Vision for a European metrology network for energy gases

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Abstract
As Europe moves towards decarbonising its energy infrastructure, new measurement needs will arise that require collaborative efforts between European National Metrology Institutes and Designated Institutes to tackle. Such measurement needs include flow metering of hydrogen or hydrogen enriched natural gas in the gas grid for billing, quality assurance of hydrogen at refuelling stations and equations of state for carbon dioxide in carbon capture and storage facilities. The European metrology network for energy gases for the first time provides a platform where metrology institutes can work together to develop a harmonised strategy, prioritise new challenges, and share expertise and capabilities to support the European energy gas industry to meet stringent EU targets for climate change and emissions reductions.

1. Introduction
Accurate and traceable measurements underpin the integrity of a successful energy gases system within Europe. For example, flow measurements are performed to determine amount of energy gas transferred (for fiscal trading), while gas quality measurements ensure the product does not damage appliance upon reaching the domestic end-users. Inaccurate measurements could lead to an inability to correctly bill customers and higher risk of reducing appliance lifetime. In more recent years, there has been a worldwide effort to decarbonise our energy gases systems in order to reduce carbon dioxide and other harmful emissions and this has required the efforts of National Metrology Institutes (NMIs) and Designated Institutes (DIs), with active collaboration from laboratories and instrument manufacturers, to develop the required measurement capability including primary standards, methods, instruments and good practice. This paper provides an overview of new trends in the European energy gases market, current measurement needs required to support the decarbonisation of energy gases in Europe and the purpose and objectives of the recently founded European metrology network (EMN) for energy gases.

2. Energy gases
Many European countries have set out plans for current and future energy gases through published strategies, policies or legislation with a focus on reducing emissions. A communication from the Commission of the European Parliament in 2015 [1] explained the need for an Energy Union, which provides five dimensions including ‘decarbonising the economy’. The communication called for:
• Security, solidarity and trust—diversifying Europe’s sources of energy and ensuring energy security through solidarity and cooperation between EU countries
• A fully integrated internal energy market—enabling the free flow of energy through the EU through adequate infrastructure and without technical or regulatory barriers
• Energy efficiency—improved energy efficiency will reduce dependence on energy imports, lower emissions, and drive jobs and growth

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• Climate action, decarbonising the economy—the EU is committed to a quick ratification of the Paris Agreement and to retaining its leadership in the area of renewable energy
• Research, innovation and competitiveness—supporting breakthroughs in low-carbon and clean energy technologies by prioritising research and innovation to drive the energy transition and improve competitiveness.

The renewable energy directive (2018) [2] supports the increased use of energy from renewable sources, highlighting the benefits as ‘security of energy supply, sustainable energy at affordable prices, technological development and innovation as well as technological and industrial leadership while providing environmental, social and health benefits as well as major opportunities for employment and regional development, especially in rural and isolated areas, in regions or territories with low population density or undergoing partial deindustrialisation’. In particular, the directive promotes the use of renewables to decarbonise the electricity, heating and cooling, and transport sectors. The directive provided national overall targets for expected share of energy from renewables sources in 2020 which ranged from 13% to 49%.

It is clear that a focus for the energy gases market is towards decarbonisation; reducing the use of fossil-based fuels that emit carbon dioxide into the atmosphere. This section provides an overview of current energy gases that are being used or are emerging in the European energy gases market including carbon dioxide for carbon capture utilisation and storage.

2.1. Natural gas

Natural gas is a fossil fuel that primarily consists of methane (CH₄), along with some other gases including nitrogen (N₂), carbon dioxide (CO₂), helium (He), hydrogen sulphide (H₂S), and noble gases; the composition will vary depending on its origin [3]. Natural gas consumption represents over 20% of the total primary energy consumed in Europe [4]. In 2018, it was predominantly supplied from Russia, Norway, Belarus and Ukraine [5]. The demand for natural gas in most applications is expected to decline in several countries in Europe due to a growing consensus that we must replace natural gas with renewable or low carbon sources in line with the shared ambition of tackling climate change. Taking the UK as an example, UK production of natural gas expanded in the early 1970s and its demand grew rapidly, reaching a record high in 2004 of 1125 TW h. Since then, demand has seen an overall decline and in 2017, demand was around a fifth of the 2004 peak at 868.6 TW h [6].

