NPL

National Physical Laboratory

# Measurement challenges in the hydrogen sector

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**Contact**
To find out more about NPL's hydrogen work, contact our scientists or apply to join our Industrial Advisory Group please visit us at:

www.npl.co.uk/hydrogen

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# Executive summary

**As hydrogen technologies are being developed and deployed at unprecedented speed, metrology must support operations, standardisation, and innovations throughout the hydrogen economy** [1]**. This report presents a diverse array of current and future measurement challenges faced by the hydrogen industry within the UK and globally. These challenges were identified using stakeholder outreach through our Industrial Advisory Group and also with the desk-based research of NPL scientists.**

NPL has been working in the clean hydrogen sector for over 15 years and as of 2024 has approximately 30 experts from across multiple scientific disciplines working to develop the necessary measurement techniques, protocols, modelling tools and standards. Over that period, NPL's work in hydrogen has focused on supporting the development of fuel cells & electrolysers, providing reliable gas quality measurements, and developing new test capabilities to support the deployment of hydrogen infrastructure.

As we look to the future of hydrogen it's clear that there is a diverse range of measurement challenges that need to be addressed. Within this report, these measurement challenges are summarised in four different sections, production, storage, distribution, and end-use, each representing a crucial aspect of the hydrogen value chain.

Solving these challenges can help support the hydrogen economy and reach net-zero goals by:

- Reducing the production cost of electrolytic hydrogen.
- Supporting the rollout of hydrogen storage and distribution infrastructure.
- The development of new test facilities capable of advanced material research to support emerging hydrogen technologies.
- Filling gaps in regulation, technical and measurement standards throughout the hydrogen value chain.
- Supporting the decarbonisation of different industries by supporting the progression of hydrogen end-use technologies.

This document discusses these challenges along with case studies to show how NPL is looking to support the UK hydrogen strategy. A full list of challenges can be shown on page 17 of this report.

# Contents

# Introduction

## Purpose

The National Physical Laboratory (NPL) is a public sector research establishment founded in 1900 to **'bring scientific knowledge to bear practically upon our everyday industrial and commercial life'.** Part of our role is acting as the UK's National Metrology Institute. This means that alongside maintaining and developing the nation's primary measurement standards, we develop the measurement science required to ensure the timely and successful deployment of innovative technologies and work with organisations as they develop, testing new products and processes.

In 2017 NPL published its 'Energy Transition Report: Measurement Needs in the Hydrogen Industry' [2]. Since then, hydrogen has unequivocally become a key energy vector for the world to meet its climate ambition of maintaining average global temperature rises below 1.5 °C above pre-industrial levels, with many countries publishing ambitious hydrogen strategies. The UK is no exception and the government's 2021 hydrogen strategy includes estimations that between 20 % and 35 % of the UK's end-use energy demand will be met by hydrogen in 2050, with its use principally in the industrial, heat, power, and transport sectors [3]. As a result of this increased focus, this report looks to capture the new and continuing challenges faced by the hydrogen industry as technologies improve and scale rapidly.

The purpose of this report is threefold. It highlights a selection of key challenges across the hydrogen value chain where measurement science is a critical enabler of an accelerated transition to clean hydrogen. It summarises a range of specific measurement challenges identified by our UK based stakeholders as being important to their businesses and research. Finally, it provides examples of how NPL is deploying its capabilities to enable and accelerate a transition to hydrogen across the energy system.

## Methods

To identify and prioritise current and emerging measurement challenges, NPL engaged UK-based industrial stakeholders through its Industrial Advisory Group (IAG) and an online survey throughout 2023. This was combined with information from interviews, meetings, the views of NPL's scientists and other authoritative reports [4], [5], [6] to generate a robust list of challenges across production, storage, distribution, and end-use. This document introduces examples of key measurement challenges in each of these sectors and provides a list of the measurement challenges identified. Flow metering is not reported in this document as it falls within the remit of the National Engineering Laboratory.

### NPL's current research

NPL has been working in the clean hydrogen sector for over 15 years and as of 2024 has approximately 30 staff working on developing capabilities specifically to serve the hydrogen sector, as well as deploying existing measurement expertise where needed. Our core areas of hydrogen-specific capability include:

**Electrochemical hydrogen technologies** with a focus on low temperature fuel cells and electrolysers in areas including materials characterisation and supporting prototype device design and measurements.

**Hydrogen quality** with an accredited measurement service meeting industry needs and the development of new analytical techniques and international standards.

**Hydrogen emissions** with the development and validation of new techniques to measure fugitive hydrogen emissions from infrastructure, to limit product loss and greenhouse gas emissions.

**Hydrogen materials** with a focus on the development of standard test methods to assess the suitability of materials for hydrogen storage and distribution.

NPL has invested significantly in capability development through capital equipment procurement and research funded by the National Measurement System (NMS). NPL's capability development is informed by feedback from the **Metrology for Clean Hydrogen Energy Industrial Advisory Group** (IAG), which has technical representatives from over 30 UK based organisations with representation from start-ups to multinationals and across the hydrogen value chain.

