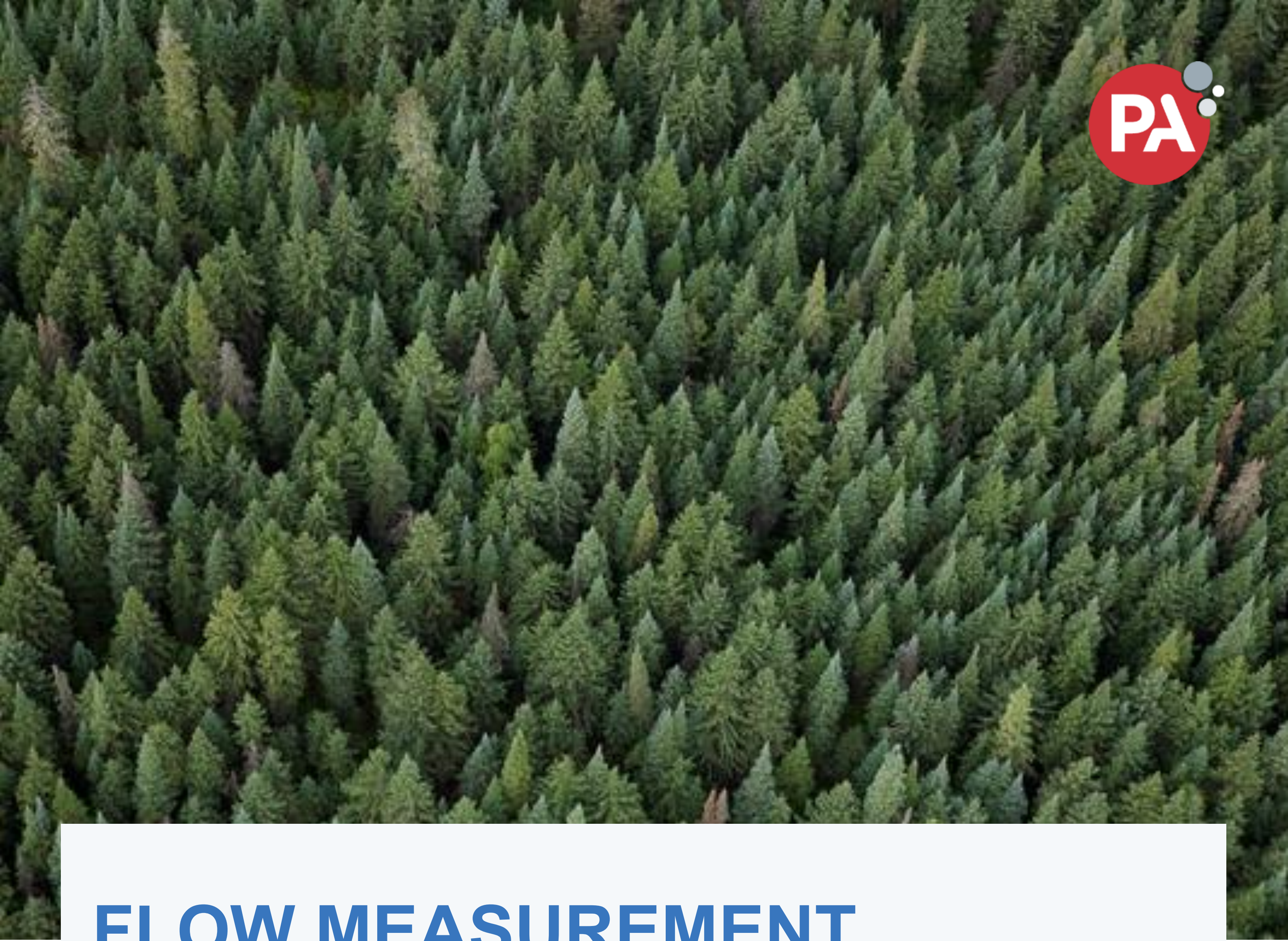

FLOW MEASUREMENT REQUIREMENTS FOR LOW CARBON FUELS (HYDROGEN)

18 November 2020

Bringing Ingenuity to Life
paconsulting.com

Corporate Headquarters
10 Bressenden Place
London
SW1E 5DN
+44 20 7730 9000

paconsulting.com

Prepared by: PA Consulting

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Executive Summary

In the UK and internationally, hydrogen is being increasingly seen as a key component of the global energy transition. Currently, most hydrogen is produced from fossil fuels and has a consequently high carbon footprint (*grey* hydrogen). However, technological advances are opening up the opportunities for low- or no-carbon hydrogen. Whether it is *blue* hydrogen, produced from fossil fuels with associated carbon capture and storage, or *green* hydrogen produced via an electrolysis process using renewable electricity.

Hydrogen is a highly versatile energy fuel, vector and storage medium. G*rey* hydrogen is currently considerably cheaper than *blue* or *green*. But further investment and support around hydrogen production, storage and distribution, and hydrogen consumption technologies (e.g. fuel cell vehicles, hydrogen domestic boilers etc.) will continue to drive down supply chain costs and lead to economies of scale. Therefore, hydrogen is set to become more cost effective with an increasing range of uses.

Hydrogen has physical and chemical characteristics quite different to natural gas or other hydrocarbon fuels. It is exceptionally light, with less energy by volume, but far more by mass, than conventional fossil fuels. These characteristics can be challenging for the flow meters most commonly used today and many are not fully tested or calibrated to accurately measure hydrogen.

All major economies see a role for hydrogen in their economies. And all agree that there will be a strong international market in production and consumption technologies. To ensure that this market (or any other) can operate effectively, there will need to be an international harmonisation of a range of standards including those for flow measurement. As the cash registers of the future hydrogen economy there has to be total user acceptance and confidence in the accuracy of hydrogen metering. This report looks in detail into the suitability of the metering technologies and flow measurement standards for three use cases for hydrogen in a low carbon economy. They are:

- Domestic - As a replacement fuel for domestic heating and cooking. We are assuming that this relates to consumers using hydrogen methane blend and connected to existing gas grid.
- Industrial - As a replacement fuel for industrial applications. We are assuming that this relates to grid-connected consumers
- Transport - As a replacement fuel for transport system (primarily HGVs, forecourts applications, etc.)

Domestic & Industrial

The UK has an opportunity to use its extensive natural gas transmission and distribution network to distribute hydrogen (pure or blended) direct to domestic of industrial customers. This report identifies a number of schemes and pilots that are exploring the feasibility of hydrogen (having been transported by the natural gas network) being used in domestic and industrial settings.

But there needs to be a real drive to understand the accuracy of, and establish standards for, the metering of the hydrogen blends and pure hydrogen. This would need to be an international endeavour because many of the meter manufacturers are based overseas, and the network is physically connected to other networks overseas.

Transport

This is an international sector, with significant cross-border traffic flows. The UK's closest trading partners will be facing the same challenges with regards to accuracy and reliability of flow measurements in hydrogen refuelling stations (HRS). So there needs to be continuing collaboration to explore the best ways to test and calibrate flow meters within HRSs, and to provide traceable measurement in deployed HRS.

Actions

The physical characteristics of hydrogen, the variability of temperature and pressure in measuring systems, and the absolute need for consumer confidence and enthusiasm make the harmonisation of flow measurement standards essential. There is an urgent need to identify and harmonise flow measurement standards, and test and calibration techniques. The report identifies a number of actions that are needed on hydrogen flow measurement:

1. The UK Government, working with industry, should publish a National Hydrogen Strategy as soon as possible (at least by the end of 2021) and ensure that the vital importance of harmonised standards, including for flow measurement is given clear priority.
    a. And as an interim measure, there needs to be a growing clarity about the role of hydrogen in the long-awaited Energy White Paper.
2. The UK Government needs to provide Physical Primary Standards for hydrogen for the UK to ensure that a traceable and suitably accurate measurement chain exists.
    a. This is essential to enabling domestic and international trade and markets – you can't sell what you can't measure.

3. The UK Government needs to help the relevant bodies develop the correct regulatory regime and documentary standards.
    a. Tight enough to ensure control, relaxed enough to enable affordable and technologically feasible. compliance
4. Supported by BEIS, the UK's Designated Institute for Flow and Density Measurement (NEL) needs to help industry to implement flow measurement in compliance with regulations and documentary standards.
    a. For example, today such support is in place to help industry meet the OGA's fiscal regulations in the North Sea for oil and gas production; we will need to do likewise for hydrogen and CCS.
5. The UK Government and relevant agencies need to develop a full engagement programme allowing them to participate fully in all relevant international hydrogen metrology and standards fora.
    a. Leadership in this area will provide considerable confidence and clarity to the sector as a whole.
    b. Being at the table is essential and being there early and leading the conversation is even better. This will help the UK's progress to net zero, enhance clean growth and facilitate global standards that are well suited to UK's commercial success in the global marketplace.