Nevertheless, it is estimated in mid-term projections that natural gas will remain a crucial energy gas across Europe, particularly in heat, transport and industry. Natural gas is viewed as a key transitional energy gas because it produces less CO₂ emissions than coal or oil and these emissions can be captured and utilised or stored through carbon capture, usage and storage (CCUS) either pre- or post-combustion. Furthermore, the decline in natural gas utilisation in several sectors might also be somewhat offset by a new demand to produce other gases such as hydrogen (through steam methane reformation). It is projected that the transition to hydrogen and other low carbon energy gases in most sectors will not be a quick process, for example in the heat sector, replacing natural gas with hydrogen in natural gas grids is likely to be carried out step-wise in most cases, by injecting hydrogen at low concentrations alongside natural gas and making incremental increases, known as ‘hydrogen enriched natural gas’ (see section 2.1.2).

2.1.1. Liquefied natural gas

Due to the EU’s large import demand for natural gas, there is a crucial need for diversification of its sources in order to meet energy demand, improve energy security, diversify gas supply, and to promote competitiveness. Liquefaction of natural gas (LNG)—achieved by cooling natural gas to approximately −162 °C—is primarily carried out as a more efficient means of transporting natural gas without the need of pipelines [7]. This is due to the volume of LNG being 600 times less than in its gaseous form. Utilising LNG also increases safety during transportation due to it being non-flammable in this state (until it begins to vaporise) [8]. It is projected that LNG imports to Europe will increase by 20% in 2040 compared to 2016 levels and its LNG import capacity could provide approximately 45% of the continent’s total gas demand [9, 10]. As a result, the EU’s ‘Energy Union Strategy’ [11] has highlighted a key objective of ensuring that all members states have access to LNG markets.

In most cases in Europe, LNG is re-gasified and the corresponding gas utilised to meet the peak demand of natural gas. The associated measurement challenges are related to custody transfer, either when used as a transportation fuel (small to mid-scale applications) or in the large-scale application (LNG carrier (un)loading).

LNG is increasingly being used as transportation fuel [11]. In some countries, it is utilised as fuel in heavy duty trucks and lorries due to lower emissions when compared to diesel. It is also promoted as a good alternative to heavy oil as a marine or shipping fuel particularly in short to mid-term projections due to stringent environmental regulations [12]. The European Metrology Programme for Innovation and Research
(EMPIR) ‘LNG III’ project worked on addressing measurement challenges associated with LNG utilisation as transport fuel.

2.1.2. Hydrogen enriched natural gas

Hydrogen deployment at scale could play an important role in achieving decarbonisation targets across Europe. One of the major challenges in meeting these targets is decarbonising heat which will require replacing natural gas with hydrogen or other low-carbon energy gases. However, network modifications and retrofitting are required before the conventional gas networks can be repurposed to carry 100% hydrogen. While these network upgrades are undertaken, hydrogen could be injected alongside natural gas into the gas network in a blend, to facilitate the phasing out of fossil-fuel derived energy gases. This blending is termed ‘hydrogen enriched natural gas’ (HENG).

Utilising HENG can lead to a reduction of GHG emissions and decreases the carbon intensity of natural gas use. It is particularly promoted for the decarbonisation of heat but recent projects including the ‘Hydrogen Grid to Vehicles’ (HG2V) project in the UK is looking into the feasibility of utilising the distributed gas from the network for decarbonising transport [13].

While hydrogen and natural gas can be mixed in any proportion, studies indicate that up to 20% hydrogen (volume) can be injected alongside natural gas without any modifications to most natural gas grids, reducing the immediate requirement for expensive infrastructure investments. The threshold for permitted concentrations of hydrogen in the grid varies in different countries across Europe and depends upon the network infrastructures in place, as well as the end uses of the distributed gas. In domestic use, the type and age of connected appliances plays an important role in the allowable limits for hydrogen. There are strict national regulations in most European countries with regards to permissible volume of hydrogen allowed in the gas grids; for example, the UK and Belgium presently allows a maximum blend level of 2% molar volume of hydrogen in its natural gas grids whilst France, Germany and the Netherlands allows a maximum of 8%, 12% (in some cases) and 14% molar volume of hydrogen in their gas grids [14]. Nevertheless, several deployment projects have begun in several European countries with the view of reviewing this set blending limits and also promote HENG as part of the energy gas mix.