Over the last five years, NPL has worked on over 50 different projects in the hydrogen sector. NPL generates direct impact from its work in hydrogen by meeting stakeholder needs either through routine services, bespoke consultancy work, or participation in grant-funded projects such as those from Innovate UK and the EU's Clean Hydrogen Partnership. NPL's more fundamental research, performed for the public good, is often disseminated through conferences, workshops, and publications, a selection of recent peer reviewed publications is presented in Annex A. This work is often performed with collaborators in international research organisations and academics across the UK, with NPL staff routinely co-supervising PhD students. Finally, NPL staff act as experts on hydrogen topics for all relevant national and international standards setting organisations.

# Production

For hydrogen to meaningfully contribute to a net-zero society it must be produced at scale, low cost and with minimal environmental impact. In 2023, the UK defined the Low Carbon Hydrogen Standard (LCHS) which constitutes the greenhouse gas emission intensity required for produced hydrogen to be deemed ‘low carbon’ and set a target of installing 10 GW of low carbon hydrogen production capacity by 2030 [7]. Meeting these goals will require significant improvements to the performance, durability and cost of clean hydrogen production technologies and deployment at an unprecedented scale.

There are many methods to produce clean hydrogen and the UK government’s position is broadly agnostic to the technology used [8]. The challenges identified by stakeholders prioritised electrolytic hydrogen production and this is therefore the focus here. Those challenges related to carbon capture, utilisation and storage, necessary enablers for hydrogen produced by reforming, are addressed in a separate NPL report [9]. Emerging methods of hydrogen production, such as waste and biomass gasification, may also play an important role in decarbonising hydrogen production and new challenges are expected to be identified as the sector evolves.

**Scalability**
Scalable to 1 TW installed capacity by 2050

**Cost**
Cost of hydrogen to be competitive with alternative energy vectors

**Cleanliness**
Meet low carbon hydrogen production emission standards

Key benchmarks to meeting low carbon hydrogen production goals

### Example challenges

#### Measuring operando performance & durability of new materials

A major pathway to reducing the cost and increasing the scalability of electrolytic hydrogen is by developing higher performance, more durable electrolyser components which use fewer critical raw materials. As new materials and components are invented, their performance and durability needs to be assessed in a laboratory using test methods representative of real devices. NPL offers this testing as a service to academics and companies, enabling independent verification of performance claims and de-risking investment. NPL is working internationally to standardise these test methods and assess reproducibility, to provide increased confidence in the data generated.

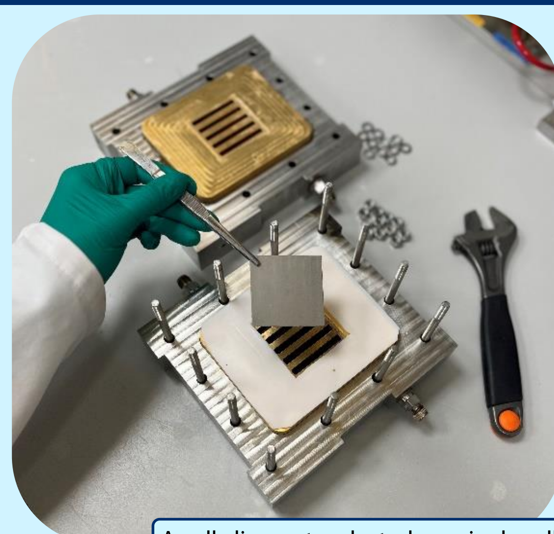
#### Measuring conditions & processes inside operational electrolysers

Accurately measuring the conditions and processes inside operational electrolysers underpins the understanding required to develop next generation devices; but making reproducible *operando* measurements without perturbing the subtle processes occurring in a device is highly challenging. Measurements of conditions and processes are used to parameterise and validate high fidelity simulations of electrolysers, to understand which processes cause electrolysers to lose performance over time, and to develop methods to assess the lifetime of materials more accurately, reducing materials conservatism.

## Case study: measuring electrode performance

**NPL supported Oxford nanoSystems (OnS), a UK SME, to help develop their catalytic coating technology for alkaline water electrolysers.**

As part of an Analysis for Innovators (A4I) project, NPL developed bespoke methods to measure the performance and durability of electrodes with OnS' novel catalytic coatings. By measuring the active surface area of the electrodes and performing single cell testing to simulate their operation in alkaline water electrolysers, NPL were able to provide OnS with an assessment of their electrode's performance relative to a state-of-the-art benchmark.



