Consultative Committee for Amount of Substance; Metrology in Chemistry and Biology
Gas Analysis Working Group
Strategy for Rolling Programme Development (2021-2030)

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.

In the next 10 years, 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 and airborne molecular contamination in clean rooms.

The strategic agenda 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 (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, particle metrology to underpin new measurands, measurement capabilities and reference materials to underpin challenging 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 (for example there is potential to collaborate with Consultative Committee for Thermometry on metrology for climate action).

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 WMO-GAW 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 World Meteorological Organisation's Global Atmosphere Watch (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 of the Essential Climate Variables identified by the Global Carbon Observing System (GCOS) of the WMO 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, the large range of particle sources (from the directly-emitted to those 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.

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, anions and cations and major metals (lead, arsenic, cadmium, mercury, nickel). In recent years, the GAWG has stepped up its programme on particle metrology and has coordinated the first key comparison on particle number and charge concentration.

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).

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 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 and ammonia.

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 feasible 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 simple and 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 a requirement for reproducible, accurate and traceable breath sampling and measurement methods. The GAWG has a vital role to play in the heath sector by enabling non-invasive devices for early diagnosis and developing a database for breath analysis and personalised medicines by providing the means to underpin impurity measurements for a range of medical gases produced by the specialty gas industry.

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 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.

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 this strategy document, a survey was prepared and distributed to the membership of the GAWG. 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 in the forthcoming period. 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.

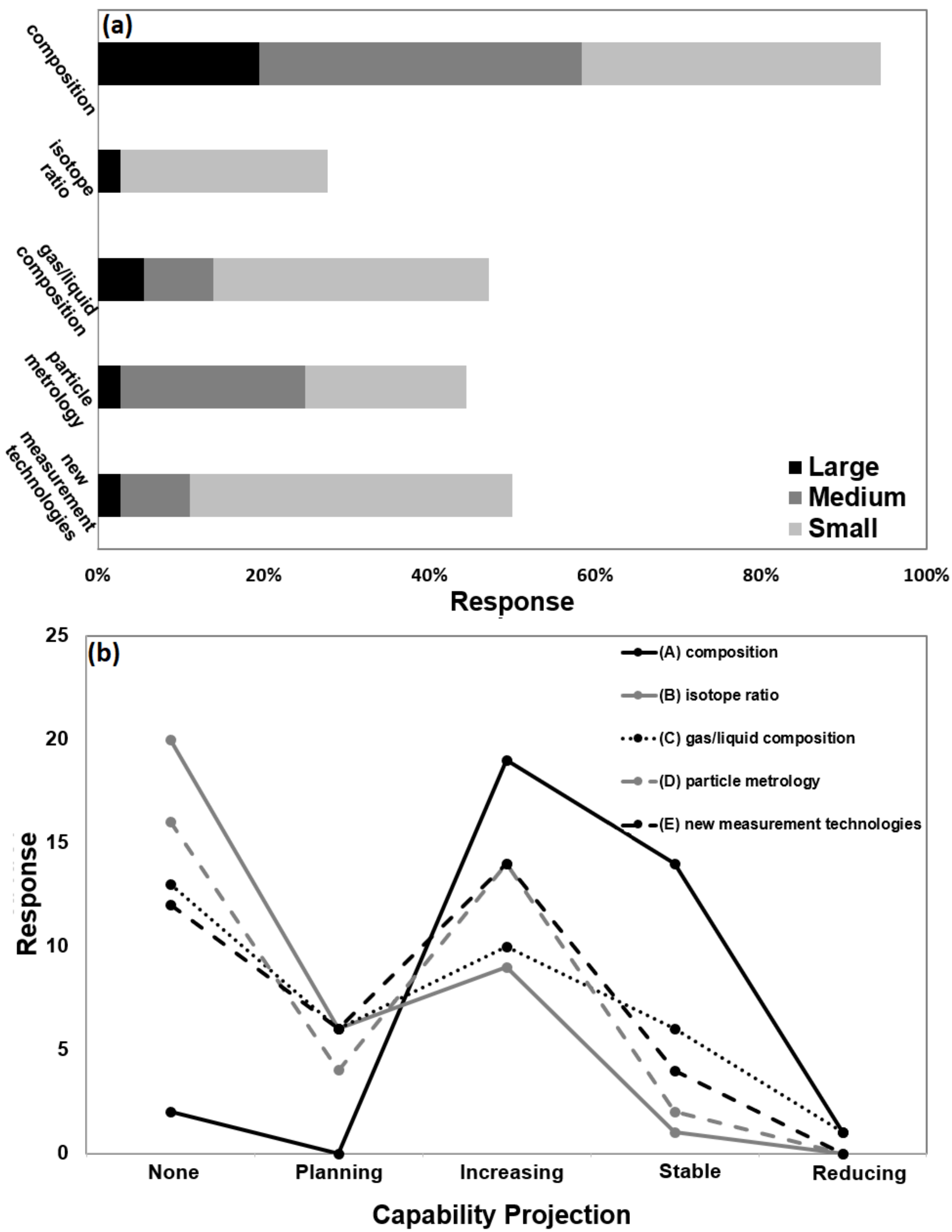

Figure 1 Institute's programme size (a) and future projection (b) against five measurement capabilities, as indicated by the GAWG strategy survey participants.

