NPL

Energy transition:

Measurement needs within the hydrogen industry

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National Physical Laboratory

The National Physical Laboratory (NPL) is the UK's National Measurement Institute. At the heart of our mission is delivering impact by disseminating research and measurement best practice and traceability for the economic and social benefit of the nation.

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Executive summary

Hydrogen has the potential to decarbonise electricity generation, transport and heat. It has historically experienced cycles of interest within the UK and internationally but has often been discounted due to the novelty and cost of the technologies in question, and a lack of evidence of not only their performance but their ability to be commercialised. This is changing. Discussions around hydrogen in the UK have begun to shift from hypothetical debates to practical roll-outs. There is an ever-growing evidence base within the hydrogen industry – of roadmaps, reports, projects and practical infrastructure implementations – demonstrating that hydrogen can play a feasible role in the efforts to decarbonise the UK's energy system.

Industry and academia highlight that there are a number of measurement challenges that need to be addressed to facilitate the hydrogen industry. As the UK's National Measurement Institute, the National Physical Laboratory (NPL) has a responsibility to tackle priority measurement challenges. Tackling these challenges will require both the right expertise and a harmonised effort from funding bodies, industry, research institutes, standardisation bodies and policy makers. The UK has an internationally-prominent measurement capability, as well as established research institutions, which could enable us to develop and host a world-leading hydrogen industry.

This document analyses the processes behind the production, storage, distribution and end-uses of hydrogen, and identifies and prioritises the measurement challenges that may have the potential to create hurdles and bottlenecks in progress towards a growing UK hydrogen economy. These challenges can be found in the blue boxes throughout and are summarised in section 7 of this document.

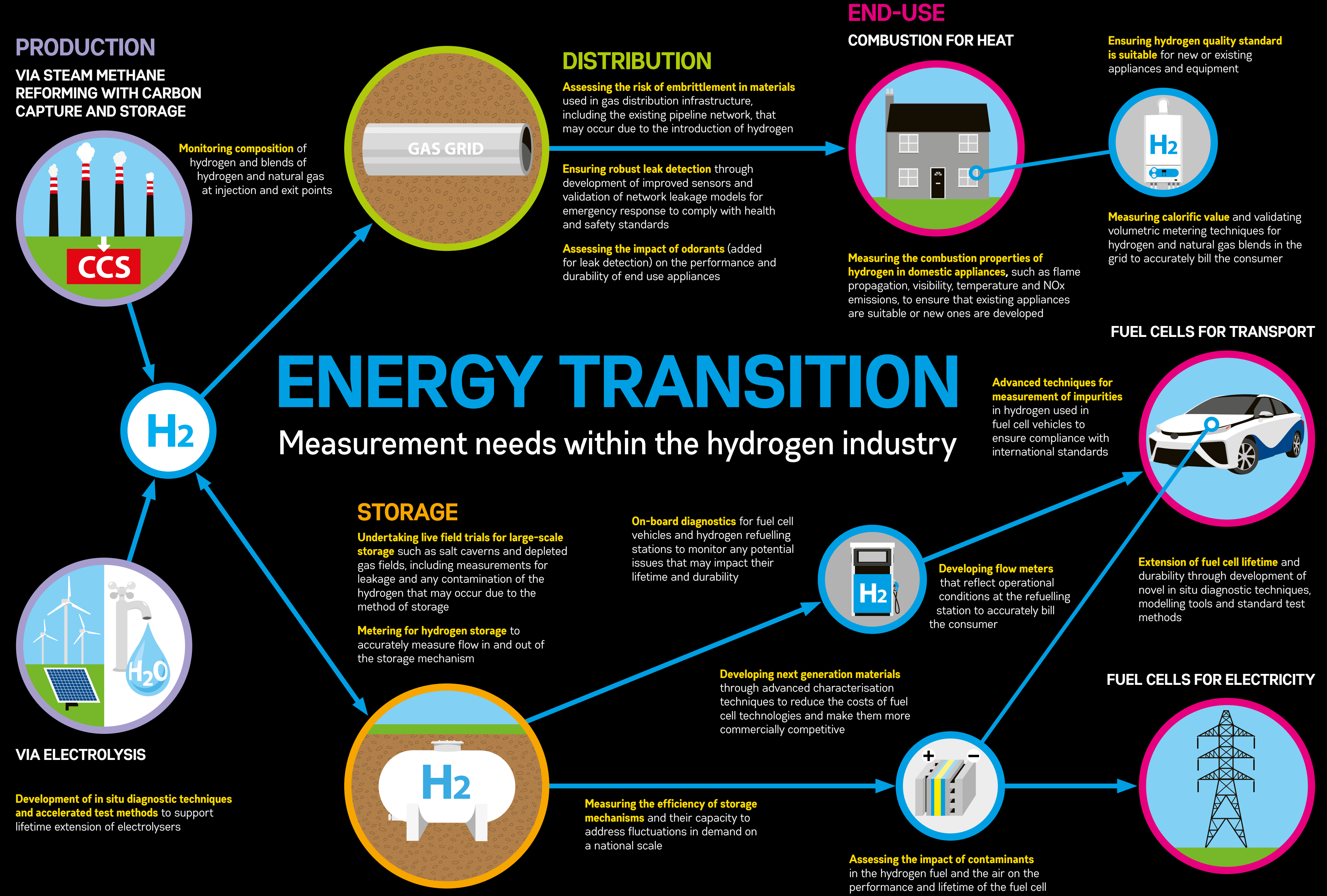
Six challenge areas were ranked as high priority:

1. **Material development for fuel cells and electrolysers,** to reduce costs and assess critical degradation mechanisms - extending lifetime and durability is key to the commercialisation of these technologies;
2. **Impact assessment of added odorant to hydrogen to aid leak detection.** Measurement of its impact during pipeline transportation and on the end-use application (particularly fuel cell technology) will be important to provide assurance that it will not affect lifetime and durability;
3. **Determination of the blend ratio when hydrogen is mixed with natural gas in the gas grid.** Accurate flow rate measurement and validated metering methods are needed to ensure accurate billing of the consumer;
4. **Measurement of the combustion properties of hydrogen** including flame detection and propagation, temperature and nitrogen oxides (NO_x) emissions should it be used for heat applications, to ensure existing and new appliances are suitable for hydrogen;
5. **Assessment of the suitability of existing gas infrastructure and materials for hydrogen transportation.** Building an understanding of what adaptations might need to be made to avoid for example air permeation, metal embrittlement and hydrogen leakage;
6. **Validated techniques for hydrogen storage,** which will require measurement of the efficiency and capacity of each mechanism, through robust metering, leakage detection and purity analysis to ensure they are optimised for the storage of hydrogen gas.