An alkaline water electrolyser single cell

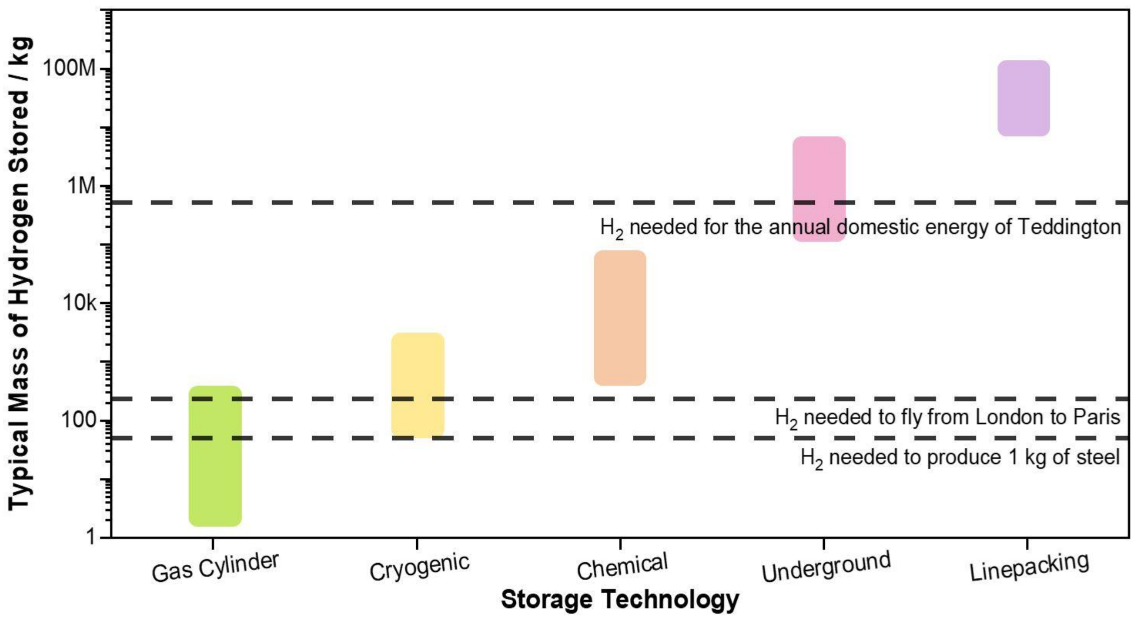
**"We partnered with NPL to gain insights into the capabilities of our technology. This analysis has empowered our product performance, strengthening our value proposition."**

- Alexander Reip, CTO of Oxford nanoSystems

**Find out more about validating alkaline water electrolysers performance**

# Storage

Different storage methods are used for the wide range of hydrogen end-use applications, each optimising hydrogen's relatively low volumetric energy density against cost and efficiency [4]. For example, while light-duty fuel cell electric vehicles have opted for compressed gaseous hydrogen, heavy-duty applications such as the aviation sector are likely to adopt liquid hydrogen, see graph below. A huge advantage of hydrogen is its long-term energy storage capabilities, with the UK committed to storing hydrogen in large underground salt caverns, such as those found at Teesside, repurposing current natural gas stores [10]. Optimising each of these energy storage solutions for different applications represents an essential element to unlocking the hydrogen economy.




Graph showing a range of storage methods and their likely range, corresponding to examples of end-uses

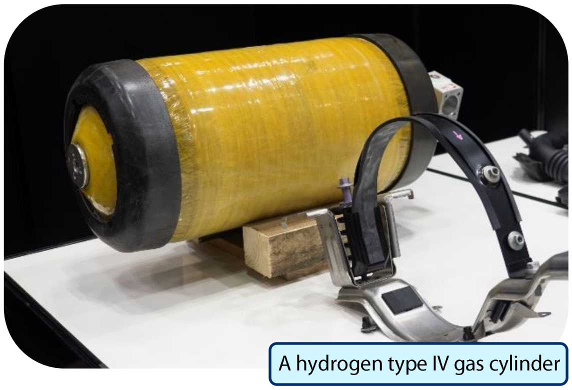
### Example challenges

#### Assessing material suitability for cryogenic hydrogen storage

Cryogenic or liquid hydrogen ($LH_2$) is a method of storing and transporting hydrogen at nearly twice the volumetric energy density of gaseous hydrogen at 700 bar [10]. It represents the technology with the greatest potential to decarbonise the aviation industry [11]. However, the hydrogen must be cooled to a temperature of -253 °C leading to challenges in material property requirements, increased safety risks and the need to control boil-off losses [12]. Advanced materials are essential for applications like on-board vehicle storage, and so, establishing validated measurement methods for these materials at cryogenic temperatures, and in the presence of $LH_2$, is essential. Furthermore, realising the potential of this technology is dependent on filling gaps in regulation, technical and measurement standards. This will require producing the necessary testing infrastructure to tackle this challenge [13], [14].

### Hydrogen permeability

Hydrogen can readily permeate through materials. Measuring permeation rate accurately is crucial in understanding how to prevent leakage in many types of storage. The state-of-the-art tanks used in hydrogen vehicles (type IV tanks) are defined by ISO 19881, which states that the steady state permeability of hydrogen should be less than 6 N $cm^3h^{-1}L^{-1}$ [15]. Exploring which lightweight materials can be used for the next generation of tanks and improving the measurement of hydrogen permeability is an active measurement challenge NPL is pursuing.