Figure 2 shows the 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.

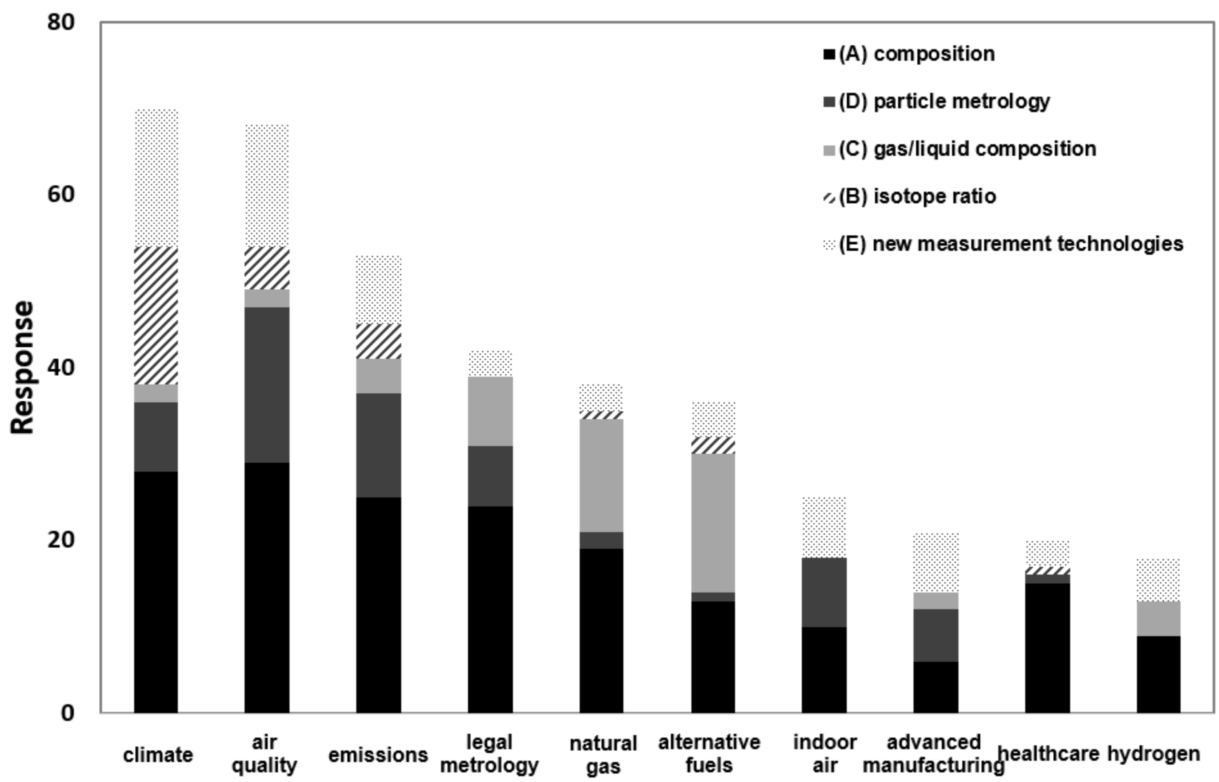

Figure 2 Application of the five measurement capabilities against the sectors described, as indicated by the GAWG strategy survey participants.

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 was 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 nanoparticles in indoor and urban air). 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, the 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.

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.