The infographic on the following page is a visual summary of the measurement challenges identified throughout this report.

ENERGY TRANSITION

Measurement needs within the hydrogen industry



PRODUCTION

VIA STEAM METHANE REFORMING WITH CARBON CAPTURE AND STORAGE

Monitoring composition of hydrogen and blends of hydrogen and natural gas at injection and exit points

VIA ELECTROLYSIS

Development of in situ diagnostic techniques and accelerated test methods to support lifetime extension of electrolysers

DISTRIBUTION

Assessing the risk of embrittlement in materials used in gas distribution infrastructure, including the existing pipeline network, that may occur due to the introduction of hydrogen

Ensuring robust leak detection through development of improved sensors and validation of network leakage models for emergency response to comply with health and safety standards

Assessing the impact of odorants (added for leak detection) on the performance and durability of end use appliances

END-USE

COMBUSTION FOR HEAT

Measuring the combustion properties of hydrogen in domestic appliances, such as flame propagation, visibility, temperature and NOx emissions, to ensure that existing appliances are suitable or new ones are developed

Ensuring hydrogen quality standard is suitable for new or existing appliances and equipment

Measuring calorific value and validating volumetric metering techniques for hydrogen and natural gas blends in the grid to accurately bill the consumer

FUEL CELLS FOR TRANSPORT

Advanced techniques for measurement of impurities in hydrogen used in fuel cell vehicles to ensure compliance with international standards

On-board diagnostics for fuel cell vehicles and hydrogen refuelling stations to monitor any potential issues that may impact their lifetime and durability

Developing flow meters that reflect operational conditions at the refuelling station to accurately bill the consumer

Extension of fuel cell lifetime and durability through development of novel in situ diagnostic techniques, modelling tools and standard test methods

FUEL CELLS FOR ELECTRICITY

Developing next generation materials through advanced characterisation techniques to reduce the costs of fuel cell technologies and make them more commercially competitive

Assessing the impact of contaminants in the hydrogen fuel and the air on the performance and lifetime of the fuel cell

STORAGE

Undertaking live field trials for large-scale storage such as salt caverns and depleted gas fields, including measurements for leakage and any contamination of the hydrogen that may occur due to the method of storage

Metering for hydrogen storage to accurately measure flow in and out of the storage mechanism

Measuring the efficiency of storage mechanisms and their capacity to address fluctuations in demand on a national scale

1 Introduction

1.1 The use of hydrogen as an energy vector in the UK

The UK urgently needs to find cost-effective and scalable ways to decarbonise our energy sector. Domestic policy, such as the Climate Change Act (2008), commits the UK to reduce its 2050 greenhouse gas emissions by at least 80% compared to 1990 levels [1]. On an international scale, the Paris Agreement also requires significant decarbonisation to keep global temperature increase 'well below' 2 °C [2].

The energy sector is pivotal in this and hydrogen as an energy vector can play a significant role in the transition to a low-carbon economy. Hydrogen is abundant in nature, however to be able to generate pure hydrogen for energy consumption, energy is required [3]. Dependent on the method of production, and possible use of carbon capture and storage (CCS) technology, hydrogen has the potential to be a climate-friendly replacement for fossil fuels at the point-of-use.

Hydrogen can be utilised across the energy supply chain; for use within the electricity grid, as well as the transport and heat sectors.

- Within the UK's electricity grid system, there is a growing need for grid-scale storage technology to mitigate the intermittency of renewables and enable the transition away from fossil fuels [4]. Hydrogen can be produced via electrolysis using electricity generated from renewable energy systems during times of high supply. It can then be stored for use during periods of high demand (hydrogen for storage is further explored in section 3), or transferred to the gas grid (see section 4 for hydrogen distribution);

- The transport sector accounts for over 20% of the UK's greenhouse gas emissions [5]. Fuel cell based vehicles that utilise hydrogen as the fuel are one option for the decarbonisation of this sector. Fuel cell electric vehicles (FCEVs) are already widely exploited in countries such as Japan [6]. The UK has recently begun preparing the infrastructure required to support these vehicles including the roll-out of refuelling stations. FCEVs have a similar refuelling time to petrol or diesel vehicles, something that electric vehicles (EVs) for instance are currently still working towards. The only exhaust emission from FCEVs is water, therefore they do not contribute to the air quality issues currently caused by conventional combustion engine vehicles (hydrogen for use in fuel cells is further explored in section 5.1);

- The UK heating network has a structural dependence on gas as an energy source; 84% of homes are heated by gas [7], with most of the supply coming from non-renewable natural gas sources. Combustion of hydrogen for heat could support decarbonisation, as, unlike natural gas, hydrogen does not produce pollutants when combusted. Hydrogen could either be blended with natural gas or combusted directly. Transporting hydrogen via the gas grid would enable the UK to utilise existing gas infrastructure assets and could reduce the costs associated with electrification of the energy system (hydrogen combustion for heat is further explored in section 5.3);

- Using hydrogen as fuel for vehicles and heat also presents an opportunity to increase energy security by reducing reliance on imported fuels (for example petrol) from other countries, as hydrogen can be produced in the UK from wind and solar power in addition to the domestic supply of natural gas.

A more robust understanding of how the existing energy and transport infrastructure would cope with the addition of hydrogen is crucial in assessing the feasibility of the UK transitioning to a hydrogen economy. In a number of cases, advances cannot be made without addressing the measurement challenges that underpin them.

1.2 Purpose of this document

The document analyses the processes behind the production, storage, distribution and end-uses of hydrogen, and identifies and prioritises the measurement challenges that may have the potential to create hurdles and bottlenecks in progress towards a UK hydrogen economy.