2.1.3. Biogas/biomethane

Biogas is an energy vector and sustainable fuel which has the potential to play a huge role in the energy transition in Europe; it could have a role in the present and future energy mix scenarios for heat application, power and transport, as well facilitating the reduction of emissions from waste and agriculture. Biogas is composed of varying levels of CH4 and CO2 as well as water vapour, and small amounts of H2S, nitrous oxide (N2O) and ammonia (NH3) [15]. The biogas market in Europe varies for different individual countries with regards to maturity, method of production and its overall development and deployment. It is utilised in most countries across Europe due to its ability to support increased energy security alongside its environmental benefits, as it aligns with many renewable energy and climate policies. It is generally accepted that the utilisation of biogas alongside other low carbon energy gases such a hydrogen will be essential in meeting the targets for renewable energy in the energy mix in Europe (target of 27% renewable energy in the energy mix in 2030) [16].

Biogas is generally produced through anaerobic digestion using agricultural waste, manure, and energy crops in Europe [17]. It can also be produced from landfill gas recovery and wastewater treatment [4, 16] and from the gasification of biomass. Biogas production represented 8% of renewable energy production in Europe in 2015 with a major share of this produced in Germany [18]. In 2017, there were over 17 000 biogas plants across Europe primarily used to generate heat and electricity [16]. Biogas is also upgraded in some cases through the removal of CO2, moisture and other contaminants to produce ‘biomethane’, which is growing in popularity across Europe as a direct replacement to natural gas in several applications, particularly in the natural gas grids and transport.

Biogas can either be utilised directly for heat and electricity or it can be upgraded to biomethane which could replace natural gas in gas distribution networks. Over 90% of biogas produced in Europe is utilised directly for bio-power generation and capacity, which is utilised in ‘electricity only’ plants, or combined heat and power (CHP) plants [18]. The electricity realised from biogas plants in Europe amounted to over 11 000 MW in 2018, with an average electrical efficiency between 35%–40% [16, 19, 20]. Heat generated from the combustion of biogas can be used for local heat demand or distributed into district heating networks or off-grid installations.

There is a growing belief shared by several European countries that biogas should be upgraded to biomethane as opposed to its utilisation for direct heat and electricity generation. This belief is due to a combination of factors including low demand at present for heat generated from biogas, and poor economics of electricity biogas plants [21]. The high quality of the upgraded gas or biomethane also means that boilers and other appliances do not need modification or increased maintenance [17].
The utilisation of biomethane in the gas grid might be an energy efficient solution to decarbonising the gas networks in Europe. Biogas can be upgraded to biomethane (>96% CH₄) through the removal of CO₂, H₂S, H₂O and other trace contaminations. There are more than 600 biomethane plants in operation across Europe and similarly to biogas, it can be utilised for heat and electricity generation in CHP’s. However, more focus is being placed in Europe on its use as a substitute for natural gas in existing natural gas grids due to the similar gas composition and physical properties.

Similarly to natural gas, biomethane can be compressed or liquefied to compressed biomethane (CBM) or liquefied biomethane (LBM), which facilitates its transportation and storage as existing facilities and vehicles can be utilised. CBM and LBM can also be used as fuel in natural gas-powered vehicles, thus supporting some emissions reductions along the fuel supply chain for a large section of the transport market (namely HGVs).

Biomethane can also be reformed to produce ‘blue hydrogen’, and if combined with CCS would lead to negative carbon emissions (net removal of CO₂ from the atmosphere) [22]. The negative emissions might also be realised if the biogas digestate is used as agricultural fertiliser [22]. Aiming for these types of negative emission technologies might be crucial across Europe to meet its future emission targets due to the scale of the task at hand. There are several projects being undertaken by individual member countries in Europe with the view of deploying biogas and biomethane as an energy gas, one example of which is the EMPIR biomethane project, which is working on improving test methods for purity analysis for biomethane before its injection in the gas grid or use as a vehicle fuel.