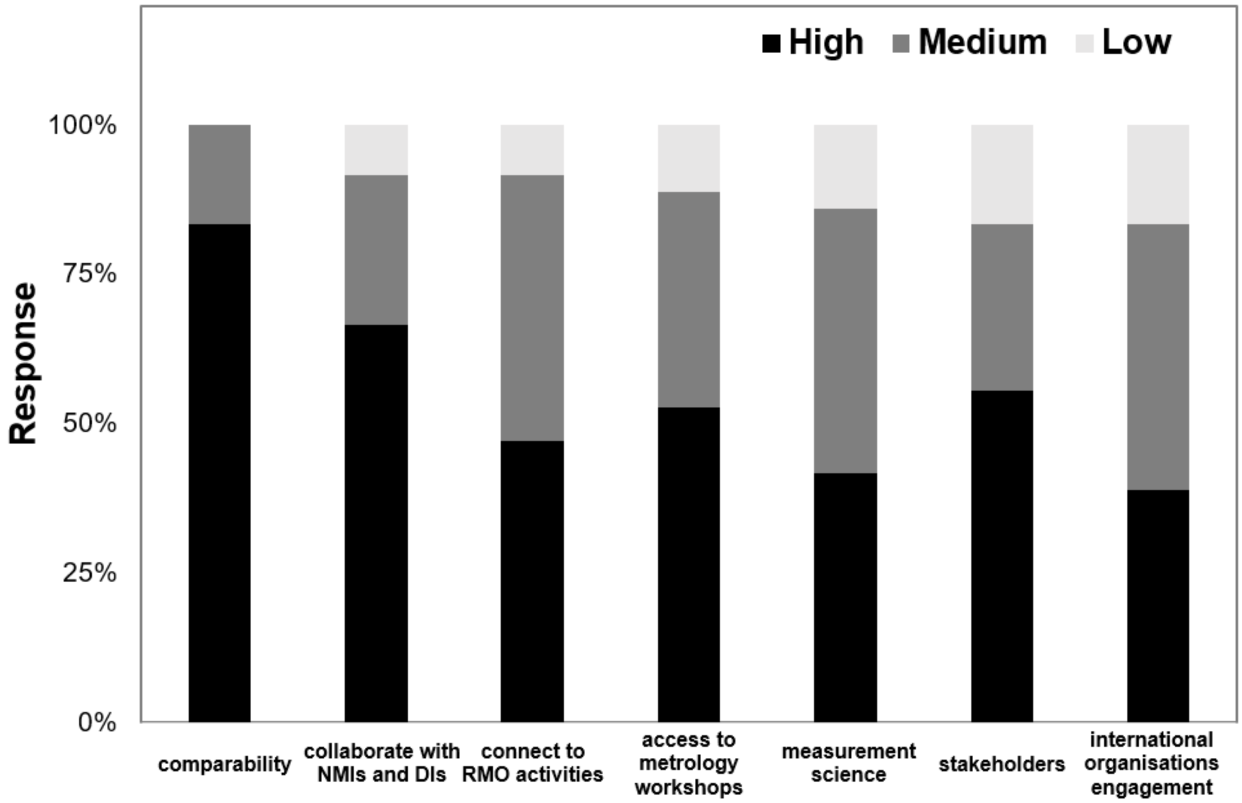

Figure 3 Interest in the general objectives of the CCQM and the benefits of participation in the CCQM-GAWG, as indicated by the GAWG strategy survey participants.

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 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.

CCQM-P204 is in progress to assess laboratories' capabilities for realising the VPDB scale for carbon and oxygen isotope ratio in pure carbon dioxide. A future study is planned 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 $\mu mol\ mol^{-1}$, 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 looking at the feasibility of setting up such systems, which could lead to national and regional greenhouse gas scales with scale conversion equations, maintained by CIPM MRA on-going key comparisons.

The GAWG has ambitions to establish a task group and develop 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 $\mu mol\ mol^{-1}$ level and an on-going comparison that will demonstrate the maintenance or divergence of the relationship between scales based on different sets of primary carbon dioxide in air reference materials. In addition, an on-going key comparison (BIPM-QM.K5) is planned that will be coordinated by the BIPM to demonstrate the maintenance or divergence of the relationship between scales based on different sets of primary carbon dioxide in air reference materials.

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) will assess current capability and set 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. Particle 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 mechanism 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 methods uncertainties of particle mass, size and number concentration measurements and the characterisation of regulated components.

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, ozone and formaldehyde, 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, 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. A current pilot study CCQM-P172, focuses on assessing the comparability of laboratories' capabilities to value assign the amount fraction of nitric acid in mixtures of nitrogen dioxide in nitrogen by spectroscopic methods. This is important because nitric acid is present as an impurity and influences the uncertainty. Further work will focus on understanding the stability of nitrogen dioxide in high pressure cylinders and a future key comparison is planned for 2024.

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. In a planned key comparison (CCQM-K174), 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. 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.

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. Initially the GAWG is seeking relative combined uncertainties of < 0.5 %, with longer-term goals at 0.05 % level. The GAWG has plans to establish a task group to tackle these issues and potentially organise a pilot study to assess current capabilities.

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 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

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 and eight 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 are co-coordinating 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 gatherings 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)

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

- Input and participation in the BIPM Climate Metrology Symposium planned for 2022;
- The establishment of a GAWG task group on greenhouse gas scale comparisons, which would lead to the development of: procedures for carbon dioxide in air scale establishment, maintenance and value transfer, validated by measurements performed by members of the task group; a comparison protocol to enable the mathematical relationship between independently held sets of primary carbon dioxide in air standards to be developed, enabling dissemination of standards on related scales with consistency at the 0.02 $\mu mol\ mol^{-1}$ level; a protocol for an on-going comparison that will demonstrate the maintenance or divergence of the relationship between scales based on different sets of primary carbon dioxide in air standards; documented characteristics and quality criteria for carbon dioxide in air standards and ensembles, including scrubbed whole air matrix gases and data handling systems, for their suitability for greenhouse gas scale development, maintenance and dissemination.

- 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 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.