The conclusions presented in this document are based on individual in-depth interviews with hydrogen experts from across the supply chain, an industry workshop held at NPL, and several roadmaps and project reports published recently that address overarching issues within the hydrogen industry and outline what a hydrogen future may entail.

The document also highlights the areas that will require further investigation and investment, and it could therefore be used to inform calls for collaborative research activities.

2 Hydrogen production

The main driver for using hydrogen as an energy vector is to decarbonise the UK's energy sector. The lifecycle emissions of the fuel are therefore critical. Lifecycle pollutants associated with the use of hydrogen as an energy vector are determined by a) the primary energy source and b) the process used for hydrogen production.

There are a number of ways that hydrogen can be produced, including:

- Steam reforming of natural gas (or other hydrocarbons);
- Electrolysis of water;
- Gasification;
- Extraction of 'bio-hydrogen' from biogas produced by fermentation of organics or cyanobacteria;
- As a by-product of larger industrial chemical processes, such as chlor-alkali production [8].

Measurement challenges for all types of hydrogen production

Measuring the purity of the hydrogen produced is imperative to define quality control specifications, as each method may introduce its own impurities. We need to understand which impurities are introduced, in what quantities and how producers will collect this information. Each method may require specific validated purification or filtration methods to protect consumers and ensure the durability of the end-use application without compromising performance. A new international standard (ISO 19880-8) for hydrogen quality control is currently under development by ISO TC 197 which aims to explore this challenge further.

Currently, there is no understanding of the level of silicon that would be deemed acceptable in hydrogen, nor any techniques available to measure it. Hydrogen produced from biogas is not covered in current quality standards. If it were to become a conventional production method, then new impurities including silicon would need to be addressed.

2.1 Steam methane reforming (SMR)

Almost all of global hydrogen production (96%) comes from hydrocarbon sources and SMR currently accounts for around half of this [9]. During the 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 (H_2) and carbon monoxide (CO), which is then converted to CO_2 via a water gas shift reaction [10]. As a result of the chemical mix, there is a risk with SMR that impurities may be present within the hydrogen gas produced. If this gas were to be fed directly for use in a fuel cell, for example, treatment to remove all impurities to meet purity specifications (explained further in section 6.2) may be required. In addition, to meet the UK's decarbonisation targets, it is important that the carbon-based emissions that are produced via SMR are captured and stored (through CCS).

The development of CCS technologies will be essential should SMR be pursued as a carbon-neutral method for hydrogen production. If the captured carbon is to be stored for example above ground or under the sea, a robust understanding of how the gas is transported and stored in terms of methods and materials would be needed to reduce any potential environmental impacts. If, for example, the CO_2 is injected into aquifers or transmitted along oil pipelines, 'local, regional or transboundary assessment of potential significant environmental impacts on the natural areas' may be required [11].

Measurement challenges for SMR with CCS

The ability to model and monitor the longevity of carbon storage techniques and accurately measure the conditions under which it is stored (for example, pressure) to make sure it is robust will be imperative if SMR with CCS is to play a viable role within a decarbonised energy system.

2.2 Electrolysis

Electrolysers are used to split water (H_2O) into hydrogen (H_2) and oxygen (O_2) gas with energy input. If the energy input used to power the electrolyser comes from a renewable source and the hydrogen produced is used in a fuel cell or combusted, then the entire energy process would create no net emissions.

Electrolysers have the ability to be scaled up or down to meet demand. When scaled down, they could be used at a local level and fed by small-scale renewable systems such as solar photovoltaic (PV) panels on rooftops and solar farms. This provides a viable option should a decentralised approach to decarbonisation be adopted in the UK. When scaled up, electrolysers would use central energy generation facilities and the hydrogen would then need to be transported to the point of use.

Only 4% of global hydrogen production is currently from electrolysis [9] and although it is pre-emptive to assume that electrolysis will become the primary method for producing hydrogen in the UK, this method currently dominates the hydrogen transport sector. Most of the hydrogen refuelling stations in the UK utilise electrolyser technology to produce hydrogen fuel for FCEVs.

Measurement challenges for electrolysis

Exploring novel materials to reduce the cost of electrolysers without compromising their performance or lifetime is important to the industry, as they often use expensive noble metals. The measurements challenges here are:

1. To establish standard test methods to determine if and why degradation is happening, to increase the lifetime of the electrolyser;
2. To develop *in situ* diagnostic techniques, modelling tools and standard test methods to probe critical degradation mechanisms;
3. To create online measurement techniques to improve quality control.

The hygrometer within an electrolyser, which is used to monitor water content in the hydrogen, will need to be validated against traceable standards to ensure it can provide accurate measurements. Currently, hygrometers can only be calibrated in nitrogen, whereas they need to be calibrated in hydrogen for this application.

Measuring the capacity and efficiency when introducing electrolysers at a large scale and the impact this may have on the electric grid in terms of balancing renewables and the high electricity demand required. This will be imperative to ensure that the grid is fit for purpose and able to cope with these new demands.

2.3 Emerging technologies

Emerging technologies are under development which could provide either lower cost or more efficient processes for the production of hydrogen. These include:

- **Photo-electrochemical reactors:** these devices use semiconducting electrode materials that combine two process steps for hydrogen production into one device (solar PV and electrolysis). Development of such devices is being undertaken at Imperial College London as well as other research institutes globally;

- **Chemical looping:** methane is converted to hydrogen and carbon monoxide through cyclic reduction and oxidation reactions of fuel with an oxygen carrier. This produces two separate pure streams of hydrogen and carbon dioxide (from methane and water), without the need for a separation process. Development is ongoing at Newcastle University and the University of Cambridge;

- **Thermochemical processes:** this includes, for example, 'cracking' water at elevated temperatures aided by chemical reactions [9].

Measurement challenges for emerging technologies

As these technologies and methods potentially become more established, measurement challenges could arise which will need to be addressed. Presently, challenges here are emergent and less urgent, and therefore lower priority.

3 Hydrogen storage

Once produced, hydrogen can 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 [4].