1 Scope, objectives and methodology

1.1 Background

In the UK and internationally, hydrogen is being increasingly seen as a key component of the global energy transition.

Though demand for hydrogen is not new, it is increasing, having grown threefold globally since 1975 and is set to grow further. To date, hydrogen production is almost entirely supplied by fossil fuels, with a consequently high carbon footprint (this is referred to as grey hydrogen). Where the current political, technological and business momentum is focussed is on clean hydrogen. This is hydrogen that is generated with low (or no) carbon emissions. Blue hydrogen is produced from fossil fuels but with associated carbon capture and storage, whereas green hydrogen is produced via an electrolysis process using renewable electricity (e.g. from wind, solar or hydro). Currently, grey hydrogen is considerably cheaper than green or blue hydrogen. However, as we see more national and international commitments to carbon reduction targets, we also see increasing rollout of renewable electricity generation, which in turn is bringing down renewable electricity costs.

Further investment and support around hydrogen production, storage and distribution, and hydrogen consumption technologies (e.g. fuel cell vehicles, hydrogen domestic boilers etc.) will continue to drive down supply chain costs and lead to economies of scale. Therefore, hydrogen is set to become more cost effective with an increasing range of uses.

1.1.1 Potential uses

Hydrogen can be combusted for heat without producing any pollutants (just water) or can generate electricity through a fuel cell, again without producing pollutants. It is also used directly as a feed stock or additive in some industrial processes.

These key properties make it of particular interest in the energy transition and the International Energy Agency identifies the following broad uses.

- Industry – in addition to its use as a chemical feedstock, Hydrogen could be used as a replacement combustion fuel in this high-emissions / hard to decarbonise sector. Using Hydrogen, instead of natural gas, oil, propane etc. in glass, cement, steel production could yield considerable carbon savings.
- Transport – there are existing hydrogen fuel cell land vehicles available. Battery powered electric cars and light vehicles are popular at present and will provide stiff competition to hydrogen fuel cell cars. For heavier goods vehicles and trains, however, there is considerable potential for hydrogen to become the fossil fuel replacement of choice. Shipping and aviation have limited low-carbon fuel options available and therefore represent an opportunity for hydrogen-based fuels.
- Buildings (domestic and commercial) - using the existing natural gas networks, hydrogen can be blended in with the natural gas to replace part or all of the hydrocarbon fuel in the space-heating and hot water applications.
- Power - hydrogen is one of the leading options for storing variable renewable energy. Storage could be intraday and inter-seasonal. Hydrogen stored could be used in hydrogen networks as described above, used to generate electricity to the grid when needed, or exported to other markets.

1.1.2 Hydrogen Economy

Within the UK there has been growing interest in the role that Hydrogen can play in clean growth and developing a successful low-carbon economy and meeting its enshrined-in law for 2050 net-zero commitments. Government, the Committee on Climate Change and others are recommending or planning for a future economy with hydrogen playing a key role in the decarbonisation of heat, transport and certain industrial processes. And, in line with this, Government is increasingly supporting Hydrogen-related trials and technologies. However, there is still not a clear and distinct UK Hydrogen Strategy. Something that is being called for by all sectors, as hydrogen could be part of the decarbonisation solution across the board be it energy, transport, industry, commercial or residential. It is hoped that 2020's expected Energy White Paper will feature some clearer signals on hydrogen. This could then act as a catalyst providing greater confidence and direction to those involved in the hydrogen economy to invest and develop innovative technologies, uses and standards.

The hydrogen economy has considerable cross-border and export potential too. In Europe there will likely be export from countries with large scale renewable electricity generation which can be used to produce green low-carbon hydrogen through electrolysis. Germany are already considering the need to import blue and green hydrogen to facilitate their decarbonisation programmes. They may also see value in a linked but reverse trade in CO_2. For example, the UK could export Hydrogen via pipeline to Germany (in particular using renewable generation from offshore, Scotland and northern England. And Germany could export CO_2 to the UK for storage and sequestering in exhausted North Sea oil and gas wells.

Below is a simplified value chain for hydrogen, detailing the primary production, storage, distribution and usage components.

Table 1: Hydrogen value chain (simplified). The use cases considered in this report are highlighted in blue

Production and energy sources			
Type	**Carbon Intensity**	**Energy source**	**Production**
Grey	High	Oil, coal, gas, biomass, indirectly from industries	Steam reforming
Blue	Low		Steam reforming with CCS
Green		Renewable electricity	Electrolysis
Storage and distribution			
Pipeline			
Transport using trucks, train and shipping			
Long-term storage			
Green / Blue Hydrogen Usage			
Industry	• Replace grey hydrogen • Zero-carbon steel • Industrial heat • Batch processing		
Domestic	• Water and space heating		
Transport	• Transport on land • Aviation • Shipping		
Energy system	• Energy system		

1.1.3 Underpinning the hydrogen economy

Supporting our conventional hydrocarbon fuel economy is a capability with known measurement uncertainties, deployed in a range of regulations, treaties, documentary and safety standards. It is vital that a similar capability exists for low carbon fuel (including hydrogen) flow measurement capability to underpin trade, consumer protection and confidence, taxation, health and safety and environmental protection. Such a capability comprises a range of national and international reference measurement standards (primary standards, validated through scientific research), transfer standards and accepted techniques and methods.

If the UK invests in the deployment of Low Carbon Fuel (LCF), then supporting measurements of flow will be required. It is anticipated that current capability will be inadequate for confidence in trade at the levels required. This report will examine these potential inadequacies and will identify solutions which can close the gaps and help the UK become world leaders in this emerging green technology.

1.2 Objectives

This review considers whether flow measurement capability requirements vary between the three use cases:

- Domestic
  - As a replacement fuel for domestic heating and cooking. We are assuming that this relates to consumers using hydrogen methane blend and connected to existing gas grid.
- Industrial
  - As a replacement fuel for industrial applications. We are assuming that this relates to grid-connected consumers
- Transport
  - As a replacement fuel for transport system (primarily HGVs, forecourts applications, etc.)

And whether the nature of hydrogen is known to present any novel measurement challenges. It focusses on the gas distribution of Hydrogen or blended Hydrogen with Natural Gas.

This review frames the imperative, use cases, main technical challenges of metering technologies and the need for investment in new metering design and standards. It provides an assessment of the current position of hydrogen flow measurement capabilities and a review of Hydrogen-related national and international reference measurement standards across certain key jurisdictions.

1.3 Structure of report

This report provides an overview of the role (actual and potential) of hydrogen in the energy transition and economy. It highlights the key physical and chemical properties of hydrogen that determine its metering characteristics and requirements.

There is an examination of the main metering technologies available and used for hydrogen and natural gas flow measurement, their application to specific use cases (Domestic, Industrial and Transport), and a review of the flow standards internationally.

The structure is set out below:

- Scope, objectives and methodology
- Hydrogen use cases
- Hydrogen flow measurement
- Metering technologies
- Standards
- Liquid Hydrogen
- Review findings
- Bibliography

1.4 Research methodology

The content in this report was developed through a combination of workshops with NEL flow metrology subject matter experts, desktop research, and existing industry knowledge from, PA Consulting.

2 Hydrogen use cases

Below we briefly expand on the three use cases of hydrogen which are under review in this report.

2.1 Domestic – space heating, hot water and cooking fuel

The domestic sector accounts for almost 40% of global energy demand in buildings and industry, with the majority of household CO_2 emissions coming from heating (including generating hot water). Any efforts in reducing these emissions requires a substantial shift in heating technologies, namely natural gas, towards low carbon fuels such as hydrogen. In homes, hydrogen could be used to power fuel cell micro-CHP, direct flame combustion boilers (similar to existing natural gas boilers), catalytic boilers and gas-powered heat pumps.

As mentioned above, HMG is currently considering the potential transition to a Hydrogen Economy, and supports the trialling of hydrogen usage in the natural gas network as part of the decarbonisation of heat (including space heating, hot water and cooking fuel), as detailed in *Clean Growth: Transforming Heating*. Additionally, in February 2020, the Government announced increased funding to a range of hydrogen innovation projects. (see below HyNet North West pilot in industrial applications)

The GB gas distribution network is currently being upgraded. Iron mains pipes are reaching the end of their useful life and are being replaced with polyethylene (PE) pipes. The programme is set to run until 2032 and at this point there will be a safe, low cost and reliable network, that could support 100% hydrogen distribution.

