledge and technical expertise and to engage with stakeholders (e.g. the specialty gas industry). As a result of an APMP NMI Directors' workshop in 2015, a Focus Group on Climate Change and Clean Air (FG CCCA) has have been formed to survey regional and national capabilities, measurement issues and needs, and determine how APMP can respond. It is also focuses on developing a multi-year work programme to address the needs for climate change and air quality in the region. The APMP FG CCCA meets annually in conjunction with the APMP TCQM Gas Analysis workshop. Its objective is to establish national measurement standards related to the climate change and clean air and exchange information on how NMIs can support national climate change and clean air bodies. The focus group also provides strategic advice and technical training to NMIs developing measurement capabilities in this area. The ultimate goal is to increase the impact of metrology on the public and society in the region by increased engagement with local and regional stakeholders.

In SIM, the NIST-SIM Engagement Opportunity provides support to NMIs or DIs affiliated with SIM. NIST supports SIM efforts to promote an integrated metrology infrastructure throughout the Americas by supporting guest researchers, calibrations services, reference materials and/or training workshops for representatives from partner institutions in the Americas.

In 2020, EURAMET organised a workshop on isotope ratio measurements for gas analysis which included participation from members of GAWG and IRWG. The aims of the workshop were to highlight novel research and advances in isotope ratio measurements for gas analysis, to promote scientific exchange amongst NMIs, DIs, expert laboratories and stakeholders and to identify future measurement requirements and opportunities.

In each RMO, there are many activities engaged with local and regional stakeholders (e.g. industry, governmental environmental agencies and research institutes) to discuss key metrological requirements. Although some issues are local, some extend to the broader GAWG community. RMOs will play a role in stakeholder engagement and where relevant, will feed this information back to the GAWG. The GAWG will work closely with RMOs to provide the technical support and metrological recommendations to the RMO stakeholders to address local as well as broader issues.

For capability building and knowledge transfer, researchers at developing NMIs have actively participated in training and education programmes provided by other organisations (e.g., The Korean Research Institute for Standards and Science (KRISS), the National Institute for Standards and Technology (NIST), and the BIPM) in order to expand their capabilities and provide measurement services to their stakeholders. This aligns with point 6 of the CCQM strategy (section 4).

ANNEX

1. GENERAL INFORMATION

Established: 1997
Number of members: 43
Number of participants at last meeting: 71 (38 in person) (October 2024)
Periodicity between meetings: 6 months
Chair: Paul Brewer (NPL), appointed April 2019
Vice Chair: Sangil Lee (KRISS), appointed April 2019
Key comparisons completed: 48
Pilot studies completed: 27
CMCs published in KCDB (up to and including 2024): 2194

The GAWG has participants from NMIs and DIs around the world as well as the BIPM, the WMO, the IAEA, the Swiss Federal Laboratories for Materials Science and Technology (EMPA), Leibniz Institute for Tropospheric Research (TROPOS), the Scripps Institute of Oceanography and Karlsruhe Institute of Technology (IMK-AAF). From these, 43 institutes have participated in key comparisons and 38 have CMCs in the KCDB. The work of the NMIs and DIs in gas analysis was established before CCQM and the development of the CIPM-MRA. The comparability of these services is now coordinated within the GAWG and promoted through the CIPM-MRA. The GAWG has performed a variety of key comparisons and pilot studies in conjunction with RMOs.

Scope

- Reference materials and calibrations for composition of components in the gas phase (binary and multi-component mixtures)
- Reference materials and calibrations for isotope ratio of components in the gas phase
- Reference materials and calibrations for composition of gas/liquid mixtures (e.g. LPG and LNG)
- Reference materials and calibrations of particles and aerosols in a gas matrix
- New measurement technologies (e.g. advanced spectroscopic techniques for absolute measurements)

Objectives

- To establish the degree of equivalence of national measurement standards maintained by NMIs in all areas of gas analysis (all areas covered by the scope).
- To assist the CCQM and the RMOs in matters related to the mutual recognition of calibration and measurement certificates issued by NMIs and DIs for all areas of gas analysis (all areas covered by the scope).
- Support the development of activities in the RMOs and provide a mechanism to ensure developing NMIs and DIs have access to Track A comparisons under the new strategy for broader application of key comparisons to CMCs in the gas analysis area, to accelerate their progression.
- To initiate in the coordination of research between NMIs and DIs aimed at improving and developing new capabilities for gas analysis (all areas covered by the scope).
- To collaborate with stakeholders, including international bodies e.g. the WMO-GAW, the IAEA and ISO within the scope agreed by the CIPM.
- To provide gas users and suppliers of services with a metrological infrastructure establishing traceability and comparability of measurement results in all areas covered by the scope. This includes provision of

a traceable infrastructure for the certified reference materials (including reference gases) and liaising with normalisation and accreditation bodies and independent NMIs.

- To give strategic advice to the BIPM Chemistry Department, especially the gas metrology group, on its work programme.