Options include storing hydrogen:

- **As a gas in salt caverns (purpose-built geological features or 'natural aquifers') or in depleted natural gas fields**
  Salt caverns are man-made underground holes created by washing salt out of large geological structures that are composed of almost pure sodium chloride. These could be used to store hydrogen gas at large volumes to address seasonal fluctuations in demand. The UK currently stores around 10,000 GWh of natural gas in salt caverns [4], which means there is a large resource of storage available for hydrogen to replace. There are substantial caverns in Teesside that have been operational since the 1960s, and are proposed for hydrogen storage by the H21 Leeds City Gate project [12], as well as in East Yorkshire, the Cheshire Basin and the Weald Basin [9]. Some hydrogen is currently stored in salt caverns, predominantly for use in chemical plants and oil refineries [4].

- **Compressed within specialised on-site tanks at high pressure**
  This is the primary method for storing hydrogen at refuelling stations within the UK. There is ongoing development of these tanks – the University of Ulster, for instance, has completed projects on explosion-resistant composite tanks for storage of high-pressure gases.

- **In a solid state (for example, within a powder form)**
  When using FCEVs, the hydrogen fuel can be stored within a powdered material, such as a hydride. Research is still being undertaken to establish materials that can store hydrogen efficiently without impacting the performance of the gas as an energy vector.

- **Cryogenically (in liquid form)**
  Liquefaction can increase the energy density of the hydrogen; however, this process requires energy. For example, the energy density of gaseous hydrogen would increase 'from 1.4 kWh/litre at 700 bar to 2.3 kWh/litre as a liquid'; however, the liquefaction process could require as much as 30% of its energy content [9].

- **Within ammonia**
  Ammonia (NH_3) has the potential to provide an on-demand and *in situ* vector of hydrogen fuel and has many advantages compared to the direct storage of compressed or cryogenic hydrogen. Ammonia is already produced on an industrial scale, can be easily liquefied and has a volumetric density of hydrogen around 45% higher than that of liquid hydrogen. Generating power from ammonia is possible either as a direct fuel or by 'cracking' the ammonia to isolate the hydrogen for use in a fuel cell. However, there are a number of technical challenges in scaling both methods that need to be addressed to give the public confidence in the potential use of ammonia, outlined in the 'Measurement challenges for hydrogen storage' box below.

Measurement challenges for hydrogen storage

Measuring the efficiency of each storage mechanism for potential use on a national scale, as well as understanding the efficiency of the intraday storage mechanisms (fluctuations in demand during a single day as opposed to seasonally) as these will be important in establishing which is the most appropriate storage solution.

Measurement of the potential leakage from salt caverns or depleted gas fields will be fundamental in addressing safety concerns as well as the efficiency of these storage solutions.

Further live field trials for large-scale hydrogen storage mechanisms such as salt caverns and depleted gas fields need to be carried out to not only demonstrate the suitability and capacity available, but to understand any implications of contaminating the hydrogen from remnant gas and establishing the purity of the gas once removed from the storage mechanism.

Measuring the capacity, efficiency, rates of charge and discharge for cryogenic storage mechanisms, as storing hydrogen as a liquid at low temperature means a substantial amount of energy is consumed in the liquefaction process. Difficulties are also faced during handling of the liquid, as well as losses due to boil-off – these issues need to be explored further to understand how they can be addressed.

Establishing the type of material best suited to storing hydrogen within a tank, to avoid leakage and embrittlement, will be important as liquid hydrogen tanks can store more hydrogen in a given volume than compressed gas tanks.

There are a number of measurement challenges surrounding the use of hydride storage in FCEVs, including the ability to measure the amount of stored hydrogen so it can accurately inform the driver when to fill up again. Additionally, car manufacturers will need to understand whether the purity of the hydrogen changes as a result of storage within the hydride for instance.

The hydrogen extracted from ammonia when used as a storage mechanism must be compliant with the ISO standard for use in a fuel cell, and therefore cannot contain more than 0.1 parts-per-million of ammonia (explored in section 6.2). It will also be vital to be able to make accurate leakage measurements to provide safety assurance and establish the efficiency of this process.

4 Hydrogen distribution

Once produced, hydrogen can be fed into storage mechanisms (as outlined in section 3) or directly into the distribution network. It is currently unclear whether the existing energy infrastructure can support the introduction of hydrogen gas and hydrogen technologies. Some of the current reports and roadmaps predict hydrogen will most likely be produced at central locations upstream, similarly to conventional gas, which would take advantage of the existing gas infrastructure when it comes to its distribution.

However, generating hydrogen at the point of use would save on transport costs and reduce emissions related to transporting the gas. Currently, 95% of hydrogen produced globally is created and used in the same location [13]. Having the appropriate infrastructure for its production and use *in situ* may not always be feasible, so robust and efficient distribution and transportation methods will be required in some cases.

4.1 Hydrogen in the grid and integration within the existing energy infrastructure

Industry experts have noted that the most practical method for the deployment of hydrogen into the grid would be by initially converting sections of the distribution network and then later linking those together with the transmission network. If several 'hub' areas were to invest in this model, this may make a business case for them to 'share the load' when demand is high [14].

In terms of the existing infrastructure in the UK, the NTS (National Transmission System) and LTS (Local Transmission System) are both designed and built to the same technical standards and specifications with regards to the materials that are used [12]. As the NTS and LTS are constructed using a hard steel, they are not optimised for the transportation of hydrogen at high pressures due to hydrogen embrittlement issues and potential leakage. These issues are likely to occur at weak points such as at welded joints, but have the potential to arise almost anywhere within this high-pressure system [12].

At present, polyethylene (PE) pipes are considered a suitable material for carrying hydrogen up to 100% concentration. PE pipelines have also been seen to be more appropriate for distributing natural gas safely and efficiently, which has led to the current national Iron Mains Replacement Programme in the UK, due to be completed in the early 2030s [15].

Nevertheless, it is vital to establish a regulatory framework for the blending of hydrogen into the natural gas grid, as it is likely that the integration of hydrogen will involve a gradual mix, where the ratio of hydrogen to natural gas is increased incrementally over time. Should the UK wish to introduce blends of hydrogen and natural gas, or a 100% hydrogen concentration into the existing grid before the completion of the Iron Mains Replacement Programme, then further research would be required on the impact that the injected hydrogen would have on grid infrastructure and vice versa.