2.2. Hydrogen

Hydrogen is being explored by many European countries as a zero or low carbon alternative to natural gas that can be produced domestically, thus improving energy security and resilience. Hydrogen is abundant in nature, however to obtain pure hydrogen gas (H₂), energy is required [23]. Depending on the method of production, hydrogen has the potential to be a climate-friendly replacement for fossil fuels at the point-of-use. The ‘Hydrogen Roadmap Europe’ report from the ‘Fuel Cells and Hydrogen Joint Undertaking’ (FCH JU) estimates the potential of generating 2250 TW h of hydrogen in Europe by 2050 in an ambitious scenario [24]. This would lead to a significant reduction of carbon and NOx emissions and as such play a crucial role in achieving emission reduction targets in Europe [25].

The produced hydrogen can be utilised across the energy supply chain; for power generation, as well as in the transport and heat sectors [26]. The EC through its ‘European industrial strategy’ has also initiated a ‘Clean Hydrogen Alliance’; this initiative will aim to identify technological needs and barriers towards production of clean hydrogen in Europe [24]. The Alliance will bring together investors, government and industrial partners to identify technological needs, regulatory barriers and investment opportunities for clean hydrogen in Europe [24]. A hydrogen strategy for a climate neutral Europe has also been released by the EC; the main key actions from the strategy is to have and support coordinated strategic investment into clean hydrogen, boost demand and scale up hydrogen production, design an enabling and supportive framework for hydrogen, and promote research and innovation in hydrogen technologies [27]. The ‘Hydrogen Energy Network’ (HyENet) in Europe is also supporting member countries on policies that could lead to upscaling and deployment of hydrogen. The network will act as a platform for the exchange of information, good practice and developments among EU member states [28]. The EMN for energy gases looks to work in a similar function but with a specific focus on metrology across all types of energy gases.

The means of producing hydrogen will be key to its potential role as a low-emission alternative to natural gas in Europe. Hydrogen can be produced through several different means:

Steam reforming of natural gas (or other hydrocarbons)—during the steam methane reforming (SMR) reaction, natural gas is mixed with steam, heated to over 815 °C and reacted in the presence of a nickel catalyst to produce hydrogen (H₂) and carbon monoxide (CO), which is then converted to CO₂ via a water gas shift reaction [29]. The reforming of fossil fuels could also be carried out in an autothermal process; this process is projected to also play a key role in the production of hydrogen in Europe [25].

Electrolysis of water—electrolysers are used to split water (H₂O) into H₂ and oxygen (O₂) gas with electricity (power-to-hydrogen). This process is particularly important for the generation of green hydrogen due to the significant reduction in emissions if the energy input used to power the electrolyser comes from a renewable source.

Other hydrogen production methods include its production from biomass; this could be a thermochemical process where the biomass is gasified or pyrolyzed at elevated temperatures. Hydrogen could also be produced in the future through the extraction of ‘bio-hydrogen’ from biogas through fermentation of organics or cyanobacteria.

The thermochemical production of hydrogen either through reformation or gasification processes like SMR is termed ‘grey hydrogen’. This method leads to the release of CO₂ and hence has little impact on reducing emissions and meeting climate targets. However, an emissions reduction can be realised when CCUS is deployed.
alongside thermochemical hydrogen production processes—this is known as ‘blue hydrogen’. Further emission reduction benefits can be achieved when hydrogen is produced from renewable sources such as wind, hydro power and solar, termed ‘green hydrogen’.

Projections in Europe indicate that blue hydrogen will be deployed in the short to mid-term while technologies for the preferred green hydrogen continue being developed [4]. At present, hydrogen produced via the SMR process is considered to be the lowest cost option for the production of bulk volumes of the gas [30]. For hydrogen refuelling stations where the gas will be used in a fuel cell electric vehicle (FCEV), electrolyzers can be utilised onsite to produce hydrogen, primarily due to the demands for high purity hydrogen to be used in fuel cell systems to avoid degradation of these technologies [26].