2. LIST OF PLANNED KEY AND SUPPLEMENTARY COMPARISONS AND PILOT STUDIES

Refer to the diagram in figure 6.

3. SUMMARY OF WORK ACCOMPLISHED AND IMPACT ACHIEVED (2021-2024)

In the past four years, the GAWG has published 9 key comparisons and five pilot studies. This includes a Track A comparison (CCQM-K3.2019) and the first key comparison on particle number and charge concentration (CCQM-K150). The latter compared the accuracy of different laboratories' measurements of particle charge concentration by aerosol electrometers, and particle number concentration in the CPC plateau region. Aerosol particle number concentration has recently featured in vehicle emission legislation and is becoming increasingly important in other areas such as ambient air and workplace monitoring. The GAWG has also commenced pilot studies in emerging areas such as CCQM-P204 which assessed the level of compatibility of laboratories' measurement capabilities to value assign isotope ratios in samples of pure CO_2 gas, expressed as isotope delta values relative to the relevant international scale: δ^{13}(C)VPDB and δ^{18}(O)VPDB-CO_2. A pilot study (CCQM-P229) on absolute line intensities of selected $^{12}C^{16}O$ transitions was the first of its kind and involves distinct primary measurements of amount fraction based on linear absorption spectroscopy. CCQM-P172 assessed the level of comparability of laboratories' spectroscopic methods for trace gas quantification using nitric acid as a model system, chosen due to its presence in NO_2 gas standards as an impurity. The results, provide evidence to support reproducibility of the same FTIR methods (referenced to HITRAN data) employed in different laboratories for the measurement of HNO_3 amount fractions in the 100 to 1000 nmol mol^{-1} range.

The GAWG has organised several workshops with the goal of exchanging information on research and development and connecting with stakeholders. In particular, workshops on Statistical Methods for Key Comparisons (NPL, 2022), Carbon Dioxide and Methane Stable Isotope Ratio Measurements (LATU, 2023), Green Hydrogen (LATU, 2023) and Global and National Greenhouse Gas Monitoring Initiatives (KRISS, 2024), have provided opportunities to promote scientific exchange amongst NMIs, DIs and stakeholders and ensure a clear translation of metrology intervention through to impact and uptake. The GAWG also uses its biannual meetings for members to make technical presentations on research and development activities.

Case Study 1: A new measurement infrastructure for underpinning atmospheric observations of key greenhouse gases to meet global net zero initiatives

Since the first observations of atmospheric carbon dioxide concentrations at the Mauna Loa Observatory in Hawaii in 1958, a global observing system has been established and relies on a network of measurements sites measuring background levels. This reflects the important role of this greenhouse gas as the main driver of climate through anthropogenic emissions and its strong radiative forcing, although other greenhouse gases and air pollutants also affect the climate. There is an urgent need to reduce carbon dioxide emissions. Tracking the effectiveness of policies to reduce emissions though measurement requires a much denser network of monitoring sites at regional and national levels, as reflected by the World Meteorology Organization's Integrated Global Greenhouse Gas Information System (IG3IS) project and Global Greenhouse Gas Watch (G3W) programme.

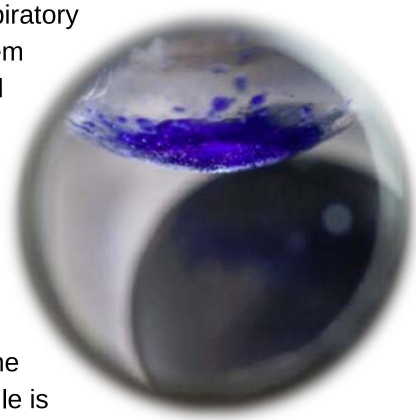
With a planned growth in monitoring comes a requirement for increased calibration standards. The metrology community, which has the capacity to support a global quality infrastructure to enable accurate measurements of greenhouse gas amount fractions and fluxes across the globe, is responding to this [5]. The GAWG has been working on increase the accessibility of greenhouse gas reference materials that will allow the provision of carbon dioxide in air refence materials that are internally consistent at the 0.02 µmol mol^{-1} level, through the establishment of local greenhouse gas scales that allow measurements to be reported on the same common scale. The programme will be supported by on-demand comparisons coordinated by the BIPM headquarters with two recently established central facilities.

The BIPM manometric system, the central facility operated for the on-demand comparison BIPM.QM-K2 of SI traceable amount fractions of carbon dioxide in air standards was launched in October 2024. This system relies on accurate pressure measurements of the initial air sample and the fraction of carbon dioxide extracted from it by cryogeny, thus providing a method independent of the gravimetric technique used by NMIs to produce gaseous reference materials. The performance of the facility has been validated within the CCQM-P225 study (2023), by comparison with independent primary standards from 6 laboratories.