These are some projects that aim to demonstrate how hydrogen could be integrated into the grid:

- Hydrogen is known to cause embrittlement issues for many metals and is also extremely light, so can more easily leak than methane. The National Grid aims to better understand this through the '**HyDeploy**' **project**, which will introduce hydrogen onto a live gas network and test hydrogen blends with natural gas to assess how it behaves within the grid, without needing to replace appliances or equipment within the existing network;

- The '**H21 Leeds City Gate**' project (for which an extensive feasibility study has already been published) aims to assess the viability of transforming to a hydrogen economy both from a technical and commercial viewpoint [12], by converting Leeds's existing natural gas infrastructure incrementally to 100% hydrogen dependency.

Measurement challenges for hydrogen distribution

Impact analysis of odorants on end use applications. Similarly to natural gas, hydrogen is odourless. The likely solution to ensure hydrogen gas leaks are detected is to add an odorant. Once a suitable odorant has been identified to make it detectable and to give hydrogen a recognisable smell, it will be important to understand how this odorant would be added, by whom, and at what stage of distribution, as well as how the odorant behaves with the hydrogen within the pipes or in appliances. If the grid hydrogen is required for transport applications, effective methods of removing the odorant would be required.

Purity and gas blend concentration analysis across the gas network. If several different companies are injecting hydrogen at different places, then this may cause issues when establishing what the concentration is at a certain point or time. Therefore, providing traceability with regards to where the gas supply has come from if hydrogen were to be injected into the natural gas grid, as well as measuring what the purity and concentration are at the time of injection, and what these are at each exit point, are vital issues to address. It has been proposed by several industry experts that each energy unit containing hydrogen could have metadata attached to it, which specifies its origins, whether or not it came from a carbon-intensive source, whether it was imported and other such factors, which would give it not only 'traceability' but 'value'.

Measurement of the blend ratio if hydrogen were to be mixed with natural gas would be important for a scenario where it is incrementally added into the existing gas network because it would affect the cost that consumers are charged for it per unit volume.

Recalibration of gas detectors for hydrogen distribution pipelines, at substations and at refuelling stations will be important to ensure they are suitable for sensing hydrogen in the air in terms of adequate leak detection for health and safety standards and emergency response.

Measurement of material performance and lifetime within the distribution pipeline is essential to ensure the material selection is adequate and to mitigate against potential leakage should hydrogen be introduced at varying concentrations and blends.

Measuring which impurities are currently present within the grid distribution network, and subsequently testing the effect of these impurities on fuel cells, as this will be vital for end-user reassurance of the quality of hydrogen they are receiving and the potential impact of the odorant on lifetime and durability of the end-use appliance.

5 Hydrogen end-use

Hydrogen must be converted from its gaseous form for energy to be harnessed, either through an electrochemical reaction in a fuel cell or when burned directly to produce heat. This requires specialised technologies and appliances that are compatible with hydrogen.

These hydrogen end-use applications are often subject to limitations due to their capital cost as they require the use of expensive materials; however, economies of scale and mass production could allow these technologies to compete economically with other low-carbon alternatives [16].

5.1 Transport

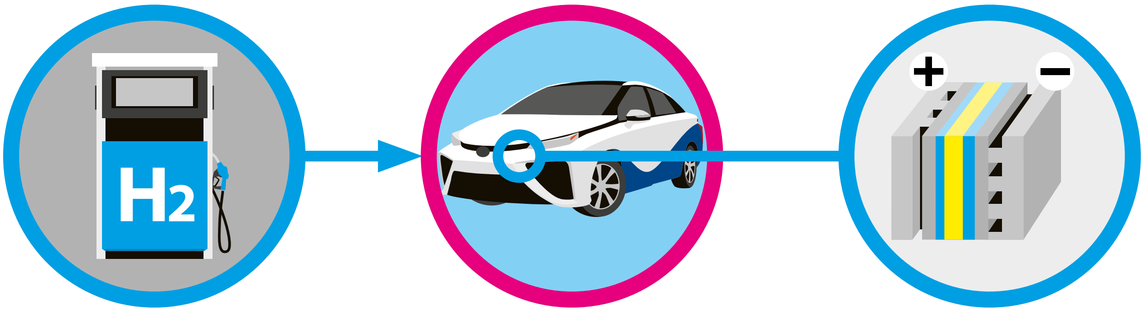
According to the International Energy Agency, deploying a 25% share of FCEVs on to the roads by 2050 'could contribute up to 10% of all cumulative transport-related carbon emission reductions' globally [3]. FCEVs also support efforts to improve air quality as they do not emit the pollutants associated with fossil-fuel combusting vehicles.

FCEVs are better suited to longer-distance road transport such as vans, small boats, buses and HGVs [16] than EVs, as they have a much faster refuelling time, a longer range and require few behavioural changes from the end-user in terms of refuelling habits.

The UK H2Mobility project made the case for FCEVs and outlined the benefits to the UK energy system should an up-front investment be made by government [17]. In October 2014, the UK Government announced the Hydrogen for Transport Advancement programme (HyTAP) 'to break the chicken-and-egg problem of no refuelling infrastructure meaning no vehicle deployment and no vehicle deployment making infrastructure un-investable' [16].

In addition to this, the European Union HyFive project brought together a consortium of stakeholders to promote the use of FCEVs within London and aimed to deploy a number of refuelling stations in the UK (the first being at NPL which opened in May 2016 [18]), and the H2ME project, which is co-funded by the European Union's Horizon 2020 programme through the Fuel Cells and Hydrogen Joint Undertaking (FCH JU), will see a further 325 vehicles using fuel cell technology and 25 refuelling stations deployed throughout 10 European countries including the UK by 2019 [19]. A report by UK H2Mobility estimates there will be 1.6 million FCEVs in the UK by 2030 [17], and these projects and infrastructure roll-outs could see this figure become a reality.