2.2.1. Hydrogen for heat

Hydrogen is an important industrial element and is utilised in several applications. It is also well suited as a low carbon energy fuel for use in energy-dense applications such as long-distance HGV and ship transportation, as well as for electricity and heating generation during peak periods [30]. Hydrogen is projected as the best choice in Europe for at scale decarbonisation of several sectors particularly transport, industry and buildings [25]. The potential for repurposing the conventional gas networks to carry 100% hydrogen is already being investigated in several European countries, notably Germany, the Netherlands, the UK and France. Hydrogen can also act as both a short and long-term energy store to balance supply and demand of renewable energy at different scales, geographies and weather conditions. It can therefore meet the need for a low-cost, ‘on-demand’ power supply that only fossil-fuelled power plants can currently satisfy [31].

Within Europe, there are several projects as well as ongoing research activities that look to support the development and deployment of hydrogen technologies. The ‘Hydrogen for Europe’ pre-study was undertaken by SINTEF to evaluate the current potential of hydrogen in Europe; it took into consideration different production mechanisms proposed for upscaling activities [32]. The findings indicate that hydrogen has the potential to reduce GHG emissions in several sectors in Europe by 2050 and can provide one quarter of the total energy demand in Europe by 2050.

The majority of the forecasted scenarios and projections of the energy mix in Europe indicate that hydrogen will make a significant contribution to the decarbonisation of heat [25]. In the buildings sector, post-2050 projections indicate that hydrogen boilers could be deployed alongside heat pumps in a fully decarbonised system [33]. Hydrogen boilers would be effective in buildings with poor insulation and in colder climates where the use of heat pumps is uneconomical. Projections indicate that the utilisation of hydrogen for domestic heating and in buildings could supply 15% of the total energy demand in buildings across Europe [34]. The hydrogen roadmap for Europe report also estimates that hydrogen can cover the heating demand of more than 11 million households in Europe in 2040 and could heat more than the equivalent of 52 million households in Europe by 2050 [35].

Hydrogen is projected to contribute to the decarbonisation of non-process heat in industries; which could be heat utilised in energy intensive industries [36]. Hydrogen can also be used in several production processes for industries including steel, plastic and ceramic production [37]. Furthermore, hydrogen can be utilised to produce synthetic methane in a process called ‘methanation’, which could function as a replacement for conventional natural gas in existing gas grids.

2.2.2. Hydrogen for transport and storage

Hydrogen could play a crucial role in decarbonising transport as it can be used as fuel in passenger and heavy-duty vehicles that utilise fuel cell technologies. It is particularly well-suited as a low carbon fuel in freight such as commercial vehicles, heavy goods vehicles (HGVs), trains and ships where the use of electric vehicles might not be sustainable. Hydrogen might also be used to produce synthetic fuels for aviation transport, which is being investigated in Europe currently [25].

There is a high interest in the development of infrastructure and techniques to ramp up the deployment of hydrogen in the transport sector in Europe. Several European countries including Germany, the UK, France, Scandinavia and the Netherlands have begun to invest in hydrogen infrastructure such as refuelling stations for transport applications [38] with projections indicating an additional 750 hydrogen refuelling stations by 2025 [35]. However, the deployment and uptake of FCEVs will depend very strongly on the interactions between vehicle costs, fuel costs and the cost of alternatives alongside policy drivers and evolving habits in different European countries [39]. Nevertheless, there could be a fleet of 3.7 million fuel cell passenger vehicles, 500 000 fuel cell light commercial vehicles and about 45 000 fuel cell trucks in Europe in 2030 [35].

2.2.3. Hydrogen storage

Hydrogen could allow for long term energy storage from renewable electricity, which can then be used in the power sector, and as such play a vital role in Europe’s energy mix. The utilisation of hydrogen in the power sector could provide grid balancing for intermittent renewables, which will help to provide load balancing for
times that there is insufficient wind or solar energy. Projections indicate that this could account for up to 15% of the electricity utilised in 2050 across Europe [34].