However, as the current network is a blend of iron and PE pipes it cannot effectively distribute 100% hydrogen. It is thought able to handle blends of up to 50% hydrogen. Historic evidence for this is the fact that these same assets previously distributed Town Gas which had hydrogen levels up to 50%. There are already ongoing trials of blending hydrogen into networks and the percentage of hydrogen in these blends will vary. For example, the HyDeploy trial at Keele University uses a blended hydrogen/NG mix with hydrogen content up to 20%.

It is important that as we move towards a Hydrogen Economy, any upgrade on domestic appliances (such as boilers and cookers), in order to burn hydrogen, happens with minimal consumer disruption so that to ensure high user acceptance for the new fuel. Within this scope, the Government has set up a programme, Hy4Heat, to show if it is technically possible, safe and convenient to replace natural gas with hydrogen in residential and commercial buildings and gas appliances. The programme covers multiple areas of research, from appliance specification to developing hydrogen meters.

Specific to the metering equipment and flow measurement requirements, it is essential that domestic consumers end up having the same confidence and acceptance to the new fuel, as they have today towards natural gas; after all, flow meters act as 'cash registers', ensuring that consumers pay a fair and validated amount of money for the energy they consume.

The Hy4Heat programme has awarded contracts to two-meter manufacturers (Fiorentini and MeteRSit) to develop hydrogen smart meters that will be no bigger than existing natural gas meters (i.e. can still fit in UK homes) and will also follow the SMETS specifications.

2.2 Industrial

Hydrogen already has several applications in industrial processes, as well as used as a raw material in the chemical industry and also as a redactor agent in the metallurgic industry. According to Hydrogen Europe, about 55% of the hydrogen produced around the world is used for ammonia synthesis, 25% in refineries and about 10% for methanol production. The other applications worldwide (such as flat glass production, the electronics industry or in electricity generation) account for only about 10 % of global hydrogen production[1].

However, within the decarbonisation context, hydrogen's leading role in the industrial sector is seen in fuel switching for natural gas applications. The main component of the sector's emissions is combustion emissions; the Industrial Fuel Switching Market Engagement Study, prepared by Element Energy and Jacobs[2], concluded that hydrogen had the highest technical potential for fuel switching, compared to electricity and biofuels. More specifically, hydrogen has been recognised as a replacement to natural gas for fuelling industrial heating processes. Natural gas is used in direct-firing applications, for example, glass furnaces or kilns, in boilers for raising either high- or low-pressure steam (or hot water) and in combined heat and power applications.

Similar to the domestic sector, wide-spread use of hydrogen in Industry is likely to involve re-purposing the natural gas distribution grid to carry hydrogen, and specific to the various industries, it might also require converting gas end-use technologies to run on hydrogen. However, converting existing natural gas equipment is

[1] https://hydrogeneurope.eu/hydrogen-industry
[2] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/824592/industrial-fuel-switching.pdf

considered financially more viable than full replacement (for example, in the case ofc fuel switching to electrification).

The UK Government is currently funding a world-first pilot project to demonstrate how hydrogen fuel can be used as a low-carbon alternative to natural gas at an industrial scale; HyNet North West will supply hydrogen to 10 energy intensive industrial gas users with up to 100% hydrogen via a dedicated hydrogen pipeline.

2.3 Transport fuel

The Government's Transport Decarbonisation Plan is still yet to be published, but it is already known that the solution will most probably come from multiple technologies and innovations, depending on the type of vehicles and use cases. And even though it seems that battery electric vehicles (BEVs) are dominating the shift when it comes to personal transportation, hydrogen is considered a strong contender for Heavy Goods Vehicles (HGVs) and professional fleets (see Figure 1 to the right).

There are two clear advantages that hydrogen vehicles have over traditional hydrocarbon internal combustion engine vehicles. Firstly, there are no operational CO_2 emissions and therefore a far lower lifetime carbon footprint. Secondly, they have near zero tail pipe emissions, emitting just water vapour and trace NOx. In addition, range and refuelling time are comparable to hydrocarbon fuelled vehicles.

When hydrogen fuel cell electric vehicles (FCEVs) are compared with BEVs it is thought that improving technologies in both efficiency (supply and fuel cells) and capacity (mobile storage) FCEVs have the potential to satisfy the medium- and long-range requirements, though BEVs seem to currently have the advantage in the personal vehicle and short-range markets.

FCEVs and BEVs have a comparable drive train and high torque performance at low speeds, but FCEVs typically deliver greater range. And the refuelling of hydrogen vehicles is much more rapid than recharging battery electric vehicles. One ideal use case is therefore commercial fleets which do not have extended periods of downtime in their duty cycle (e.g. forklifts operating in a 24-hour warehouse and commercial and public sector fleets).

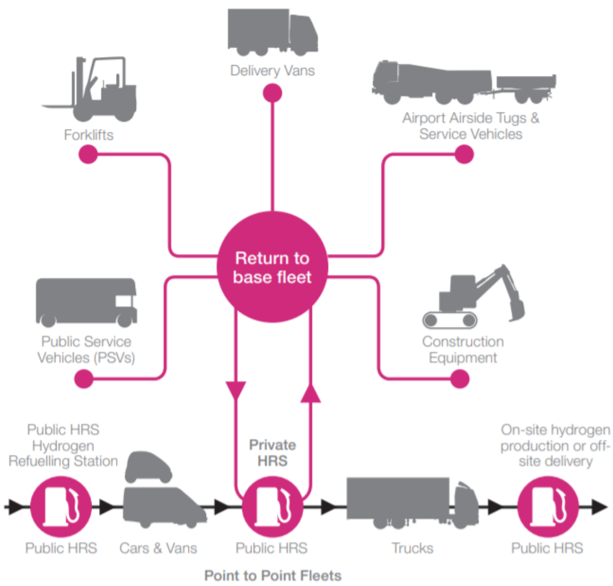

Figure 1: Potential vehicular users of hydrogen (Source: Arup)

In addition, on-site production of hydrogen by electrolysis from sources of renewable distributed generation is able to accommodate fluctuating power input or draw off-peak electricity from the grid.

Out on the open road, there are currently limited hydrogen refuelling stations (HRSs) which may appear to be a handicap for a growing FCEV fleet. However, operators of heavier and/or longer distance vehicles, which carry out a high proportion of point-to-point travel can see immediate advantages in FCEVs when combined with their own onsite HRSs or known public HRSs close to their depots. In particular, trains and hub-to-hub HGVs fall within this category and we would expect much FCEV growth in these markets.

3 Hydrogen flow measurement

3.1 Hydrogen as a fuel

Hydrogen can be used for a number of different purposes. In this paper we are just considering its use as a fuel. That is, to store and release energy.

There are two main ways that this occurs. Firstly, via combustion with oxygen to release heat and form water vapour. Secondly, hydrogen can be used as a fuel to directly generate electricity via a fuel cell, again with water being the only exhaust.

There are two physical states that hydrogen can be used, gas or liquid. Liquid hydrogen which has an extremely low boiling point below -250ºC. Gaseous hydrogen is exceptionally light with low energy density (by volume) so hydrogen is most often stored and used as pressurised gas or liquid.

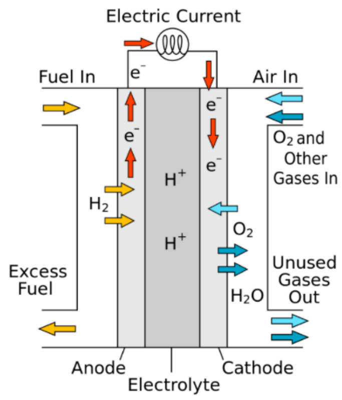

Figure 2: Scheme of a proton-conducting fuel cell (Source: Dervisoglu)

3.2 Metering characteristics

Energy Density - hydrogen has about a third of the energy density of natural gas (by volume) so greater flows are needed to deliver the same calorific value. Meters need to be able to accurately measure at these greater flow rates.

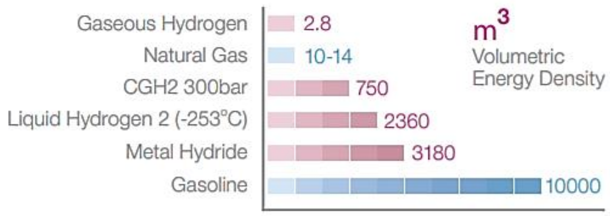

Figure 3: By volume, gaseous hydrogen contains a third of the energy of the same volume of natural gas (kWh/m³) (Source: Arup)

Leakage – hydrogen (H_2) is the smallest molecule in the universe and as such it has a greater propensity to leak (by a factor of three) when compared to methane (Arup, 2016). Hydrogen's extremely high buoyancy ensures rapid dispersal of leaks but can lead to potential trapped overhead gas pockets.