Two GAWG task groups on particle metrology and ozone cross-section, both established in 2015, have completed their work including stakeholder engagement, and achieved the following:

- Identified key issues for making measurements of black carbon and elemental carbon comparable and traceable, and set out a way forward in the form of a roadmap;
- Organisation of 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

The GAWG comparison, BIPM.QM-K1, SRPs for surface ozone, is referenced in the WMO-GAW quality guidelines for surface ozone measurement.

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

- The establishment of a GAWG task group on ozone cross section implementation, which will be created to manage the change process for the ozone cross section value, with membership to include all stakeholder communities. It is estimated that the change process may take between three to five years to complete, noting that documentary standards and air quality regulations will require updating as part of the change process. A detailed plan and roadmap for the change process will be developed by the task group.
- 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.

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 REMCO (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 REMCO 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 in 2020 have been identified as:

- TC 158 (Analysis of Gases)
- 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)
- REMCO (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 Netherlands Standardisation Institute (NEN) and ISO) and metrology research programmes (e.g. the EURAMET European Metrology Programme for Innovation and Research (EMPIR)). The EMPIR 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 2021 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 EMPIR (relevant examples are listed in section 5.4).

Academic Community

NMIs and DIs interact with the academic community via the EMPIR 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).

NMIs and DIs within the GAWG determine amount fractions of gases based on the knowledge of atomic weights which is reported biannually by IUPAC, as these laboratories typically do not determine isotopic compositions and the atomic weights in their own facilities. The GAWG will continue to play a vital role in recommending to the Commission on Isotopic Abundances and Atomic Weights (CIAAW) of IUPAC as one of the stakeholders that appropriate uncertainties are established and used for atomic weights within the gas community.

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

- Task group on advanced spectroscopy
- NMI interactions with stakeholders via research programmes such as EMPIR (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 38 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.

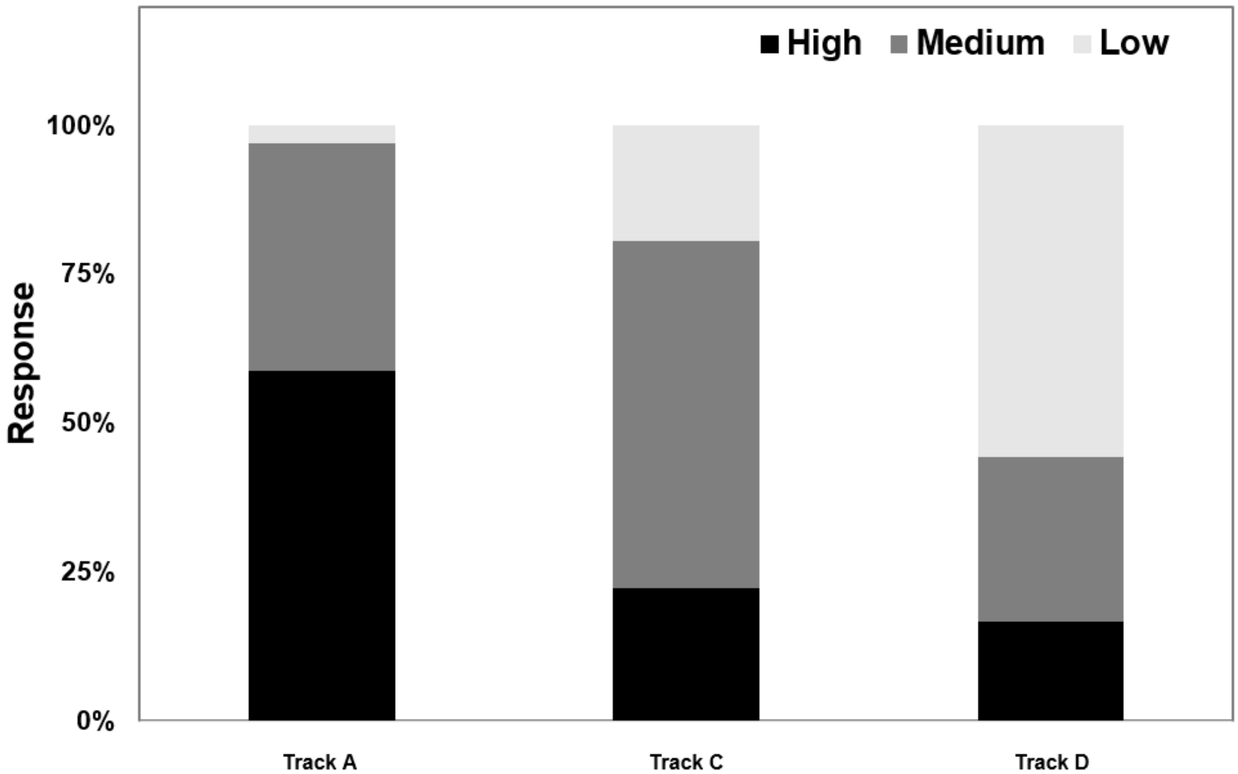

Figure 4 Interest in each comparison type, as indicated by the GAWG strategy survey participants.