Cost effective and sustainable transport and storage mechanisms are key to the deployment of hydrogen as an energy gas. Hydrogen can be transported as a liquid or gas; liquid hydrogen can be loaded in insulated cryogenic tanks which are then transported via lorries, trailers or other means of transport. Hydrogen can also be transported as a gas in compressed gas containers or tube trailers, which can then be transported via lorries. Another means to distribute hydrogen, particularly for energy gas utilisation over long distances, is through pipelines. Pipelines may be the best option for large scale distribution for energy use in Europe [40]. At present, there are several hydrogen pipelines globally; the longest pipelines in Europe are situated in Belgium and Germany and can transport hydrogen for 613 km and 276 km respectively.

Storing hydrogen will provide a crucial solution for grid balancing and ensuring adequate and sustainable energy supply, particularly during periods of renewable intermittency. There are several techniques being investigated for hydrogen storage in Europe:

- Hydrogen can be stored in natural spaces including underground in salt caverns, natural gas stores and depleted gas reservoirs or aquifers.
- The gas distribution network itself can serve as a storage mechanism while distributing hydrogen.
- Hydrogen can also be stored in solids, liquids and on surfaces; this includes hydride storage systems based on metals such as palladium, lanthanum and aluminium. It also includes surface storage in sorbent materials such as zeolites or carbon nano tubes. Storage in liquid can be done with chemical compounds with high hydrogen absorption capacities such as N-ethyl carbazole and toluene.
- Hydrogen can also be converted to ammonia, which as a liquid, is very easy to store and transport.

The technology readiness level (TRL) of some of the storage mechanisms for hydrogen are still being developed, and the EMPIR ‘Metrology for Hydrogen Storage’ (MefHySto) project is poised to support advancement of these hydrogen storage technologies by addressing several metrology challenges that might arise during the process.

2.3. Carbon capture utilisation and storage

It is important to note that not all emissions will be abated if only the above strategies outlined in the previous sections are followed, as several of these novel energy gas production methods produce CO2. Some of the suggested low carbon sources including blue hydrogen and biogas production, still lead to the emission of CO2 and as such, carbon capture and storage (CCS) and carbon capture and usage/utilisation (CCU) technologies are required. These technologies are likely to be crucial in the decarbonisation of energy intensive sectors like power, transport and industry. CCS is a technique for capturing and trapping CO2 emitted in processes and transporting it after compression to a safe and suitable storage mechanism (both long and short to mid-term storage), while CCU involves the use of the trapped CO2 in other processes, for example food and drink production. CO2 can also be recycled as a reactant for the production of chemicals, synthetic fuels and industrial processes. Furthermore, CO2 is utilised in the production of urea but can also be used to produce synthetic methane through reversed water gas shift reactions or methanation. The synthetic methane can thereafter be utilised as an energy gas.

It is important to note that the varying methods for the removal and capture of CO2 are likely to impact the gas quality and therefore could prevent potential further usage of the gas itself.

The deployment of CCUS has been identified as a crucial part of the long-term strategy in Europe for achieving their climate ambitions [41]. There is the potential that CCUS may be the only option in reducing emissions from several hard to decarbonise industrial processes including forging of steel and iron, natural gas processing, cement and ammonia production. It is also a viable means of reducing emissions from the production of low carbon sources and fossil fuel combustion in the short to mid-term.

In Europe, CCU deployment is being carried out in some industrial applications; this includes the fertiliser industry, where CO2 trapped from ammonia production is used for different chemical production processes. An example of a CCU demonstration project is the ‘Power to Methane’ project in Germany [42], where CO2 captured from bioethanol plants is utilised in producing synthetic methane. The synthetic methane produced can then be used as an energy gas in several sectors including heating, power, transport and industry.

3. European metrology network for energy gases

For decades NMIs and DIIs have collaborated within European Association of National Metrology Institutes (EURAMET) and worked together in grant-funded European Metrology projects as part of several EURAMET
Programmes including the European metrology research programme (EMRP) and EMPIR to progress the development of new measurement capability required to support the energy gas industry (Table 1). Such collaborative projects have been vital as they allow NMIs from different European countries to share knowledge (where one country is more experienced than another) and to validate standards and methods by testing against each other.