A hydrogen type IV gas cylinder

## Case study: hydrogen permeation cell

**NPL's Advanced Engineering Materials and Energy Gas Metrology groups have developed an innovative method for investigating hydrogen permeability through different materials using a device called a permeation cell.**

The cell works by utilising two chambers, the top filled with high-pressure hydrogen gas, and the bottom with a low-pressure inert gas. Hydrogen permeates through the test material from one chamber to the other and the amount of hydrogen that permeates is measured by the increase in pressure in the bottom chamber. Recent work at NPL has demonstrated the improved barrier properties that certain epoxy-based composites have when compared to conventional thermoplastics, such as LDPE & HDPE.

**This technique is expected to enable more accurate, accessible, and quicker measurement of hydrogen permeability.** The team is currently working to develop this technique as a measurement service and to expand its capability to measure permeability over an extended range of temperatures.

The hydrogen permeation cell

**Find out more about the hydrogen permeation cell**

# Distribution

Hydrogen is most easily generated close to renewable electricity sources and stored in places with the correct geology or processing equipment but will be used in population centres. Hydrogen must therefore be safely and efficiently distributed. Within the UK and globally, existing natural gas networks are likely to be repurposed, but a large proportion of hydrogen will also be delivered via enhanced freight and shipping networks, particularly for the exporting and importing of hydrogen internationally [16]. Throughout the world, new distribution infrastructures are being installed to support 100 % hydrogen distribution using composite materials made from polymeric materials [17]. To support the repurposing of old infrastructure and development of new infrastructure, many challenges that encompass the hydrogen economy must be studied and overcome.

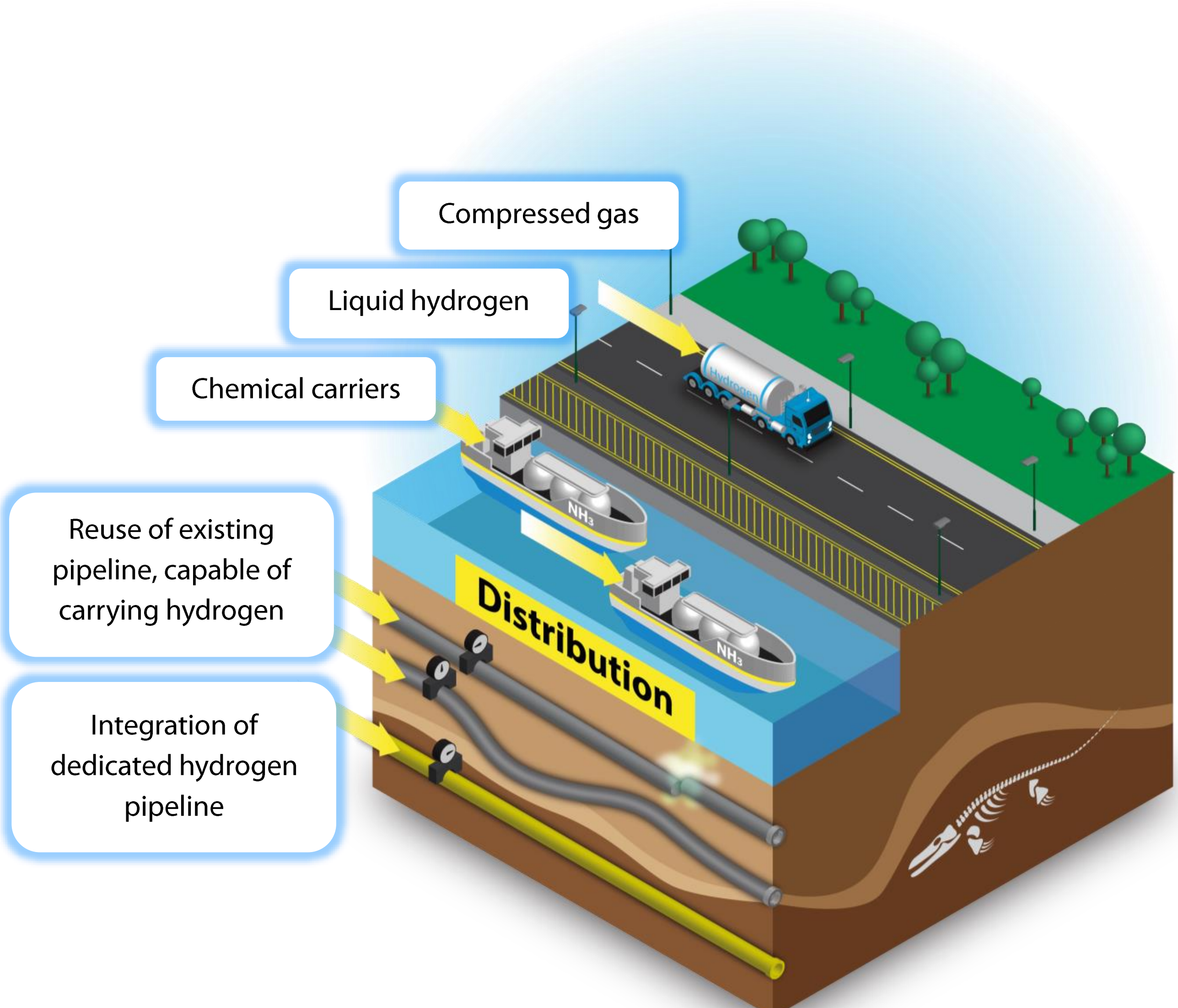



Illustration showing examples of how hydrogen can be distributed via freight in different forms, as well as through existing, and new pipeline