Embrittlement – exposure to hydrogen can cause embrittling and weakening of certain materials including steel. Though this process is more likely at elevated temperatures it is a consideration when selecting suitable metering technology

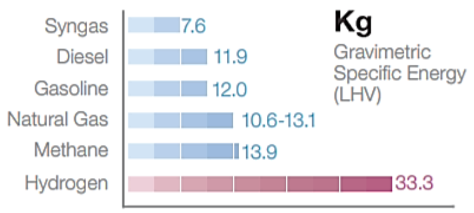

Figure 4: On a weight basis H_2 contains 3-times the energy of natural gas (kWh/kg) (Source: Arup)

Odour and flame - Like methane Hydrogen gas is odourless so leaks can be difficult to detect. Odour chemicals can be added to aid detection, though these would be an added impurity in hydrogen. Impurities can accumulate and damage fuel cell components. Hydrogen flames are invisible to the human eye but can be coloured with the inclusion of additives. Again, impurities can damage the catalytic convertors in fuel cells.

Liquid hydrogen – the extreme low temperature of liquid hydrogen can pose challenges for metering, including physical stress to materials and moving parts.

3.3 Current metering of natural gas

Diaphragm meters are the predominant natural gas meter type in domestic and small commercial settings in the UK. It is unclear whether these meter types will be fully compatible with 100% hydrogen gas flows. Accuracy and safety (through increased hydrogen leakage) will possibly decrease as more hydrogen is blended into the mix but the practical upper limit is not yet known and may vary from model to model.

Ultrasonic meters are more commonly used in higher pressure industrial and commercial scenarios, these are seen as being more compatible with hydrogen, as they are essentially sealed units with no moving parts. More expensive than diaphragm meters; development is ongoing to bring them to mass market.

The UK Government sponsored Hy4Heat programme aims to establish if it is technically possible and safe to replace methane with hydrogen in commercial and residential buildings and gas appliances. The programme has awarded contracts to two meter manufacturers to develop hydrogen smart meters that will be no bigger than existing natural gas meters, suitable for the domestic and small commercial markets.

4 Metering technologies

4.1 Overview

The need to accurately meter the flow of gases and liquids is not a new requirement. There exists a range of meter technologies that are currently used to do this. In this section we will look at the main meter technologies used in Natural Gas and Hydrogen metering. We shall consider their basic operation and the positives and negatives of their potential usage.

The main meter types considered and described in greater detail are:

- Positive Displacement (Volumetric "Pulse") Meters
  - Diaphragm (incumbent technology for residential NG)
  - Rotary
- Turbine
- Ultrasonic
- Thermal Mass
- Coriolis
- Differential Pressure
  - Includes: Dall Tubes, Orifice Plates, Venturi (tubes, cones, nozzles)

In addition to the above technology types, there are several alternative meter technologies. We have conducted an initial appraisal but will not be investigated further. The meter technologies and reasons for non-investigation are listed below.

- Variable Area Meters (Rotameters etc.)
  - Not investigated further: Not appropriate due to poor accuracy, generally manual readout (typically only 2 – 4%)
- Multiphase Metering
  - Not investigated further: high cost / specialist devices, typically used in oil industry not multipurpose
- Vortex Flow Meters
  - Not investigated further: More commonly used for steam applications, poor accuracy
- Sonic nozzle meters
  - Not investigated further: Could be the future transfer standard but not currently used widely due to difficulty of operation.
  - Initial results of high-pressure nozzle calibrations show that the relevant standard, ISO 9300[3], is not applicable for hydrogen with sufficient accuracy. Additional nozzle calibration results with hydrogen are needed to populate an adequate database of calibration results and to update sections of ISO 9300 for hydrogen.

4.2 Positive Displacement Meters

These are mechanical flow meters where the movement of the fluid (gas) physically moves a part of the measuring device by a consistent, known and repeatable volume. By counting the rate at which this known volume is physically displaced, the flow rate of the moving gas can be readily quantified.

They are cheap and widely used for metering domestic and industrial natural gas. There are a variety of mechanisms through which the fluid can actuate the sensing (counting) mechanism. The mechanisms most relevant to the measurement of gases at real-world flow rates are limited to:

- Diaphragm Flow Sensors
- Rotary Flow Meters

These meters provide volumetric measurement. They do not detect temperature or pressure changes. Therefore, they need to be corrected for these changes, usually through additional electronic instrumentation. Hydrogen is sold by mass rather than volume, so conversions needs to be made.

4.2.1 Diaphragm meters

Operation

These are the established and most frequently used meter type of positive displacement meter currently used in the UK's natural gas distribution network. There are several measuring chambers of known volume, separated by synthetic diaphragms, within the meter. They are filled and emptied periodically. This movement of the

[3] ISO 9300:2005 Measurement of gas flow by means of critical flow Venturi nozzles

diaphragms is transferred via a gear to a crankshaft. This shaft moves the valves, which control the gas flow. The rotations of the gear are transferred via a magnetic or mechanical coupling to the counter / dial[4].

This technology is the established (incumbent) technology for Residential, Commercial and Industrial applications and is currently used for metering natural gas, propane and butane (gases to EN 437[5]).

Considerations

These are mechanical actuation meters, so measure the gas flow by volume. Therefore, you need to know the, gas composition. That is, the proportion of hydrogen within a fixed volume of the gas being metered.

The actual mass of gas within the fixed volume being metered will vary with temperature. However, temperature variation can be accurately corrected for a given known gas composition (for example, by using mechanical bi-metallic sensing element or electronic correction).

Electronic Volume Correction (EVC) can be applied through additional electronic devices e.g. for custody transfer applications. This measures and corrects for temperature and gas pressure variations and can help optimise custody transfer and industrial measurement[6,7].

Accuracy

The nominal accuracy of Diaphragm type meters is typically ±0.5%, though this will vary with meter type, size, model and gas flow rate.

Temperature, and pressure, variations will change the mass of gas in a measured volume. In addition, temperature extremes can impact the accuracy in other ways. By causing expansions and contractions of the meter and diaphragm, the geometry of the measured volume can change, sometimes permanently. This will lead to over or under measurement. In addition, temperature extremes can lead to perforation of the diaphragms.

The diaphragm can also warp or shrink over time as it is physically and chemically affected by hydrocarbon vapours. Again, this can lead to changes in volume geometry. And as with all mechanical meters, wear and tear of components over time will affect accuracy.

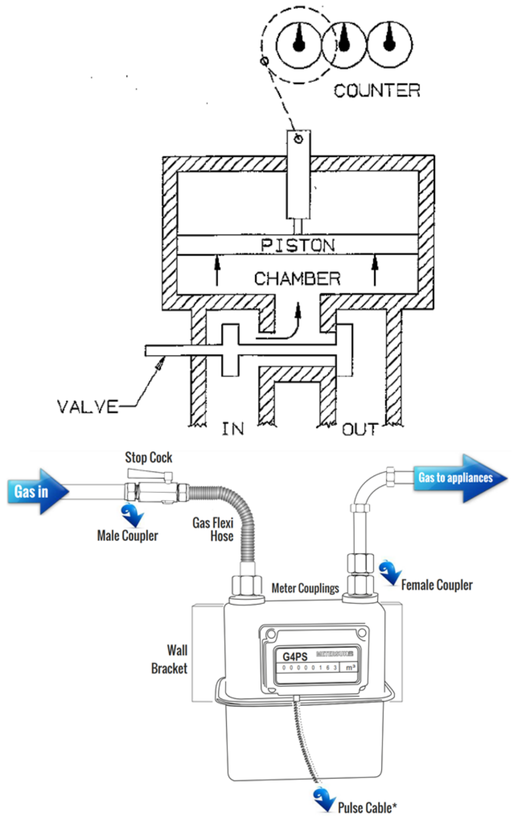

Figure 5: Diagram showing the workings of a typical diaphragm meter (Source: Sensus & Meters UK)

Pros

- Incumbent technology, broad familiarity
- Reliable
- Can measure very low flow rates
- Can run for years off one battery,
- Can be installed in a confined space

Cons

- Mechanical wear over time
- Greater potential for leakage of hydrogen (depending on model, ages etc.)

Challenges for Hydrogen / Natural Gas-Hydrogen blends

Diaphragm meters are the predominant meter type in the commercial and domestic gas network. A likely scenario will see these networks carrying hydrogen, either pure hydrogen or more likely blended up to 20% with natural gas. Therefore, it's worth considering the potential challenges to this meter type.