These types of collaborative projects demonstrated how NMIs and DIs working together can achieve more than working independently. The projects allowed experts from different countries to work together, sharing facilities and knowledge, to provide better measurement solutions than could have been developed working alone. Additionally, the projects allowed expertise to be shared from more experienced laboratories to less experienced ones. Finally, the projects allowed countries to host and join international comparisons where new analytical methods and primary reference materials could be properly compared against an agreed reference value to indicate the ability for a laboratory to correctly provide a result or reference. Following on from the success of European Metrology projects, there are other areas where enhanced collaboration between NMIs, DIs and industry could provide advantages:

- Allowing countries to access measurement services and products that their own countries NMIs/DIs could not provide
- Joint strategy and investigations into industry measurement needs ahead of European Metrology project funding calls
- Measurement service hub presenting the collective European Measurement Institute network for industry to easily access.

The EMN for energy gases was established in 2019 with the mission of providing the world’s leading metrology network comprising experts in the field of measurement science to drive forward innovation and to accelerate decarbonisation and emissions reductions within the energy gas industry in Europe. It provides the ambitious vision of enabling all countries within Europe to access the measurement tools they require to support their energy gas industries including services, products, guidance, and expertise. A key focus is the drive to decarbonise energy gases, which required new measurement solutions for applying existing measurement techniques and calibration standards to new energy gases such as biomethane, hydrogen, LNG and carbon dioxide in CCUS processes. The following activities are taking place as part of a Joint Network project funded by EMPIR:

- **Strategic research agenda**—within the first year, the EMN held a workshop with selected European industry stakeholders to discuss measurement needs related to the European energy gas market and this was used to develop the first version of the EMN for Energy Gases Strategic Research Agenda. This report provided an outline of the emerging energy gas markets and prioritised the key measurement needs (section 4). The report was used to develop proposed research topics for the proposed European Partnership for Metrology Green Deal call. The report will be updated annually to refresh the strategy and prioritisation of measurement needs for the European energy gases industry.

- **Measurement service platform**—development of an online platform that provides a detailed overview of measurement capabilities from laboratories and metrology institutes across Europe. This platform is intended to support the energy industry to easily identify calibration and measurement services that

| Project name                                                                 | Project number | Duration    |
|-----------------------------------------------------------------------------|----------------|-------------|
| Characterisation of energy gases                                            | ENG01          | 2010–2013   |
| Metrology for liquified natural gas                                         | ENG03          | 2010–2013   |
| Metrology for biogas                                                        | ENG54          | 2014–2017   |
| Multiphase flow metrology in oil and gas production                        | ENG58          | 2014–2017   |
| Metrological support for LNG custody transfer and transport fuel applications | ENG60          | 2014–2017   |
| Field trial of traceable online measurements of siloxanes in landfill gases | 14SIP06        | 2015–2016   |
| Metrology for hydrogen vehicles                                             | 16ENG01        | 2017–2020   |
| Metrology for biomethane                                                    | 16ENG05        | 2017–2020   |
| Multiphase flow reference metrology                                         | 16ENG07        | 2017–2020   |
| Metrological support for LNG and LBG as transport fuel                      | 16ENG09        | 2017–2020   |
| Flow metering of renewable gases                                            | 18NRM06        | 2019–2022   |
| Improvement of the European quality infrastructure for the measurement     | 18SIP03        | 2019–2021   |
| silicon and sulphur content of biogas                                        | 19ENG03        | 2020–2023   |
| Metrology for advanced hydrogen storage solutions                           | 19ENG04        | 2020–2023   |
| Metrology for hydrogen vehicles                                             | 20IND10        | 2021–2024   |
| Metrology infrastructure for high-pressure gas and liquified hydrogen flows | 20IND11        | 2021–2024   |
they require and facilitate international co-operation (easier access to capability from other European countries).

- **Building synergies**—a specific focus will be placed on using the EMN for energy gases to support the development of new collaborative activities such as training programmes, proficiency testing schemes and project proposals, which requires collaboration between NMI/DIs.

- **Creating impact**—the EMN partners will utilise experience and knowledge gained from previous projects to support standardisation (CEN and ISO) related to energy gases and industrial stakeholders with current measurement needs (through workshops and online media).

### 4. Measurement needs

This section provides an overview of the priority measurement needs identified by the EMN for energy gases.