## Example challenges

### Hydrogen embrittlement

Hydrogen embrittlement describes the premature failure of metals due to changes in mechanical properties caused by hydrogen atoms permeating their crystal structure. It is a concern wherever metals are in contact with hydrogen, for example in a repurposed natural gas pipeline composed of carbon steel [18]. To provide confidence in the safety of hydrogen infrastructure, robust data on the susceptibility of different metals in a range of conditions is required. Research on hydrogen embrittlement has been a theme for the corrosion team at NPL for over three decades and NPL is a world leader in the methods used to characterise hydrogen embrittlement including experimental and computational techniques [19], [20]. An important challenge in this field is the development of validated procedures for the assessment of material fatigue due to hydrogen embrittlement at high pressures up to 200 bar. An essential aspect of tackling this challenge is the development of new facilities capable of these measurements.

## Case study: rapid testing for hydrogen embrittlement

NPL has worked with several gas network operators to help investigate the susceptibility of different metals to hydrogen embrittlement. This helps inform gas distributors of the suitability of their current pipeline networks for use with hydrogen.

This recent work has involved slow strain rate testing (SSRT) of four different materials commonplace in legacy gas networks in a gaseous hydrogen environment at room temperature. The NPL team used a SSRT machine in which materials were strain tested under air, pure, and contaminated hydrogen at 1 ± 0.05 bar. No apparent effect of hydrogen embrittlement on mechanical properties was observed for all materials.

A slow strain rate testing machine

This work focused on networks operating at low pressures, such as domestic household piping. Work is underway to investigate the embrittlement of materials at higher pressures, giving an insight into how hydrogen may affect piping materials in higher capacity gas transmission systems.

**Find out more about NPL's hydrogen embrittlement work**

## Leaks and emissions

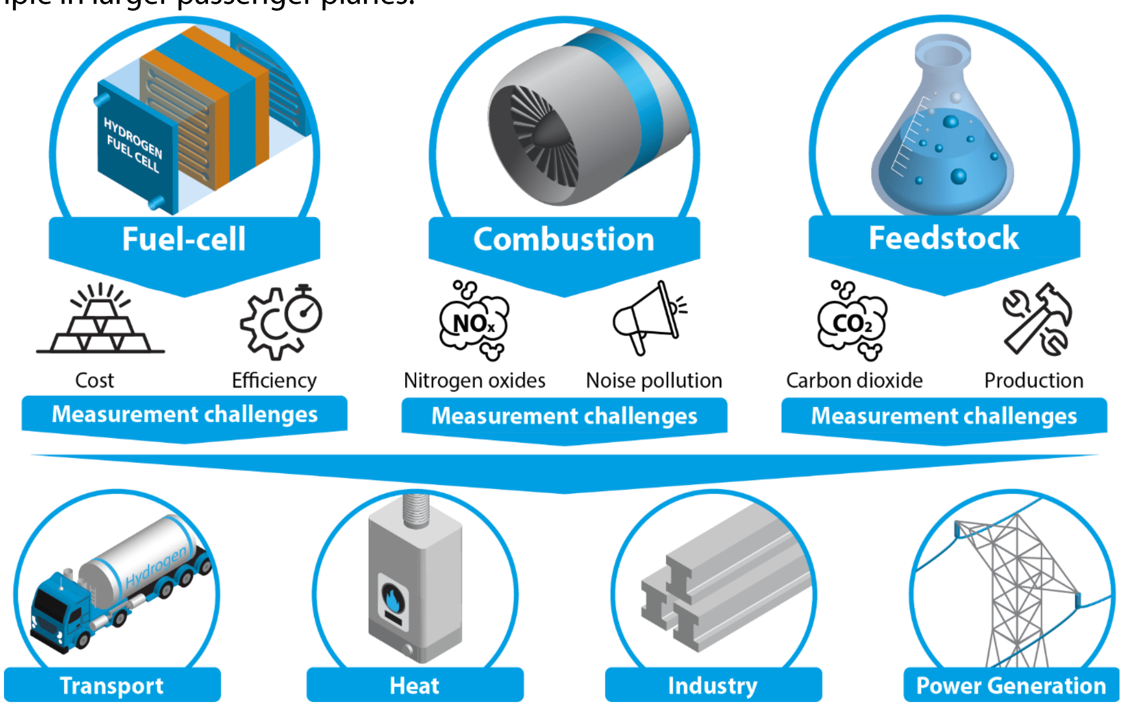
As hydrogen infrastructure is deployed, measuring hydrogen leakage will become an increasingly important challenge. While hydrogen leaks can pose a safety risk in high concentrations, a bigger challenge is quantifying these leaks to prevent both product loss and reduce harmful emissions as hydrogen can act as an indirect greenhouse gas with a 100 year global warming potential (GWP100) estimated to be 11.6 ± 2.8 $CO_{2equiv}$ [21], [22]. Detecting and quantifying hydrogen emissions requires similar technologies to those currently in place for natural gas, however due to hydrogen's poor absorbance in the infrared region, many of the methods used for leak detection in the oil and gas industry are not readily transferable to hydrogen systems. To help mitigate the risk of leakage, standardised methods capable of detecting releases at differing scales will need to be developed. NPL is helping to solve this measurement challenge by developing capabilities for both detection and quantification of hydrogen emissions at component and site area level. The approach here is to review potential emission scenarios and develop test rigs suited to detecting hydrogen and blended hydrogen natural gas.