Firstly, given that these meters measure volume, they will need re-calibration or correction of readings to meter hydrogen / hydrogen blends. Therefore, accuracy of metering will depend on the consistency of the blend in the gas feed.

[4] https://www.mwatechnology.com/wp-content/uploads/2015/07/Honeywell-BK-G1.6-G4.pdf
[5] https://www.en-standard.eu/din-en-437-test-gases-test-pressures-appliance-categories/
[6] https://www.honeywellprocess.com/en-US/explore/products/gas-measurement-and-regulation/metering/electronic-corrector-systems/Pages/default.aspx
[7] https://www.honeywellprocess.com/en-US/explore/products/gas-measurement-and-regulation/metering/electronic-corrector-systems/Pages/mini-at.aspx

Secondly, the current meters are designed for higher density / lower permeability gases: NG, propane, butane (gases to EN 437). But the low density / high permeability of hydrogen makes it more prone to leakage both through and between materials and interfaces. Therefore, Hydrogen is potentially leaked out of the meter housing into the environment. This creates an accuracy question and the potential for accumulation within confined spaces raising safety risks.

Thirdly, hydrogen may impact the durability of the materials within the meter, in particular the synthetic diaphragms.

Jarowski et al. 2020 paper looking at diaphragm gas flow meters concludes that:

> "for the tested gas meter specimens, there was no significant metrological difference between the obtained changes of errors of indications after testing the durability of gas meters with varying hydrogen content (from 0% to 15%)"[8]

4.2.2 Rotary

Operation

These meters utilise a rotary type positive displacement principle of operation which makes volumetric measurements by displacing finite volumes of gas. The positive displacement occurs within a cavity formed between the meter's internal housing and its rotating impellers. The rotating impellers separate the flowing gas into small, finite, volumes and are counted using a mechanical index.

These are currently used with dry natural gas and non-corrosive industrial gases.

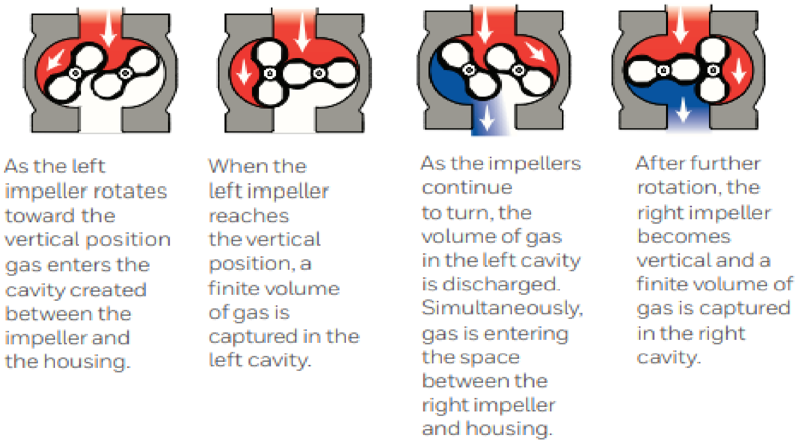

Figure 6: Diagrams showing the workings of a rotary meter (Source: Honeywell)

Pros

- Good rangeability compared to other meters (one meter can cover wide range of flows)
- Low maintenance and therefore total ownership costs
- Simple installation and commissioning
- Compact design and ease of use
- Low pressure drop across device
- Relatively quiet operation
- Should be possible to re-calibrate new k-factor for dry hydrogen / natural gas blends

Cons

- Assumes known and consistent gas composition for accurate metering (conversion to mass flow)
- Mechanical actuation / moving parts
  - Wear / damage over time
  - Relatively clean gases required (filters may be appropriate)
  - Special consideration may be required for corrosive gases (ammonia?)
- Not suitable for very low temperature operation (< -40 °C)

[8] https://www.mdpi.com/1996-1073/13/11/3006/pdf

4.3 Turbine

Operation

This is a reliable meter type that features a rotor with multiple blades installed within distribution pipework. Faster gas flows result in faster rotation of blades. Magnetic sensors or a mechanical counter produce a pulse whenever a blade rotates past them. A k-factor[9] correlates volumetric flow rate for a particular gas to the angular speed of the rotor, and so gas flow rate can be computed from the sensor output.

Turbine meters can be used across gas distribution and transmission networks and industrial gas networks. A typical use case is the custody transfer measurement of gases (including natural gas, propane, butane, air, nitrogen, hydrogen)[10].

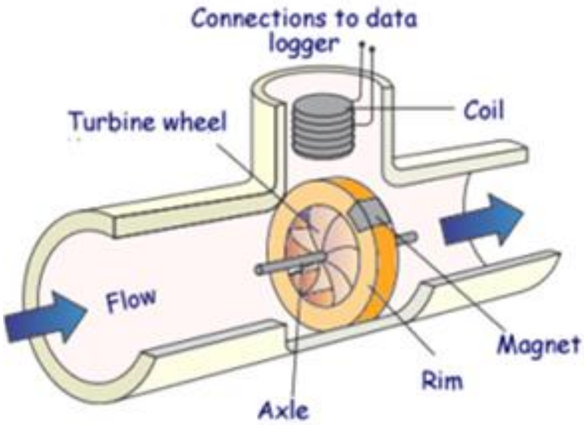

Figure 7: Diagram showing how a typical turbine meter operates (Source: modified from GPI)

Pros

- Reliable with good accuracy
- Broad range of sizes / pressures
- Incumbent technology for custody transfer measurements of gases (industrial applications)
- Compliant with international standards
- Anti-tamper devices already existing (difficult to "cheat" the measurement e.g. external magnets etc.)[11]
- Should be possible to re-calibrate new k-factor for hydrogen / NG blends

Cons

- Assumes known and consistent gas composition / single-vendor sourcing for accurate metering (conversion to mass flow)
- Mechanical actuation / moving parts
- Wear / damage over time (especially under highly pulsed flows)
- Relatively clean gases required (filters may be appropriate)
- Special consideration may be required for any corrosive gases
- Require flow conditioning for best accuracy

4.4 Ultrasonic meter

Operation

There are several types of ultrasonic meters but only transmission (contra-propagating transit time / time of flight (TOF)) ultrasonic flow meters are suitable for clean hydrogen and gas metering applications. Although Doppler meters may have a use for dirtier natural gas blends.

TOF meters measure flow rates based on the difference in propagation time of ultrasonic signals in the upstream and downstream directions. The ultrasound wave travels faster when traveling in the direction of flow and slower when against the flow. This technology works whether the ultrasonic transducer pairs are located inside of a pipe (spool piece USM) or clamped to the outside of a pipe (clamp-on USM), although the latter is less accurate.

Multiple transducer pairs can also be setup to provide detailed flow and contamination diagnostic information within the pipework.

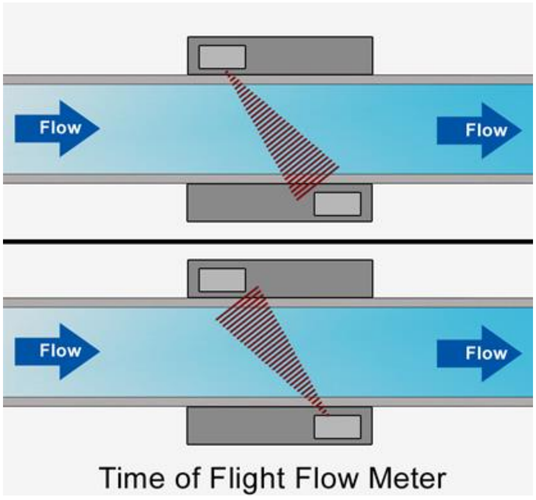

Figure 8: Diagram of a time of flight ultrasonic meter in operation (Source: Edwards & Otterson)

Because the propagation velocity of an ultrasound wave varies between a single fluid or a composition of multiple fluids in a mixture, TOF-based ultrasonic technology can potentially be used for fluid composition analysis, to give information on gas mixtures.

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9 K-factor refers to the number of pulses expected for every one volumetric unit of fluid passing through a given flow meter

10 https://www.lincenergysystems.com/gas-flow/meter/turbine/

11 https://www.honeywellprocess.com/library/marketing/brochures/Elster%20SM-RI-X%20Datasheet%20EN.pdf

Current applications

Suitable for custody transfer and metering of hydrogen and natural gas (OIML R137, Class 0.5, MI-002, AGA9)[12][13]

Domestic metering of natural gas

Pros

- May allow gas composition to be inferred from speed of sound variability
- Suitable for use under high pressures
- Not affected by large temperature / pressure swings
- Can be fitted either:
  - Externally around pipework (non-contact / non-wetted / clamp-on)
  - In-line (intrusive / wetted / spool piece)
- In line versions can potentially detect minute traces of liquid, contamination or flow disturbances in pipework (deposits, dirt, changes in surface roughness etc.)[14]

Cons

- Cheaper metering devices available for smaller-scale residential and commercial applications
- External / clamp-on meters also need to account for influence of pipework on measurement
  - Difficult for thick high-pressure gas lines
  - Clamp-on meters are not accurate enough for custody transfer applications (~3-5% of full scale
- Require flow conditioning for best accuracy (e.g. straight runs into meter)

4.5 Thermal mass

Operation

Flowing gas is passed over a heated wire. Heat from the wire will only heat locally around the wire when gas flow is low. But higher flows of gas will carry heat further downstream from the wire.