#### 4.1. Flow metering

Accurate metering of energy gases is crucial for billing the end users, whether they are receiving natural gas, hydrogen or a blend of different compositions. For CCS, flow metering is required to monitor the amount of carbon dioxide that has been released from the process and it can also be used to determine carbon dioxide losses within a system. Future work that is required in this include the development of traceable flow calibration facilities and performance testing (accuracy and precision) of various types of flow metres for:

- Hydrogen in natural gas blends (including presence of hydrocarbon compounds) or pure hydrogen in gas grids before supply to domestic or industrial users
- LNG and LBG at larger flow rates (>200 m³/h)
- Biogas or biomethane injection
- Custody transfer of hydrogen between producers and supply networks, industry or customers
- Monitoring amount of hydrogen stored
- Metering of hydrogen for all forms of transport refuelling (including light and heavy road vehicles, trains, ferries, ship and aviation) under operational variations during refuelling.
- Assessing capture efficiencies in CCS processes
- Carbon accounting in CCS involving measurement of carbon dioxide inventory and emissions.

#### 4.2. Gas quality

Gas quality measurements for energy gases are usually performed to ensure the gas does not contain impurities that could affect the integrity of network pipelines/equipment or end user appliances. Gas composition can also be used to infer other data such as caloric value using accurate and traceable models (as discussed further in section 4.3). Future work that is required for this topic includes the development of primary reference materials, good practice in sampling, validated analytical methods and NMI hosted proficiency testing schemes for:

- LNG and LBG composition for custody transfer and storage
- Hydrogen composition measurement following blending into natural gas (to maintain grid integrity and safety)
- 100% hydrogen and hydrogen enriched natural gas for safe and efficient transmission, storage and local distribution
- Uptake of odorants for safe distribution and use of hydrogen
- Supporting performance testing of domestic appliances and fuel cell systems running on hydrogen with varying impurities
- Monitoring specific impurities in biomethane before injection (such as siloxanes)
- Carbon dioxide quality for CCUS including efficiencies of capture and capture material breakdown.

#### 4.3. Physical properties

There are a variety of physical properties that provide important data required for the supply of energy gases and to ensure safe and efficient networks and operation. These measurements can be performed directly or indirectly through measurement of gas composition and conversion using a model. Examples for both of these types of measurement can be observed for calorific value, which can be measured directly using a colorimeter or indirectly by converting gas composition to calorific value using established data models. Measurement techniques or established data models are required for:
• Calorific value for 100% hydrogen, hydrogen enriched natural gas and biomethane
• Dew point measurements for 100% hydrogen (including at hydrogen refuelling stations up to 875 bar nominal working pressure), hydrogen enriched natural gas and carbon dioxide for CCUS processes
• Vapour liquid equilibria to determine phase changes of carbon dioxide for CCUS processes
• Speed of sound and density measurements required for accurate flow metering.

4.4. Leak monitoring
In gas industry processes any gas leak could lead to loss of useful product, but also will contribute to the total emissions leading to air quality and climate issues. The following developments are required to support decarbonisation of energy gases in Europe:
• Validation of portable leak detectors that are capable of differentiating between leaks of natural gas, pure hydrogen and blends
• Quantification of leaks of hydrogen, hydrogen enriched natural gas and biomethane into atmosphere from pipelines
• Monitoring of CO₂ leaks from storage sites (both on-site and sub-sea).

5. Conclusions
NMIs and DIs will play an important part in ensuring the successful transition to a decarbonised energy gas system in Europe. There are currently several key measurements that take place in this industry for the purposes of safety, billing and ensuring efficient and economical operation. The introduction of new ‘clean’ energy gases (such as hydrogen and biomethane) and new processes (such as CCUS) raise new measurement needs that need to be addressed by NMIs and DIs.

The newly established EMN for energy gases will provide the platform to enhance communication with the European energy gas industry stakeholders, provide one single harmonised strategy on behalf of all European NMIs and DIs and support the development of new EU funded projects, services and products that are current priorities for allowing Europe to meet stringent climate change targets.

Similar European metrology networks have also been established for other key areas including for smart electricity grids, climate and ocean observation, and quantum technologies [43].

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Data availability statement
All data that support the findings of this study are included within the article (and any supplementary information files).

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