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 new task group on coordinating future key comparisons has been established to champion greater diversity in the coordinating laboratories and provide more opportunity to developing NMIs. This aligns with point 6 of the CCQM strategy (section 4).

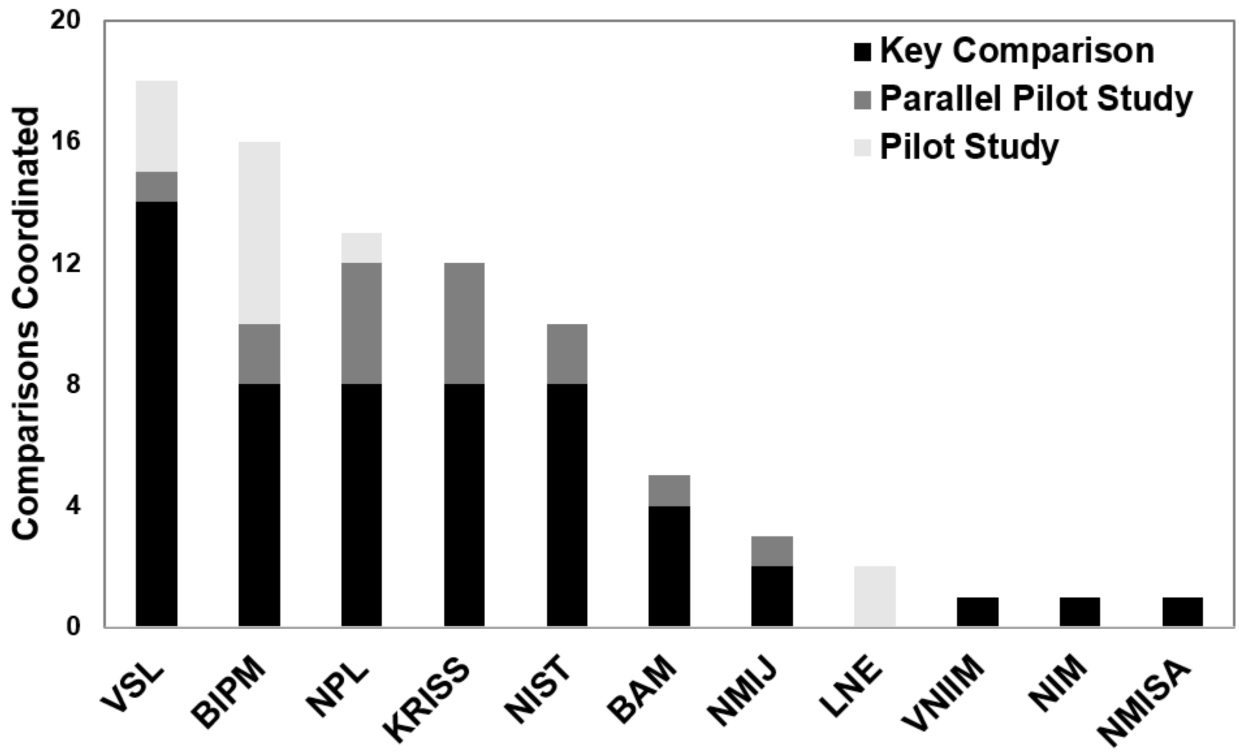

Figure 5 Bar chart showing previous coordinators of key comparisons, pilot studies and parallel pilot studies.

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 28 comparisons in this time period, with 4 core comparisons (Track A), meeting the strategic requirement to have one every 3 years, and 23 analytical challenge (Track C) comparisons, and one pilot study (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 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 and carbon dioxide in air (amount fraction and isotope ratio), providing flexibility for NMI needs in this rapidly developing field. The on-going comparison for carbon dioxide in air reference materials, BIPM.QM-K2, provides unique access to an on-demand 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-going comparison coordinated by the BIPM, BIPM.QM-K3, will allow on-demand 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-going 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.