Volumetric flow rate can be calculated by measuring the heat being carried away from the heated wire (i.e. the cooling effect of the gas under different flow rates)

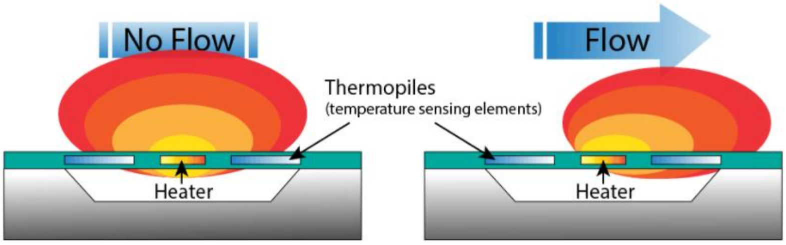

Figure 9: Diagram showing the operating principles of a typical thermal mass meter (Source: Jenkins)

This calculation requires knowledge of the composition of the gas. This is because gases (and blends of gases) have different specific heat capacities and have different thermal properties.

Pros

- Widely used
- Wide turndown – Turndown ratio of 100:1
- Very low flow rate sensitivity
- High accuracy / repeatability (assuming known gas composition: see Cons)
- Suitable for hydrogen / ATEX environments
- No moving parts
- Calibration can be quickly updated for varying gas compositions (but see Cons)

Cons

- Requires knowledge of gas composition for correct calibration factors to be applied (heat-carrying /cooling ability of a gas / blend depends on accurate knowledge of its composition).
  - Would be impractical to update in real-time to cope with “slugs” and impurities in gas stream, so requires a constant gas composition.
- Generally, not rated for very high pressures (For example, up to 700 bar can be needed for some refuelling application, some way outside normal range for these meter types.)
- Require flow conditioning for best accuracy (e.g. straight runs into meter)

[12] https://www.emerson.com/documents/automation/brochure-ultrasonic-flow-meters-%E2%80%93-dual-configuration-3410-series-meter-family-daniel-en-55880.pdf
[13] https://krohne.com/en/applications/custody-transfer-flow-measurement-hydrogen/
[14] https://www.emerson.com/documents/automation/brochure-gas-ultrasonic-flow-meters-dual-configuration-3410-series-daniel-en-55846.pdf

- Measurement sensitive to orientation (mount horizontally)
- Relatively narrow temperature window (e.g. -40 – 200°C for industrial versions)
- Potential for drift under large ambient temperature swings
- Narrow orifices may clog when using dirtier gases

4.6 Coriolis meters

Operation

Coriolis flowmeters measure the mass flow directly by taking advantage of the Coriolis effect. Simply stated, the inertial effects caused by a fluid flowing through a tube are directly proportional to the mass flow of the fluid. In a Coriolis flowmeter, vibration is induced in the fluid-filled flow tube, and then the mass flowrate is captured by measuring the difference in the vibration phase between one end of the flow tube and the other.

Coriolis flowmeters are well suited to virtually any process because they are very accurate, require little or no maintenance and have no moving wetted parts. Because they measure mass flow directly and very accurately, and are less expensive to purchase and maintain, Coriolis mass flowmeters appear to be a good solution.[15]

"*Coriolis flowmeters measure the actual mass flow by taking advantage of the Coriolis effect. Simply stated, the inertial effects caused by a fluid flowing through a tube are directly proportional to the mass flow of the fluid. In a Coriolis flowmeter, vibration is induced in the gas-filled flow tube(s), and then the mass flowrate is captured by measuring the difference in the vibration phase between one end of the flow tube and the other.*"[16]

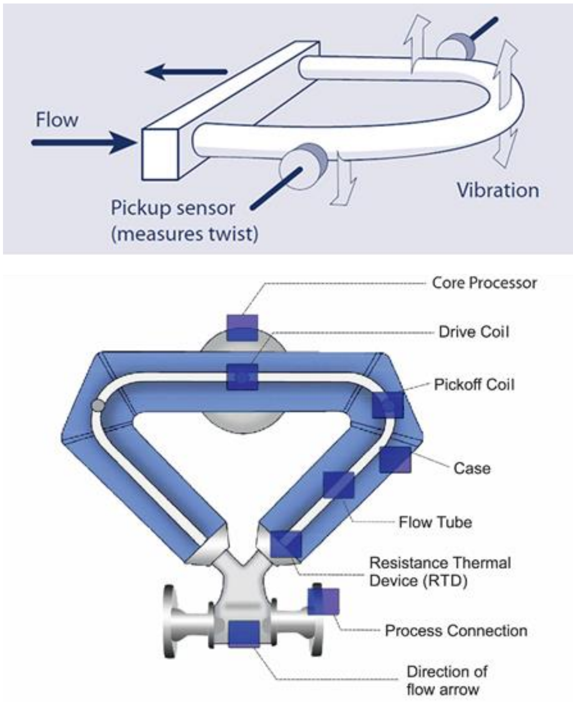

Figure 10: Diagram showing the workings of typical Coriolis flowmeters (Source: Bronkhorst & Hile)

Current applications

Hydrogen for Fuel Cell Electric Vehicles (FCEV) hydrogen refueling stations (CA accuracy class 5.0 in the USA)[17]

High-pressure hydrogen dispensing (for example large-scale custody transfer during fuelling of hybrid bus engines[18])

Industrial ATEX-rated volatiles and corrosive applications

Pros

- High accuracy / precision (±0.5% of actual reading)
- Non-contact in-line sensor
  - Can work under extremes of temperature and pressure
  - Excellent material compatibility
- Measures both mass flowrate and fluid density directly (no conversion / volume correction required)
  - Could potentially infer gas composition (hydrogen content)
  - Metering un-affected by changes in gas density (e.g. hydrogen "slugs")
  - Metering un-affected by temperature and / or pressure swings
- Easy installation and low maintenance
  - Un-affected by vortices at inlet (no straight run-ins required)
  - No moving parts

Cons

- Cheaper alternatives may be available for large-portfolio applications, such as residential

[15] https://www.emerson.com/documents/automation/article-coriolis-flowmeters-improve-hydrogen-production-micro-motion-en-65128.pdf
[16] https://www.emerson.com/documents/automation/article-coriolis-flowmeters-improve-hydrogen-production-micro-motion-en-65128.pdf
[17] Slide 4 https://www.hydrogen.energy.gov/pdfs/review16/tv037_peters_2016_o.pdf
[18] https://www.greencarcongress.com/2020/09/20200915-emerson.html

4.7 Differential Pressure: Orifice plate meters

Operation

A restriction (the orifice plate itself) is inserted into the gas pipework. When a gas is flowing, this restriction creates a drop in the pressure of the gas downstream of the orifice plate (Bernoulli effect). The difference in pressure between the up-stream and down-stream side of the restriction can be used as a measure of the flow rate once calibrated.[19]

Current applications

- Water treatment plants
- Natural gas industries
- Refineries
- Petrochemical plants20
- Often used when checking / calibrating diaphragm meters (residential etc.)