A portable sniffer for detecting methane leaks, **left**, and a portable high flow sampler for quantifying methane emissions, **right**. Both capabilities at NPL, soon to be developed for hydrogen

# End-use

As different industries transition towards decarbonisation, hydrogen represents an ideal energy vector where electrification and battery storage are unable to compete with fossil fuels. End-uses such as industry and power are expected to be the initial driving forces for low carbon hydrogen demand with up to 19 TWh being required towards 2030. Transport is set to reach this level of demand in 2035, predominantly in heavy transport modes, such as heavy goods vehicles, aviation, and maritime. In the UK, the scale of hydrogen to be deployed for heating remains highly uncertain [3] .

Hydrogen has historically been used as a chemical feedstock in processes such as ammonia and methanol production, and in the future, low carbon hydrogen will be used to produce these chemicals and others in more sustainable, and environmental manners. Burning hydrogen is a zero-emission replacement for burning natural gas. It is therefore likely to be used in industrial processes such as steel & glass manufacturing or in boilers for heating scenarios where alternative solutions are impractical. Hydrogen may also replace natural gas for on-demand electricity generation to smooth transient renewables both at the grid-scale where it may be combusted in turbines, or in local back-up and off-grid power systems [23]. Fuel cells represent a proven technology with a high efficiency, and work using electric motors. Internal combustion engines running on hydrogen or hydrogen carries have also been demonstrated and are likely to be required where very high powers are required, for example in larger passenger planes.




Methods of using hydrogen, examples of their respective challenges, and potential end-uses

### Example challenges

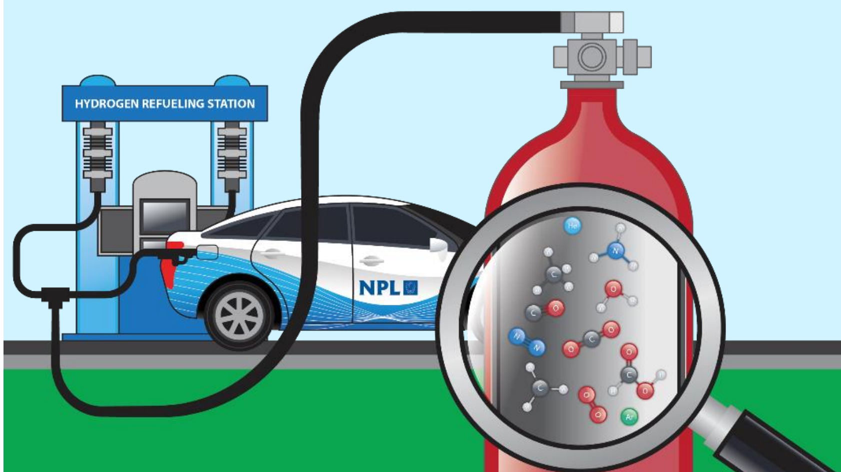
#### Hydrogen gas quality measurement

Every application of hydrogen is sensitive to the level of purity supplied and with each stage of the value chain, there is a potential for impurities to contaminate hydrogen. Therefore, accurate and traceable measurements of gas quality are imperative to protect equipment, manage processes and price hydrogen. NPL has world leading capabilities in hydrogen purity testing and is at the forefront of research publications in the area, see Annex A for more. A range of measurement challenges are associated with this research area, including making analysis more reliable and cost effective, developing new sensor technologies, and implementing online quality analysis [24].