Track A / Track C / Track D

Start			Track	Coordinator	Model
-	**BIPM.QM-K1**	**Ozone**	**C**	**BIPM**	**-**
2021	**K175**	**HCl in N_2**	**C**	**KRISS**	**1**
2021	**K174**	**Oxygenated VOCs (100-200 nmol mol^{-1})**	**C**	**VSL**	**1**
2022	Pxxx	Preparation for BIPM.QM-K2	D	BIPM	2
2022	BIPM.QM-K2	Ambient CO_2	A/C	BIPM	-
2022	**K171**	**CO in N_2 (100 µmol mol^{-1})**	**A**	**VNIIM**	**2**
2023	Pxxx	C and O isotope ratio (CO_2in air)	D	BIPM	-
2023	Pxxx	Ambient CO_2 in air scales	D	BIPM	-
2023	K82.2023	Ambient CH_4	C	BIPM	2
2023	K84.2023	CO in air (350 nmol mol^{-1})	C	tbc	1
2023	K93.2023	Ethanol in nitrogen	C	NPL	2
2024	BIPM.QM-K3	C and O isotope ratio in pure CO_2	C	BIPM	-
2024	Kxxx	Ambient SF_6	C	KRISS	1
2024	K74.2024	NO_2 in nitrogen	C	BIPM	2
2025	Kxxx	CH_4 (100 µmol mol^{-1})	A	tbc	1
2026	K116.2026	H_2O (1 µmol mol^{-1})	C	NPL	1
2026	BIPM.QM-K4	C and O isotope ratio (CO_2in air)	C	BIPM	-
2026	BIPM.QM-K5	Ambient CO_2 in air scales	C	BIPM	-
2027	K90.2027	Formaldehyde (1 µmol mol^{-1})	C	BIPM	2
2027	K137.2027	NO (30 and 70 µmol mol^{-1})	C	tbc	2
2027	K118.2027	Natural gas	C	tbc	1
2028	K53.2028	O_2	A	tbc	2
2028	K117.2028	Ammonia in nitrogen	C	tbc	1
2029	K121.2028	Monoterpenes in nitrogen	C	tbc	2
2029	K119.2029	LPG	C	tbc	1
2029	K113.2029	Noble gases	C	tbc	1
2030	Kxxx	Odorants	C	tbc	2
2030	K10.2030	BTEX	C	tbc	1
2030	K68.2030	N_2O	C	tbc	1

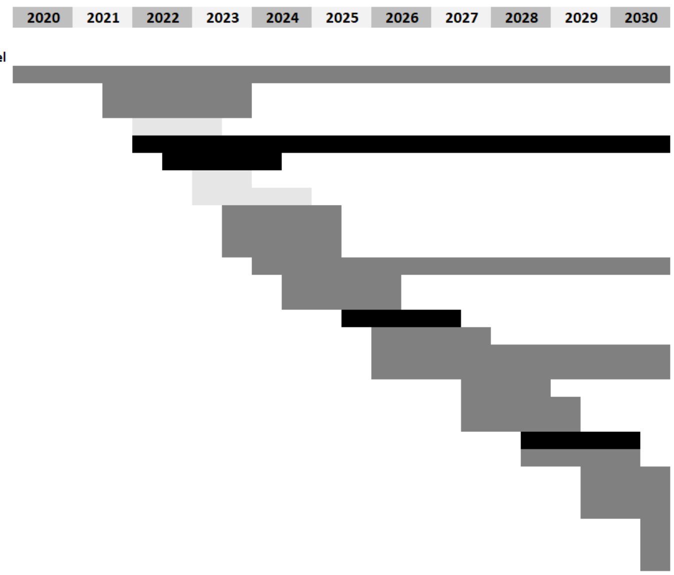

Figure 6 GAWG plan for future key comparisons and pilot studies (bold text represents those already approved by the CCQM).

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.

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 EMPIR 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 hydrogen vehicles (Energy Call, 2017-2020)
- Metrology for biomethane (Energy Call, 2017-2020)
- Metrology for light absorption by atmospheric aerosols (Environment Call, 2017-2020)
- Metrology for nitrogen dioxide (Environment Call, 2017-2020)
- Metrology for stable isotope reference standards (Environment Call, 2017-2020)
- Aerosol metrology for atmospheric science and air quality (Environment Call, 2017-2020)
- Metrology for airborne molecular contaminants II (Industry Call, 2018-2021)
- Metrology for hydrogen vehicles 2 (Energy Call, 2020-2023)
- Stable isotope metrology to enable climate action and regulation (Environment, 2020-2023)
- Metrology for climate relevant volatile organic compounds (Environment, 2020-2023)
- Advanced aerosol metrology for atmospheric science and air quality (Environment, 2020-2023)
- Improved vehicle exhaust quantification by portable emission measurement systems metrology (Environment, 2020-2023)

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 six EMNs that have been established, two (Climate and Ocean Observation 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

In order 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 will be 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: 42
Number of participants at last meeting: 64 (September 2020)
Periodicity between meetings: 6 months
Chair: Paul Brewer (NPL), appointed April 2019
Vice Chair: Sangil Lee (KRISS), appointed April 2019
Key comparisons completed: 38
Pilot studies completed: 25
CMCs published in KCDB (up to and including 2020): 2460

The GAWG has participants from 41 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 (2017-2020)

In the past four years, the GAWG has published 10 key comparisons and four parallel pilot studies. This includes the first Track A comparison (CCQM-K111) since the launch of the scheme for broad CMC claims. It has also commenced key comparisons in emerging areas such as the key comparisons on particle number and charge concentration (CCQM-K150) and hydrogen purity (CCQM-K164).

The GAWG has organised several workshops with the goal of exchanging information on research and development and connecting with stakeholders. In particular, workshops on New Measurement Challenges in Gas Analysis (IPQ, 2016), Experience with Applying ISO/TC 158 International Standards (VSL, 2017), Cutting-Edge Research for Gas Metrology (CENAM, 2018), Developments in Isotope Ratio Measurements for Gas Analysis (METAS, 2019) and Accurate Monitoring of Surface Ozone (virtual meeting hosted by the BIPM, 2020) have provided opportunities to promote scientific exchange amongst NMIs and DIs and understand and respond to stakeholder requirements. The GAWG also uses its biannual meetings for members to make technical presentations on research and development activities.