Pros

- Inexpensive and high accuracy (up to 0.5% for gases) if installed to ISO 5167 or calibrated
- No moving parts
- Robust / long service life
- Simple / high stability
- Favoured for high temperature and high-pressure applications (cheaper than Coriolis alternative)
- Can be installed in any orientation

Cons

- Rangeability (turndown) is less than for most other types of flow meter (3:1~4:1), though is becoming less of an issue with new pressure sensors
- Significant pressure drops can occur at high flow rates which can affect the consistency of any unregulated equipment downstream
- Output signal is non-linear with flow
- Pipe layout or nature of flow may affect discharge coefficient and accuracy
- May suffer from ageing effects, e.g. the build-up of deposits or erosion of sharp edges

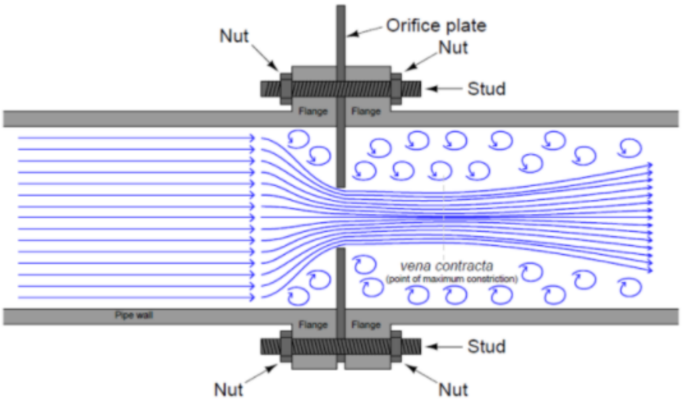

Figure 11: Diagram showing the workings of an orifice meter (Source: Varkratoond)

[19] https://www.dp-flow.co.uk/products/flow/differential-pressure-primary-elements/130-restriction-orifice-plates-and-critical-flow-devices
[20] https://www.aspireenergy.com/orifice-meter/

4.8 Summary

Below we summarise the particular positive and negatives of the meter technology types mentioned above.We then consider their current and potential applicability to the three main uses cases covered in this report.

Table 2: Comparison of meter types

Technology	Typical Application	Pros	Challenges
Diaphragm	Residential / Commercial NG Metering	Incumbent technology for domestic / commercial metering of NG. Low cost, reliable, widely available	Measures volumetric flow: gas composition, temperature and pressure need to be known for accurate metering. Moving parts (mechanical actuation), with wear over time. Not suitable for high pressures.
Rotary	Commercial / Industrial NG Metering	Mature technology, low cost, reliable, widely available	Measures volumetric flow: gas composition, temperature and pressure need to be known for accurate metering. Moving parts (mechanical actuation)
Turbine	Industrial, Utilities (water monitoring)	Mature technology, low cost, widely used	Flow rate can be calculated using k-factor for known fluid; gas composition, temperature and pressure needs to be known for accurate metering. Moving parts (mechanical actuation).
Ultrasonic	Industrial / Hydrogen custody transfer Domestic natural gas	Non-contact measurement: Suitable for low temperature / high pressures (liquid hydrogen / corrosives e.g. ammonia). Directly measures mass-flow, additional diagnostic information can be used to infer changes in fluid density (potential to compensate for variations in blend). Can give detailed diagnostic information (pipe condition, flow conditions, fluid density). No moving parts	Flow rate needs to be computed from acoustic information (introduces complexity and cost)
Thermal mass	Industrial, Precision metering (labs)	Directly measures mass flow (not volumetric). High accuracy, no moving parts	Gas composition needs to be known for accurate metering (will not compensate for variations in gas blend). Not suitable for very high pressures or larger pipework. Flow rate needs to be computed from thermal information (adds complexity and cost)
Coriolis	Hydrogen refuelling	Non-contact sensor: Suitable for very low temperature / very high pressures (liquid hydrogen / corrosives e.g. ammonia). Directly measures both mass-flow and fluid density (potential to compensate for variations in blend). High accuracy. Gaining wide acceptance for FCEV refuelling	Relatively new technology. Flow rate needs to be computed from vibrational information (introduces complexity and cost). Cheaper alternatives to Coriolis available for large-portfolio applications, such as residential
Differential Pressure (Orifice Plate)	Petrol / Diesel Re-fuelling, Industrial & Petro-chemical, Water treatment plants	Mature technology, simple, low maintenance, low-cost	Gas composition needs to be known / well blended for accurate metering (will not compensate for variations in gas blend). Relatively stable flow required. Low rangeability. Significant loss in fluid pressure may occur whilst transiting the meter

Table 3: Consideration of meter suitability for use cases

Use case (Hydrogen as a replacement fuel)	**Fuel type**	**Meter technology**							**Commentary**
		Diaphragm	**Rotary**	**Turbine**	**Ultrasonic**	**Thermal Mass**	**Coriolis**	**Orifice**	
Domestic	Legacy	Green	Red	Red	Green	Green	Red	Red	The diaphragm and rotary meters work mechanically and activate the counter directly making them easy to use and not requiring further interpretation. They will likely be fine with hydrogen blends up to 20%. And rotary beyond that.
	Hydrogen	Amber	Red	Red	Green	Green	Red	Red	
Industrial	Legacy	Green	Green	Green	Green	Amber	Amber	Green	Industrial settings typically operate at higher volumes and pressure. So, while the meters above can still perform, turbines, ultrasonic (good diagnostic data) and orifice meters currently perform well and are expected to be a good option for hydrogen.
	Hydrogen	Red	Amber	Green	Green	Amber	Amber	Green	
Transport	Legacy	Green	Red	Amber	Red	Red	Amber	Red	Coriolis and diaphragm meters are well known and accepted for flow metering of hydrocarbons in a transport setting. Coriolis meters are being increasingly used for hydrogen refuelling, having good rangeability and the ability to work under the 350 and 700 bar pressures currently being used.
	Hydrogen	Red	Red	Amber	Green	Amber	Green	Red	

Key
Recommended (Green)
Potentially suitable / less cost-effective (Amber)
Poor suitability (Red)

5 Standards

5.1 Importance

The IEA, in mapping out the opportunity for Hydrogen, called for the need to eliminate all unnecessary regulatory barriers and to harmonise standards. These are at all points in the value chain and include the need to harmonise flow measurement standards.

Without harmonisation, project developers face hurdles where regulations and permit requirements are unclear, unfit for new purposes, or inconsistent across sectors and countries. Hydrogen's complex supply chains mean governments, companies, communities and civil society need to consult regularly. Without confidence and interoperability in a future hydrogen system, consumers (domestic, commercial or industrial) will have low levels of acceptance leading to lower levels of hydrogen usage and failure to achieve decarbonisation targets.

> "THE ABILITY TO MAKE ACCURATE MEASUREMENTS IS SUCH A FUNDAMENTAL FOUNDATION OF MODERN SOCIETY THAT IT HAS BECOME LARGELY INVISIBLE."

Over the past twelve months the Flow Measurement Special Interest Group (FMSIG) of the Institute of Measurement and Control (InstMC) has noted both national and international reports calling for concerted action by policymakers to facilitate wide-scale deployment of hydrogen as an alternative to conventional hydrocarbon fuels. FMSIG is concerned that there may be gaps in the requisite flow measurement capability (knowledge, techniques and supporting infrastructure) that could significantly impede or delay wide-scale deployment of hydrogen in this way.

In a decarbonised energy system (apart from electricity) every other use, transport or storage of energy involves a liquid or gas; be it hydrogen, ammonia or biogas. Therefore, every non-electric financial and fiscal energy transaction is based upon a flow measurement. So, flow meters will be the essential cash registers of the hydrogen economy (as they are for the gas networks and oil & gas industry today).