There are also a number of small-scale hydrogen technologies, such as phone chargers, hydrogen-fuelled torches and drones that use miniature fuel cells [20]. Development and proliferation of these types of portable, light-weight technologies would allow the hydrogen industry to see near-term gains as they do not rely upon large-scale system decisions or infrastructure roll-outs.



Measurement challenges for fuel cells

Development of a suitable, validated method for particulate measurement to comply with ISO 14687-2 (the purity specifications for using hydrogen for road vehicle applications), as this is paramount for the automotive hydrogen industry to succeed, as proof of the quality of the hydrogen being produced has major implications for the functioning and durability of the fuel cell within vehicles. To refine ISO 14687-2 there needs to be an improved system for testing fuel cell degradation using controlled environments and accurate gas standards (in hydrogen) which allow the tests to be performed with high accuracy (providing a suitable uncertainty budget).

Development of diagnostic techniques for fuel cells to support the mitigation of critical degradation mechanisms such as loss of catalyst surface area, catalyst poisoning, bipolar plate corrosion, membrane thinning and loss of hydrophobicity in gas diffusion media to improve fuel cell durability.

Improved methods for quality control of manufactured components to ensure cost savings and improved performance and lifetime of commercial systems.

Development of next-generation materials for fuel cells supported by novel measurement techniques for characterisation of performance at the micro and nanoscale, for example scanning probe and spectroscopic methods, with the aim of reducing the cost of these technologies without compromising performance and durability.

Assessment of the impact of contaminants both from the fuel and airborne on fuel cell performance and lifetime. While the purity requirements for hydrogen are well established, there are no current standards for the quality of air that should be provided to the fuel cell system. Although this may not be so concerning for stationary applications in closed environments, the quality of air could cause problems on the road if, for example, a hydrogen vehicle is driving behind a petrol car that is emitting parts-per-million levels of carbon monoxide or hydrocarbons.

Fuel cell research at NPL

NPL has developed a range of novel *in situ* measurement techniques, modelling tools and standard test methods to support commercialisation of polymer electrolyte membrane (PEM) fuel cells and electrolysers.

Recent research at NPL has overcome the challenges of *in situ* measurement in PEM fuel cells by developing straightforward methods to be implemented in real systems, to monitor active surface area of electrode catalysts and local electrode potentials. NPL has developed:

1. Novel galvanostatic technique for monitoring the electrochemical active surface area of each cell in a fuel cell stack;
2. An innovative reference electrode that allows mapping of the spatial variation of electrode potential across the active area of PEM fuel cells, which is easily implemented at technical scale with minimal perturbation of the system;
3. Successful implementation of the *in situ* reference electrode in PEM electrolysers, allowing individual monitoring of the performance of the hydrogen and oxygen electrodes in a PEM water electrolyser.

To complement and better understand the mechanisms occurring inside a fuel cell, NPL is also developing a 3D multi-physics model of PEM fuel cell performance in an accessible software platform, providing a design optimisation tool for industry and enabling a better fundamental understanding of these technologies.

5.2 Combined heat and power (CHP)

Micro-CHP systems that utilise fuel cell technology with hydrogen as the fuel have been described as 'attractive solutions for decentralised electrical energy production with high efficiency' [21].

Some countries are developing policies that support and promote the use of fuel cell CHP systems, for instance, by implementing subsidies. High installation costs as well as lack of policy drivers have meant that their uptake in the UK is significantly lower than countries such as Japan and Germany. By 2020, the Japanese government has set a target of 1.4 million fuel cell CHP systems to be installed and the European Union has set a target of 50,000 systems [22]. Many research, development and demonstration programmes focus on micro-CHP development, with commercialisation targets of thousands of fuel cell CHP systems worldwide [21].

There are still some uncertainties surrounding the suitability of certain 'categories' of fuel cell to cope with the demands of a heating system and the scale of decarbonisation efforts that are required in the heat sector. For example:

- Solid oxide fuel cells (SOFCs) experience longer start-up times than other types of fuel cell, as well as facing temperature cycling issues that can impact their lifetime and thus their commercial value for domestic use;
- Low-temperature PEM fuel cells require a high-purity fuel, which may pose an issue depending on how and where the hydrogen is produced and the subsequent need for purification before use to avoid any degradation of the fuel cell.

Although these are not specifically measurement challenges, they are research and development areas that will require investigation.

5.3 Combustion for heat

In the UK, 23 million homes are currently dependent on natural gas for heat [9], and the energy required to heat hot water and for space heating alone in these properties is responsible for 20–25% of total carbon emissions [2]. Decarbonising heat is therefore pivotal to the UK's emission reduction targets.

The Committee on Climate Change has estimated that, by 2050, around 60% of heat demand in domestic, commercial and industrial applications could come from hydrogen [16]. Hydrogen combusts similarly to the natural gas that is commonly used within homes today so would not require a change in habits or any major changes to the existing heating system. Alternatives include heat pumps and electric boilers; however, these are often expensive options that are difficult to retrofit into buildings. In addition, heating creates more drastic spikes in demand on power supply as compared to electricity demand and therefore the electricity grid may be less able to accommodate this high variability [23].

If 100% hydrogen replaces natural gas for providing heat to buildings, it would require boilers, appliances and meters to be converted in a similar manner to the conversion from 'Town Gas' infrastructure in the 1970s. The development of these new hydrogen appliances will require assurance to both industry and consumers of their durability and performance. To minimise disruption and the need for behavioural changes by consumers, existing gas boilers and hydrogen boilers should be comparable in terms of cost, maintenance and ease of use.