There have been a range of research and development activities stimulated by comparisons, for example:

CCQM-K120.a,b (Carbon dioxide in air) , with publications (in Analytical Chemistry [1,2]). The first describes novel calibration methods and reference materials for carbon and oxygen isotope ratio measurements of carbon dioxide in air and enables accurate corrections to carbon dioxide in air amount fraction measurements with laser-based instrumentation. The second reveals the importance of pressure of the reference material on amount fraction. Progress in reducing uncertainties in SI traceable reference materials has led to a key comparison reference value for carbon dioxide in air amount fractions with state-of-the-art uncertainties of parts in 10^4.

Case Study 1: New Generation Reference Materials for Greenhouse Gas Monitoring

In the spring of 2015, the World Meteorological Organisation (WMO) reported that the global average amount fraction of carbon dioxide crossed the 400 μmol mol^{-1} threshold. The study of isotopic composition of carbon dioxide in the atmosphere permits the identification of sources and sinks of carbon at the local, regional, and global scale, and contributes to the understanding of their relative impacts on atmospheric amount fractions.

Over recent years the introduction of Isotope Ratio Infrared Spectroscopy (IRIS), based on various spectroscopic techniques, has revolutionised stable isotope analysis in the atmosphere, allowing in-situ field measurements of the isotope ratio of carbon dioxide in air, performed in real time directly on the air sample without separation of carbon dioxide from air. Techniques that can be used include tunable diode laser absorption spectroscopy, quantum cascade laser absorption spectroscopy, cavity ring down spectroscopy, off-axis integrated cavity output spectroscopy and Fourier transform infrared spectroscopy. At the same time the techniques are also used to measure carbon dioxide amount fractions, and for the most accurate measurements calibration gases need to have their isotope ratios of the carbon dioxide value assigned, either by sourcing air from natural sources [3,4] or by blending carbon dioxide gases from different sources to achieve close to atmospheric ratios [5].

The equivalence of the next generation of carbon dioxide in air reference materials that meet these requirements was addressed in the CCQM-K120.a and b comparisons, during which 46 reference materials were compared.

As part of the preparation for the comparison, methods to accurately calibrate optically based instruments for $\delta^{13}C$ and $\delta^{18}O$ measurements were developed and their performance validated [1]. In particular, it was demonstrated that using only two mixtures with the same delta values and different amount fractions, bracketing the amount fractions to be measured, $\delta^{13}C$ and $\delta^{18}O$ values can be measured with uncertainties of 0.1 ‰ and 1.0 ‰ respectively. The comparison supports the development of the next generation of greenhouse gas reference materials, which will be valued assigned for carbon dioxide amount fraction and isotope ratio and matrix matched to atmospheric compositions, providing instrument manufacturers and atmospheric scientists with the reference materials required to monitor carbon dioxide amount fractions and isotope ratios accurately in real time. The activities have improved the state of the art in measurement science, benchmarked comparability and supported NMIs in working towards addressing the needs of stakeholders. This has enabled benchmarking of international comparability and provided support for a change to the global scale.

BIPM.QM-K1 (Ozone), with publications (in Atmospheric Measurement Techniques [6], 2015 and Analytical Chemistry [7], 2016) providing 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. Further work [8] resulted in a CCQM recommendation 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).

Case Study 2: A New Recommended Value for the Ozone Cross Section at 253.65 nm

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 task group conducted a scientifically rigorous strategy to yield the recommended cross section and 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. The community commits to making the change in the next 3-5 years and a new GAWG task group is being established to oversee the implementation.

CCQM-K116 (Water vapour in nitrogen) demonstrated for the first time, measurement capabilities for disseminating traceability for water vapour in high pressure cylinders which is immensely challenging due to stability and adsorption loses of the target component to the wall of the storage vessel. It also provided comparison of two realisations (amount of substance and dew point). This work led to developments on a new method for negating the impact of adsorption in gas reference materials [9].

CCQM-K150 and P189 (Particle number and charge concentration) The first comparison to compare 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.

In 2019, to mark the 25th anniversary of the CCQM, the GAWG published a review paper entitled Advances in Reference Materials and Measurement Techniques for Greenhouse Gas Atmospheric Observations [10].

The GAWG establishes task groups to drive forward measurement science and understand requirements from stakeholders. The following task groups were created after 2016 and their work has been completed:

- Strategy for Particulate Comparison to plan the first key comparison on particle number and charge concentration.
- Black Carbon to identify key issues for making measurements of black carbon and elemental carbon comparable and traceable, and to set out a way forward, in the form of a roadmap.
- Ozone cross section with the task of recommending a value and uncertainty for the ozone cross section at 253.65 nm to be used in ozone reference photometers and for comparisons of these standards in BIPM.QM-K1.
- Strategy for CMC Claims, resulting in the publication of strategy document GAWG/19-41.