## Case study: quality sampling at hydrogen refuelling stations

**NPL supports the hydrogen industry by being one of a handful of labs globally capable of the analysis of hydrogen quality to the international standard ISO 14687:2019(D).**

ISO 14687:2019 Grade D, specifies the maximum threshold for many impurities in hydrogen for fuel cell electric vehicle (FCEV) applications, see table below. Measuring to this standard is extremely challenging because of the high number of compounds (chemical compounds and particulate) that must be tested for and their relatively low concentrations. NPL uses a parallel sampling strategy, in which the hydrogen fuel delivered to a FCEV by the hydrogen refuelling stations (HRS) is simultaneously sampled into an aluminium sampling cylinder, see illustration below. This cylinder is then analysed by 10 different instruments to determine the concentration of each chemical listed in the standard.




| Impurities | Tolerance Limit (µmol/mol) |
|---|---|
| Water | 5 |
| Methane | 100 |
| Oxygen | 5 |
| Helium | 300 |
| Nitrogen | 300 |
| Argon | 300 |
| Carbon Dioxide | 2 |
| Carbon Monoxide | 0.2 |
| Sulphur Compounds | 0.004 |
| Formaldehyde | 0.2 |
| Formic Acid | 0.2 |
| Ammonia | 0.1 |
| Other Hydrocarbons | 2 |
| Halogenated Compounds | 0.05 |

Illustration showing simplified parallel sampling strategy with a table listing the impurities specified in ISO 14687 Grade D

This state-of-the-art capability of the NPL Gas Metrology team has been developed by establishing a strong philosophy of accuracy, traceability, and robustness. Using this, NPL supports the development of future international standards, both for online and offline gas analysis. This is critical with the number of HRS set to increase exponentially.

**[Find out more about hydrogen quality sampling work at NPL]**

### Long term fuel cell performance & durability testing

In commercial transport applications, such as buses and other heavy-duty vehicles, fuel cells are expected to operate for > 15 years or a total driving distance of 200,000 km [25]. Rapidly assessing the durability of prototype next-generation devices during development therefore requires highly sensitive measurements and accelerated stress tests (ASTs) to collect representative data quickly.

An NPL branded Gen 1 Toyota Mirai

Developing new ASTs representative of real-world use and standardising the measurements of fuel cell performance are outstanding challenges which NPL is tackling. NPL also uses the capability developed to support UK companies with their material, component, single cell, and short stack prototype testing.

### Hydrogen combustion

The combustion of hydrogen is set to play a major role in a wide range of end-uses. Adapting conventional diesel engines for hydrogen is an attractive transition for industries looking to decarbonise but that find fuel cells unsuitable. Under certain conditions the combustion of hydrogen can release harmful NOx emissions due to the high temperatures. As well as this, the high temperature of hydrogen combustion presents its own material challenges that require scientific research [26]. Investigating the extent of this and how best to implement hydrogen combustion will be vital to unlocking the hydrogen economy while meeting air quality and climate goals.

### Quality control of fuel cell components

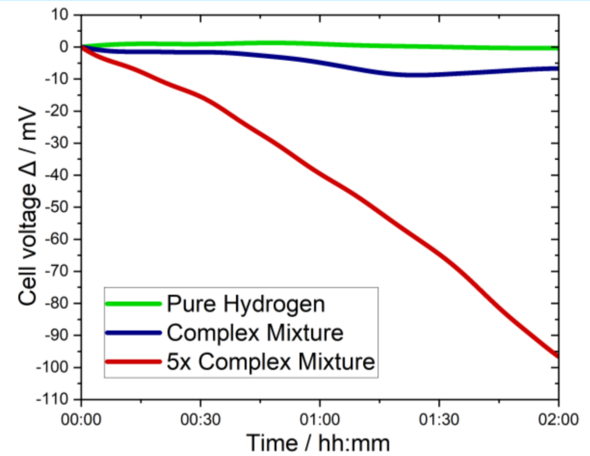
Decreasing the manufacturing cost and increasing the reliability of fuel cells is highly dependent on a high standard of quality control for its components, particularly those made of critical raw materials [27]. A key solution to this challenge is the development of standardised quality control measurements. NPL is tackling this challenge by developing a capability to measure interfacial contact resistance (ICR) of electrochemical technology components, performing measurements to assess the critical size of defects and applying online thermal and dimensional measurement technologies to assess fuel cell degradation.

## Case study: how fuel cells perform with impure hydrogen

**NPL has investigated the impact of impure hydrogen on fuel cells by measuring single cell and short-stack performance under simulated drive cycles.**

Hydrogen supplied to a fuel cell must meet the quality set out by ISO 14687:2019 (D), which sets the maximum threshold for many impurities for fuel cell automotive applications. Yet there were no reports of the actual impact of these levels of impurities on fuel cells.

In collaboration with European partners, NPL tested the same fuel cell under identical conditions with pure hydrogen and then hydrogen containing a complex mixture of impurities representative of those in the ISO standard. The results showed only a marginal decrease in performance over 2 h when impurities were supplied at the concentrations specified in the standard. However, a significant enough loss in performance to stop vehicles operating was seen when the concentrations were 5x the threshold in the standard, see graph, right.