Measurement challenges for combusting hydrogen

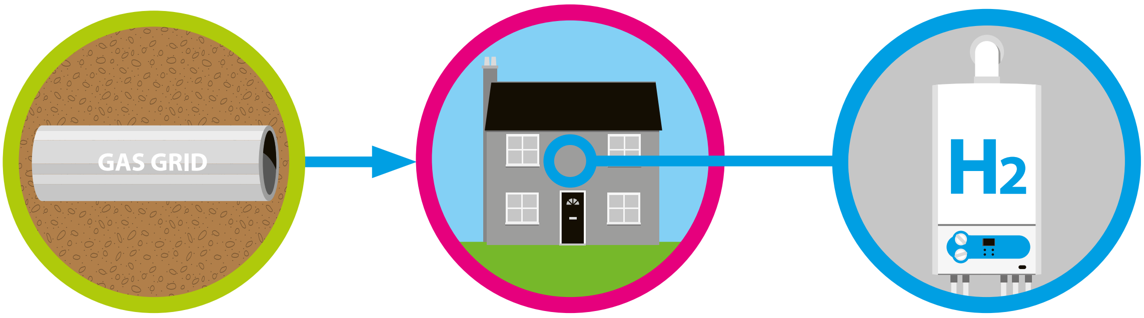
Measuring what happens quantitatively during combustion within the boiler when hydrogen is either mixed with natural gas and combusted for heat energy, or combusted at 100% hydrogen concentration. This will establish what concentration of hydrogen would require existing boilers to be upgraded for hydrogen compatibility and which new features a hydrogen boiler will require.

Measuring the emissions that are produced when burning a mix of hydrogen and natural gas to ensure standards are met in terms of purity, safety and the potential effects on the durability of the materials within the appliances.

Developing methods for detecting and measuring hydrogen flames to ensure domestic boilers and appliances conform to safety regulations. This will require the ability to measure how acceptably 'visible' the hydrogen flame is as well as its characteristics including flame propagation, temperature, radiation and NO_x emissions.

A comparison of radiation convection ratios between hydrogen and natural gas flames, as well as varying mixtures of both. The appliance industry will need to be able to compare the characteristics of the flames and establish whether there will be changes in behaviour needed by consumers. One example is whether, when used for cooking, hydrogen flames cook food in the same way as natural gas.

Measuring free oxygen and unburnt hydrogen in very wet combustion products, to assess the potential impact on the efficiency of the process and on the end-use appliance.



5.4 Metering

Accurate metering is a challenge when it comes to distributing hydrogen for its end-use application. If hydrogen is blended with natural gas or pumped as pure hydrogen for combustion, it will be important to determine the amount of hydrogen the end-user is receiving as well as its energy content.

Accurate flow metering will also be critical for the transportation sector, as FCEV users will want to know they are getting what they pay for at the pump.

To not address metering challenges may pose a significant issue and risk for scaling hydrogen dispensing methods to the global market and ultimately being able to charge consumers fairly and accurately for the amount of hydrogen they receive. These meters would need to be developed and validated in compliance with the Department for Business, Energy and Industrial Strategy (BEIS) Regulatory Delivery team, who lead the standardisation and monitoring of energy meters in the UK.

Measurement challenges for hydrogen metering

To develop accurate online hydrogen flow meters for use at refuelling stations and for domestic metering. Within the existing gas infrastructure in the UK, pressure is monitored rather than flow, as it is technically cheaper and easier to implement.

For use within a domestic or commercial property, development of these meters must include:

1. **Validation of volumetric metering** including bellow meters, smart and electronic meters, and correlation technologies at varying concentrations of hydrogen blend up to 100%, as this is imperative to ensure the accuracy of the measurement that the meter is making;
2. **Measurement of calorific value (CV) locally**, especially when the hydrogen will be blended, and knowledge of how this may affect accuracy of billing, as this is currently performed by measuring end-point flow, volume and CV;
3. **Measurement of the level of trace air in the hydrogen** that may be present by quantifying the permeation of air into the distribution pipelines, as this may have implications for the performance of end-use appliances.

For use at a refuelling station, development of flow meters must consider existing standards by which the refuelling stations operate and how these may impact the measurements.

Metering of hydrogen in storage and monitoring flow in and out of the storage mechanism accurately. This is important to ensure accurate billing and to keep track of potential leakage from the storage mechanism.

6 Standards

6.1 Distribution

In the UK, hydrogen content in the gas grid is currently limited to ≤0.1% (molar) by volume as per Gas Safety (Management) Regulations [24]. In Germany, for example, higher levels of 10% by volume are allowed, or 3% by volume where the grid gas may be fed to CHP engines or compressed natural gas (CNG) refuelling stations [13]. For hydrogen to play a role in the decarbonisation of the UK's energy system, one option is to allow for a blended mixture of hydrogen and natural gas, which would involve incrementally increasing the current standard maximum hydrogen concentration within the grid.

6.2 Fuel cells

Fuel cells utilise hydrogen combined with air with a high efficiency to produce power. However the stringent purity specifications of the hydrogen outlined in ISO 14687-2 (for road vehicle applications) and ISO 14687-3 (for stationary applications) can be a drawback for these technologies.

As low-emission vehicles such as FCEVs become more widely used, these purity standards and the required level of expertise needed to measure them could create a major bottleneck within the hydrogen vehicle industry.

International engineering and standardisation work will be required to allow technology and product transfer between countries [13], and to ensure vehicle developers are able to commercialise FCEVs internationally.

In terms of the gas itself:

- There is currently an EU Directive in place (2014/94/EU), commonly referred to as the AFID (Alternative Fuels Infrastructure Directive), which mandates that the hydrogen gas dispensed at refuelling stations in Europe must meet the purity specifications of ISO 14687-2: for use in a fuel cell vehicle;
- At present, the calibration gas standards and validated methods for measuring the 13 impurities noted within the standard are not all available and NPL is currently the only laboratory worldwide accredited to ISO 17025 that can provide purity testing of fuel cell hydrogen to demonstrate compliance with purity specifications in ISO 14687-2;
- As National Measurement Institutes, NPL and its counterpart international organisations will now work to disseminate the developed capabilities to other national laboratories to enable potential future bottlenecks for higher demand for purity analysis to be addressed;
- There remain capability gaps in measuring all impurities required within the standards as there is no known method for analysing total halogenated compounds (where the maximum limit is 50 parts-per-billion – see case study below). To address this, experts of ISO TC 197 WG 27 are proposing to replace total halogenated compounds with a list of specific compounds each with an assigned uncertainty;
- Due to the challenging measurements required by ISO 14687-2, if another laboratory were to carry out such measurements, they would need to acquire a number of state-of-the-art gas analysers at high capital cost, as well as provide evidence showing compliance with ISO 17025, which raises the need for regular inter-laboratory comparisons.