The following task groups are in progress:

- Purity Analysis to develop a guidance document on the approach of the GAWG towards purity analysis and CMC claims
- Coordinating key Comparisons to champion greater diversity in the coordinating laboratories of key comparisons and providing development opportunities to less experienced NMIs and DIs. The task group is considering the mechanisms for comparisons and the terms of reference and aligns with the CCQM strategy (section 4).

There are plans in place for future task groups on advanced spectroscopy, greenhouse gas scales and implementation of a new value for ozone cross section.

The GAWG has interfaced with the RMOs through its programme of comparisons and research activities. In EURAMET, the EMPIR programme coordinates research projects to address grand challenges and the GAWG has been involved in the following:

- Metrology for hydrogen vehicles
- Metrology for Biomethane
- Metrology for light absorption by atmospheric aerosols
- Metrology for nitrogen dioxide
- Metrology for stable isotope reference standards
- Aerosol metrology for atmospheric science and air quality
- Metrology for Airborne Molecular Contaminants II

It has also contributed to European Metrology Networks on Climate and Ocean Observation and Energy Gases 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.

RMOs organise specific workshops or focus groups to address key regional sector challenges. The GAWG has collaborated with the APMP Climate Focus Group on Climate Change and Clean Air which meets annually in conjunction with the APMP Gas Analysis meeting. In 2020, EURAMET organised a workshop on isotope ratio measurements for gas analysis which included participation from members of the GAWG and IRWG.

The work programme of the GAWG has predominantly focused on benchmarking and developing the metrology capability for environmental protection and regulation. More recently, with the energy transition towards decarbonisation becoming a reality, efforts in energy gases have increased.

Case Study 3: Diversification of the gas supply

As worldwide natural gas resources are declining and the quest for decarbonisation is driving the energy transition, there is a growing interest in exploiting alternatives (e.g. biomethane and liquefied natural gas) to the use of conventional natural gas [11].

In the GAWG, several projects were initiated to address the need for assessing the comparability of novel reference materials and calibration methods. The projects (CCQM-K1efg, CCQM-K16, and CCQM-K23) all focused on natural gas. The values and uncertainties for the amount fractions of the components as obtained from gravimetric gas mixture preparation, were used as key comparison reference values. The key comparison CCQM-K77 aimed at assessing the comparability of measurement results for the composition of refinery gases. These gases are a by-product in the processing of crude oil and rich of hydrocarbons. The measurements are generally more challenging than those for natural gas, for these gases contain also unsaturated hydrocarbons, which are not saturated on gas chromatographs configurations designed for natural gas.

A second project addressing a natural gas substitute is CCQM-K112 Biogas. Biogas is very rich in carbon dioxide and nitrogen, and usually contains 0.3 % -- 0.6 % oxygen and approximately 1 % hydrogen. The results of the key comparison underlined the challenges with measuring the amount fraction of oxygen in energy gases. The comparison is operated using key comparison reference values from analysis, thus permitting to use transfer standards prepared by a third party. This design has been explored to see whether it leads to a reduction in the costs associated with the coordination and operation of a key comparison. At around the same time, CCQM-K119 was coordinated to assess the analytical capabilities of laboratories for measuring the composition of a Liquid Petroleum Gas (LPG) mixture when sampled in the liquid phase from a constant pressure cylinder. This supports measurement of calorific value for transport of liquid fuels.

The ongoing CCQM-K118 key comparison on natural gas is operated with a similar design as the biogas key comparison. It addresses, apart from the equivalence of natural gas reference materials and calibration methods, two topics related to the diversification of the natural gas supply: (1) elevated levels of hydrogen and (2) very low levels (200 $\mu mol\ mol^{-1}$) of carbon dioxide. The elevated levels of hydrogen are relevant in those regions where hydrogen, produced from excess electricity from wind farms is injected into the natural gas grid. The very low levels of carbon dioxide occur in LNG (Liquefied Natural Gas).

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CCQM

5. DOCUMENT REVISION SCHEDULE

Title	Author	Changes	Date
GAWG Strategy Version 1	Paul Brewer	First draft prepared	11-08-2020
GAWG Strategy Version 2	Paul Brewer	Revision made to all sections.	13-10-2020
GAWG Strategy Version 3	Paul Brewer	Revision made to all sections.	30-10-2020
GAWG Strategy Version 4	Paul Brewer	Revisions made as discussed on 1st meeting of the strategy task group.	20-11-2020
GAWG Strategy Version 5	Paul Brewer	Revisions made as discussed on 2nd meeting of the strategy task group.	25-11-2020
GAWG Strategy Version 6	Paul Brewer	Revisions made by GAWG	16-12-2020
GAWG Strategy Version 7	Paul Brewer	Revisions made by CCQM-SPWG	11-03-2021