Graph showing how cell voltage changes over time at varying levels of contaminated hydrogen with ISO 14687:2019 (D)

This investigation showed the significant impact of contaminants in hydrogen fuel and will help to inform a revision of hydrogen quality standards. Future research will investigate how to detect fuel poisoning in real time operation, develop a standardised assessment of how different impurities specifically affect a fuel cell, and develop effective mitigation steps for fuel cells after being exposed to impure hydrogen fuel.

[**Find out more about how contaminated hydrogen impacts fuel cells**]

# Summary of measurement challenges

The following table summarises measurement challenges identified through research conducted at NPL. These challenges were identified through desk-based research, surveys, interviews, and workshops held with industry representatives.

| Theme | Measurement challenge | Description |
|---|---|---|
| **Production** | Quality control | Measurements of quality control in the production of electrolyser components and devices |
| | | In situ, ex situ and operando measurements on components and materials for electrolysers for example, membrane electrode assemblies, diffusion media, current collectors, and bipolar plates |
| | Modelling and simulation | Multi-physics modelling and simulations of production technologies at the micro and nanoscale to support development of next-generation materials |
| | | Simulations to support technoeconomic analysis |
| | Electrolyser testing | Measurements of the yield and efficiency of hydrogen production |
| | | Simulating conditions inside operational electrolysers |
| | | Validation of accelerated stress tests (ASTs) on electrolysers by comparing against long duration testing |
| | | Measuring operando performance & durability of new materials and components used in an electrolyser |
| | | Developing test capabilities and facilities for larger electrolyser stacks (MW scale) |
| | Integration | Development of international standards for characterising hydrogen production technologies such as electrolysers |
| | | Measurements to support the integration of electrolysers into electrical and gas grids |

| | | |
|---|---|---|
| **Storage** | Permeability | Increasing accuracy and accessibility to measurements of hydrogen permeability across a wide range of conditions |
| | Cryogenic | Developing standardised measurement methods for testing materials at cryogenic temperatures and in hydrogen environments |
| | | Measurements of capacity efficiency and boil-off losses from cryogenically stored hydrogen |
| | | Development of test facilities capable of measuring materials properties at cryogenic hydrogen temperatures |
| | Purity | Assessing the impact of storage techniques on hydrogen purity |
| | Solid-state storage | Measurements and standardised test methods on materials used for solid-state hydrogen storage (hydrogen capacity and absorption/desorption rate) |
| **Distribution** | Leakage | Improvement of techniques to detect leaks and emissions of hydrogen at differing scales (component and site area level) |
| | | Validation of techniques to detect leaks and emissions, including odorants and flame visibility |
| | | Increased clarification of autoignition characteristics of hydrogen |
| | Embrittlement | Validated procedures for testing material susceptibility to hydrogen embrittlement at increased pressures |
| | Infrastructure | Measurements to support development of technologies used for the compression and purification of hydrogen |
| | Blending | Measurements for validated equations of state for hydrogen and mixes across a wide range of conditions |

| | | |
|---|---|---|
| **End-use** | Gas quality | Measurements of current impurities in the UK's existing gas network |
| | | More accessible, cheaper, and quicker standardised hydrogen sampling and purity measurements |
| | | Accessible online measurements of hydrogen purity to a high accuracy |
| | Fuel cells | Measurements into the performance impact of different impurities in hydrogen fuel on fuel cells |
| | | Improvements in quality control techniques for components used in fuel cells |
| | | Measurement techniques to predict the performance and durability of fuel cells for heavy duty applications such as accelerated stress testing |
| | | Development of in situ techniques for online fuel cell diagnostic measurements |
| | | Measurement of hydrogen concentration in fuel cell electric vehicle exhaust |
| | | Measurement into the scale of fluorochemical fragments in fuel cells' effluent exhaust |
| | | Development of measurement capability for supporting research into high temperature proton exchange membrane fuel cells |
| | Industry | Diagnostic methods and prognostics for devices using hydrogen in industry |
| | | Improved understanding of hydrogen purity required for different industrial processes |
| | Combustion | Development of testing capability for requalification of materials in use with high temperature hydrogen combustion |
| | | Measurements to quantify hydrogen combustion emission products e.g. NOx emissions |
| | | Understanding of component wear, excess noise, and vibration for hydrogen combustion engines |

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# Annex A: List of key NPL hydrogen publications


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Arrhenius, K. Morris, A. Hookham, M. Moore, N. Modugno, P. Bacquart, T., An Inter-laboratory Comparison Between 13 International Laboratories For Eight Components Relevant For Hydrogen Fuel Quality Assessment. Measurement, 2024

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Murawski, J. et al. Benchmarking Stability of Iridium Oxide in Acidic Media Under Oxygen Evolution Conditions: A Review: part I. Johnson Matthey Technology Review, 2024

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Bethapudi, V. S., Hinds, G., Shearing, P. R., Brett, D. J. L. & Coppens, M.-O. Dynamic Acoustic Emission Analysis of Polymer Electrolyte Membrane Fuel Cells. Energy Advances, 2022

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