Hydrogen purity laboratory at NPL

NPL is a key player in the field of hydrogen purity for fuel cell vehicles, providing an accredited hydrogen purity measurement service to enable hydrogen refuelling stations to show compliance with ISO 14687-2. In addition to this service, NPL performs novel research to develop new traceable methods and primary reference materials (PRM) that allow commercial laboratories to provide a traceable purity measurement service.

NPL has developed a hydrogen impurity enrichment device for concentrating the impurities in a sample of hydrogen before performing purity analysis. This allows lower amount fractions to be measured using routine techniques, which can simplify and speed up purity analysis.

NPL's hydrogen purity laboratory is coordinating the first European Metrology Programme for Innovation and Research (EMPIR) project that focuses on some of the biggest measurement challenges faced by the hydrogen industry. The project 'Metrology for Hydrogen Vehicles' (MetroHyVe) will include four main work packages:

1. Developing traceable methods for calibrating hydrogen flow meters under refuelling conditions (700 bar and fluctuating temperatures);
2. Creating new methods and gas standards for hydrogen purity analysis in the laboratory;
3. Validating online purity analysers used for hydrogen quality control at the station;
4. Formulating best practice guides for taking representative samples of hydrogen at stations.

Project partners include other European National Measurement Institutes in addition to hydrogen producers such as Air Liquide, ITM Power, Linde and Shell.

6.3 Metering hydrogen

Refuelling stations must store hydrogen in accordance with the worldwide accepted standard SAE J2601, with nominal working pressures of 700 bar and a temperature range of -40 °C (pre-cooling) to 85 °C (maximum allowed vehicle tank temperature). These harsh operating conditions mean that it is difficult to provide sufficient traceability in flow metering measurements, which will need to be taken into account when developing hydrogen compliant meters.

The development of flow meters for use at refuelling stations must also be compatible with OIML R 139-1, which is the regulation for the equipment used to 'deliver compressed gases (natural gas, hydrogen, biogas, etc.) as fuel into fuel cell vehicles, small boats and aircraft'. This standard currently specifies that the flow meter must provide a relative accuracy of 1% (which is not achievable with commercially-available meters). A new work item proposal (NWIP) has been issued by OIML TC8 SC7 to develop a dedicated OIML standard for flow metering at hydrogen refuelling stations.

7 Summary of measurement challenges

The measurement challenges listed in the above chapters, which are summarised in the following table, were identified through desk based research, in-depth interviews with key stakeholders within the hydrogen industry and through a dedicated workshop on this topic held at NPL in November 2016. A list of the contributors can be found at the end of this document.

The table combines the challenges identified within each sector and technological application as explored throughout this document and prioritises these within the key themes of: fuel cells and electrolysers, safety, metering, combustion, distribution and storage.

Theme	Measurement challenge	Description	Priority
Fuel cells and electrolysers	Lifetime and durability	Advanced techniques for measurement of impurities in hydrogen to the threshold limits specified in ISO 14687	High
		Assessment of impact of contaminants (both fuel and airborne) on fuel cell performance and lifetime	High
		Development of novel *in situ* measurement techniques, modelling tools and standard test methods to characterise critical degradation mechanisms during fuel cell and electrolyser operation	High
		On board diagnostics for FCEV and hydrogen refuelling stations	High
	Materials development	Novel measurement and modelling techniques for characterisation of performance at the micro and nanoscale to support development of next-generation materials	High
	Quality control	Online techniques for real-time quality control of manufactured components, for example, membrane electrode assemblies, diffusion media, current collectors and bipolar plates	Medium
Safety	Odorants	Measurement of impact of odorants in hydrogen during pipeline transportation	High
		Measurement of the impact of odorants on fuel cell performance and lifetime	High
	Leakage	Recalibration of methane leak detection sensors for hydrogen	Medium
		Ability to measure hydrogen leaks and impact of release into the atmosphere	Low
		Validation of network leakage models and their accuracy	Low

Metering	Blended hydrogen–natural gas (grid)	Validation of volumetric metering including bellow meters, smart or electronic meters and correlation technologies at varying concentrations of hydrogen blend up to 100%	High
		Measurement of composition when blended and techniques for metering these new compositions in a cost-effective way	High
		Measuring calorific value (CV) locally, especially when hydrogen will be blended, and how this affects accuracy of billing as this is currently performed by measuring end-point flow, volume and CV	High
		Measurement of flow in a blended system (within the existing grid, pressure is monitored rather than flow)	High
	100% hydrogen (grid)	Determination of CV, similar to the issue for blended systems but for a scenario where 100% hydrogen is used	High
	Refuelling stations	Measuring volumetric flow rate of hydrogen dispensed from refuelling stations as required by OIML R 139-1	High
		Measurement of the temperature and pressure variation during the refuelling process	Low
	Energy metering	Ability to measure 'energy' for domestic meters	Low
Combustion	Flame detection and visibility	Methods for detecting hydrogen flames and the ability to measure how acceptably 'visible' the hydrogen flame is	High
	Combustion properties of hydrogen	Ensuring hydrogen quality standard is suitable for new or existing appliances and equipment	High
		Measurement of flame propagation, temperature and NOx emissions for hydrogen	Medium
		Measuring free oxygen/unburnt hydrogen in very wet combustion products	Low
Distribution	Embrittlement	Assessment of susceptibility to hydrogen embrittlement of materials used in construction of distribution infrastructure, including existing pipeline network	High
	Impurities from air	Determination of effect of air permeation, for example, through plastic tubing, on hydrogen composition	Low
Storage	Metering	Metering of hydrogen in underground storage for transmission network	High
	Salt caverns/depleted hydrocarbon fields	Accurate measurement of capacity and leak rate	Medium
		Measurement of hydrogen purity changes as a result of long-term storage in such locations	Low
	Solid-state storage	Measurement techniques and standard test methods for hydrogen capacity and absorption/desorption rate	Medium
	Cryogenic	Measurement of capacity, efficiency, rates of charge and discharge	Low
	For intraday use	Measuring efficiency of the storage mechanism on a national scale	Low

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