The second facility consists of two ensembles of 9 carbon dioxide in air standards that make up the BIPM scales, providing a common reference point to compare other carbon dioxide scales already established, such as the WMO-CO2-X2019 scale, or under development within the member NMIs of the CCQM Task Group of Greenhouse Gas Scale Comparisons. The Task Group has already designed the protocol of the on-demand comparison BIPM.QM-K5, to establish and monitor relationships between different scales. The comparison is based on high-precision measurements of the internal consistency of standards within an ensemble using a laser-based instrument that targets the major carbon dioxide isotopologue, complemented by measurements of the isotope ratios within the standards.

Plans are in place for online access to scales relationships stored in a database to be maintained at the BIPM headquarters. Its core components have already been implemented and will be populated in 2025 with the results of the first bilateral comparisons within BIPM.QM-K5.

Case Study 2: Global implementation of a new reference value for more accurate measurements of ground-level ozone towards cleaner air



Ozone is a powerful oxidant, can impair the functioning of the human respiratory and cardiovascular systems. Ozone pollution can affect the main ecosystem services provided by terrestrial plants. Many countries have implemented ozone air quality standards for the protection of human health. Ozone also has a role in climate.

Comparable and accurate measurements of atmospheric ozone concentrations is essential for human health and the environment. There is a prevalence of standards and instruments based on the absorption of UV radiation at the mercury-line wavelength of 253.65 nm (air) for amount fraction measurements of surface ozone and the uncertainty in the value of the ozone absorption cross-section per molecule is the biggest impediment to achieving accurate and SI-traceable values from ozone reference photometers that are useful to end users. The value is an important anchor point for referencing the absorption cross-sections of ozone throughout the electromagnetic spectrum.

Research at the BIPM [6-7], provided new measurements of ozone absorption cross sections in the UV by independent methods and with the smallest reported uncertainties to date for accurate measurements of ozone in the atmosphere. In light of these advances, a GAWG task group was established to recommend an SI-traceable value and uncertainty for ozone cross-section at 253.65 nm (air). It was also charged with comparing, evaluating, and reviewing ozone absorption cross section data in the scientific literature and assessing the completeness of the uncertainty budgets to quantify possible biases in published values. The combined uncertainty and summarised the results in a publication in Metrologia in 2019 [8]. Following this, a recommendation was approved by the CCQM for a new value of the ozone absorption cross-section per molecule at 253.65 nm for applications including the measurement of atmospheric ozone amount fractions (CCQM/20-03). A workshop was held in 2020 with key stakeholders representing international standards, calibration services, monitoring networks, air quality normative aspects and ozone analyser manufacturers to develop a plan and timetable for a globally coordinated and universal implementation of the value published in 2019 for the ozone absorption cross-section at 253.65 nm. The workshop resulted in unanimous acceptance to adopt the new ozone cross section value with the nomenclature CCQM.O3.2019.

A new GAWG task group was established to oversee the implementation. Task teams focussed on aligning the timeframe with various processes in the global traceability chain, revising documentary standards and legislation, communicating the change, developing guidance and managing historic data trends. The task group has worked with a wide range of stakeholders, including environment agencies, regulators, standards writing bodies, instrument manufacturers, air quality laboratories, networks and atmospheric scientists. The new, improved reference value has been approved and implemented. This change reflects improvements in our ability to measure ozone accurately and can lead to cleaner air.

Case Study 3: Underpinning hydrogen fuel quality to support the transition towards cleaner energy

Hydrogen vehicles are a viable option for decarbonising transport, but issues around fuel quality and safety present significant challenges. By addressing market failure, the CCQM-GAWG is working to enable a promising clean energy technology to replace petrol and diesel vehicles and help meet net zero targets.

Hydrogen fuel cell vehicles require extremely pure hydrogen otherwise the fuel cell will stop working (in worst cases permanently). If hydrogen quality is not monitored, it could lead to vehicles failing on the road and would be detrimental to their introduction to market, especially at this early stage. ISO 14687 provides guidance on the required purity of hydrogen (including a maximum threshold for 13 gas impurities at challengingly low amount fractions and particulate mass concentrations) and must be followed by all European hydrogen refuelling stations as stipulated in a recent EU Directive.

The CCQM-GAWG has coordinated the first international key comparison (CCQM-K164) on hydrogen purity to evaluate the level of comparability of NMIs' and DIs' analytical capabilities for 7 impurities in hydrogen gas at nominal amount fractions close to the ISO 14687:2019 threshold. This key comparison provides laboratories with the evidence to demonstrate capability for the quality assurance measurements for the purity of hydrogen gas. This has enabled the specifications in ISO 14687 for hydrogen purity to be rigorously and traceably enforced across Europe, ensuring appropriate regulation, facilitating fair competition, and encouraging innovation in the hydrogen industry.

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5. DOCUMENT REVISION SCHEDULE

Title	Author	Changes	Date
GAWG Strategy Version 1	Paul Brewer	First draft prepared	10-07-2024
GAWG Strategy Version 2	Paul Brewer	Second draft responding to comments.	18-11-2024
GAWG Strategy Version 3	Paul Brewer	Third draft responding to comments	26-11-2024
GAWG Strategy Version 3	Paul Brewer	Fourth draft responding to comments and adding impact case studies	29-01-2025