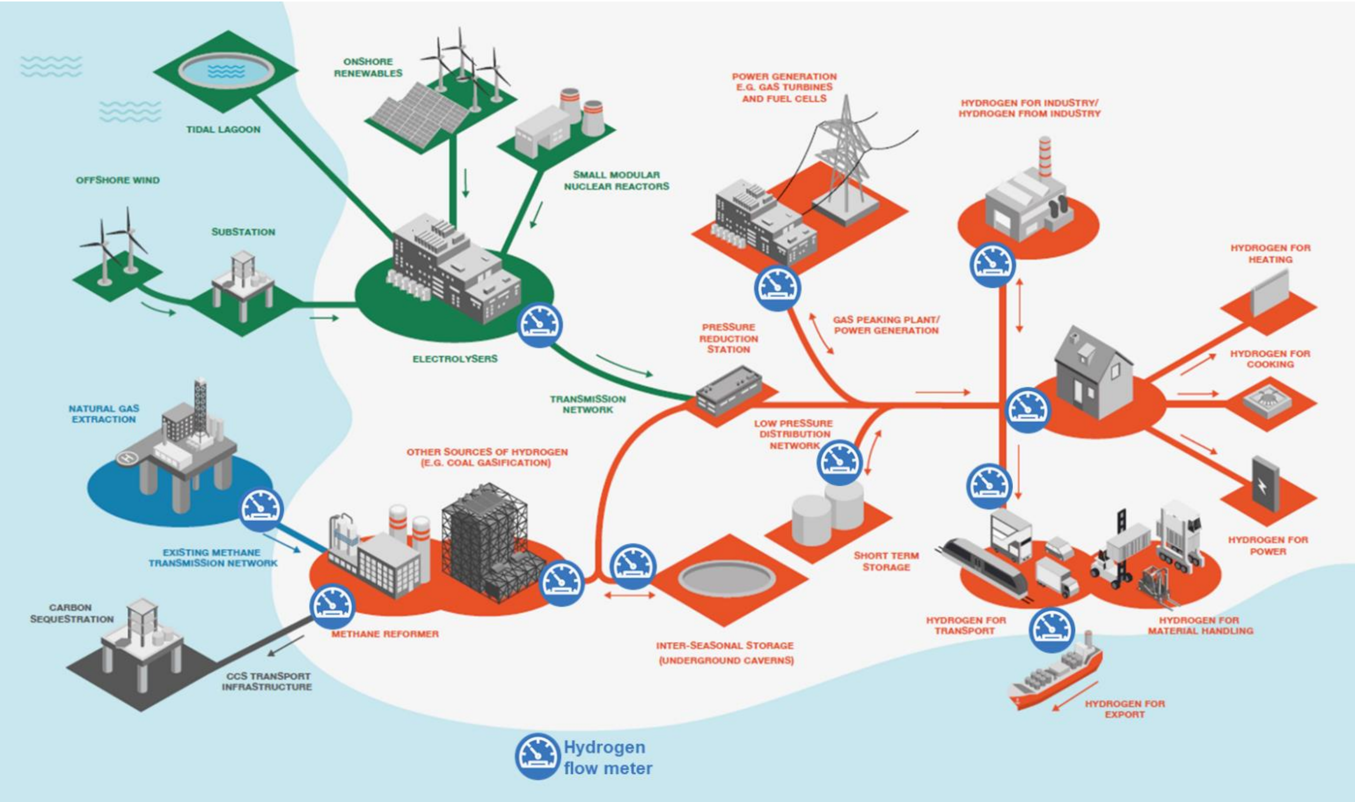

Figure 12: Image reproduced from Establishing a Hydrogen Economy: The Future of Energy 2025 (Arup, 2019), with positions of meter points added in to illustrate their importance

5.2 Existing standards and guidance

The International Organization of Legal Metrology (OIML), is an intergovernmental agency that aims to enable economies to put in place effective legal metrology infrastructures that are mutually compatible and internationally recognized. This is necessary to facilitate trade, establish mutual confidence and harmonize the level of consumer protection worldwide. They develop guidance across a range of specialist advice areas. There are several of these International Recommendations that are particularly relevant to hydrogen flow metering standards. These

Recommendations are model regulations that establish the metrological characteristics required of certain measuring instruments and which specify methods and equipment for checking their conformity. OIML Member States then implement them to the greatest possible extent. Recommendations to the greatest possible extent. The ones most pertinent to hydrogen flow metrology are:

- OIML R 117 - Dynamic measuring systems for liquids other than water
    - This Recommendation specifies the metrological and technical requirements applicable to dynamic measuring systems for quantities (volume or mass) of liquids other than water subject to legal metrology controls. It also provides requirements for the approval of parts of the measuring systems (meter, etc.).
- OIML R 137-- Gas meters
    - This Recommendation applies to gas meters based on any measurement technology or principle that is used to measure the quantity of gas that has passed through the meter at operating conditions. The quantity of gas can be expressed in units of volume or mass.
    - This Recommendation applies to gas meters intended to measure quantities of gaseous fuels or other gases. It does not cover meters used for gases in the liquefied state, multi-phase, steam and compressed natural gas (CNG) used in CNG dispensers.

Figure 13: Logo of the International Organization of Legal Metrology

- OIML R 139 - Compressed gaseous fuel measuring systems for vehicles.
    - In general, the measuring systems that are covered by this Recommendation are intended for the refuelling of motor vehicles, small boats, and aircraft with compressed natural gas, hydrogen, biogas, gas blends or other compressed gaseous fuels. They may also be applicable to other vehicles, for instance trains.
    - Measuring systems for liquid petroleum gas are not included in the scope of this Recommendation. These are within the scope of OIML R 117, which covers fluids in a liquid state.
    - This Recommendation is not intended to prevent the development of new technologies. According to the state of the art, this Recommendation is intended for measuring systems providing mass indications.

The 2014 edition was updated in 2018 and the following major changes for hydrogen fuelling systems were included:

1. two new Accuracy Classes with the following maximum permissible errors (MPEs): for meters: 1.5 percent (2.0 AC) and 2.0 percent (4.0 AC); for complete systems: 2.0 percent and 3.0 percent (2.0 AC) and 4.0 percent and 5.0 percent (4.0 AC) for type evaluation/initial verification and for systems when in service, respectively, with no changes proposed to the MPEs for CNG fuelling;
2. a minimum measured quantity (MMQ) not to exceed 1 kilogram;
3. revisions to durability test procedures to require only meters with moving parts be tested. Sections of the R 139 testing procedures were also modified making them applicable specifically to hydrogen fuelling systems; and;
4. recognizing the “pre-cooler,” depressurization correction device, and compressors as part of the measuring system, where appropriate, in (OIML) R 139, Part 1: Metrological and technical requirements, Part 2: Metrological controls and performance tests, and Part 3: Report format for type evaluation.

5.3 National and international assessment

5.3.1 Overview

There is currently much talk and planning around the opportunities presented by a growing hydrogen economy. These are happening at national and supra-national levels. Many of these approaches are collaborative, bringing together countries and organisations with vested interests in hydrogen, be they technological, commercial, societal, environmental or political.

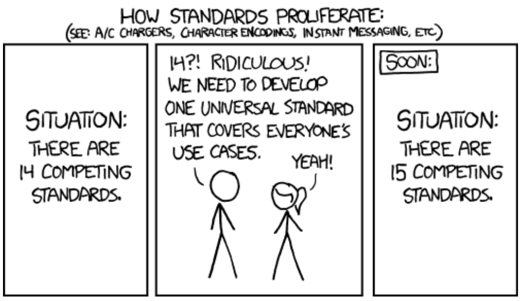

Figure 14: Harmonisation (not multiplication) of standards will lower barriers for participants in the hydrogen economy (Source: https://xkcd.com/927/)

Wherever there is collaboration, there is influencing and a potentially a degree of jostling for position. National governments will naturally represent their industrial sectors and consumers and will seek to present their view of how the standards should be developed and will want standards to not unduly limit their economy. Likewise, governments or organisations representing larger markets or producers will have the potential for greater influence given the commercial influence that scale can bring. And early adopters of hydrogen technologies will be in a position of relatively greater influence too.

All told, it is important to be at the table, to participate in these standard harmonisation collaborations for international and national benefits.

5.3.2 UK

The UK has not, at the time of writing, published a distinct hydrogen strategy. There are growing calls across the industrial, energy (renewables and oil and gas), commercial and public policy sectors for a clear hydrogen strategy and a hydrogen sector deal (as laid out in the Industrial Strategy). BEIS suggest the UK Hydrogen Strategy will be published in 2021. Though, ahead of this, there is growing expectation that the long-awaited Energy White Paper (delayed but due late 2020) will feature significant detail on the UK's hydrogen plans.

None of this is to say that the UK Government has been silent on the issue. Far from it.

The recently established Hydrogen Advisory Council[21] is a UK-wide business/academia/Government forum that serves as the primary forum for ministerial engagement with the hydrogen sectors. While the Council is initially focussing on the scale up of low carbon hydrogen production, they have set up working groups to consider and deliver key aspects of both supply and demand of low carbon hydrogen. Central to these is the *Standards and Regulations* working group. This will:

- Identify priorities for establishing common standards for low carbon hydrogen production (assessing greenhouse gas lifecycle emissions, production, transport and storage standards, safety standards, alignment with international activity).
- Identify regulatory barriers to hydrogen deployment and prioritise regulations to establish or amend in relation to hydrogen production and suggest solutions.

In addition to this, the UK Government has funded or managed a range of hydrogen research and development projects. These are designed to accelerate technology development in key areas or to identify and remove barriers that would otherwise prevent of slow the rapid and large-scale uptake of hydrogen within the UK.

These include:

Hy4Heat – examining the safety and feasibility of blending or replacing natural gas with hydrogen in domestic and commercial sector in GB.

HyDeploy – live trial of hydrogen (at 20%) blended with natural gas in a gas distribution network at Keele University.

HyNet North West – pipeline distribution of 100% hydrogen to 10 energy intensive industrial gas users.

5.3.3 European Union

Though European Union Member States have their individual approaches to decarbonisation and the role that hydrogen plays with that (see below), the European Union is leading the efforts to develop a coherent and collaborative approach to hydrogen for Europe as a whole.

The European Commission published its Hydrogen Strategy in July 2020. It states that hydrogen is essential in helping EU reach carbon neutrality by 2050 and represents a solution to decarbonise industrial processes and economic sectors where reducing carbon emissions is both urgent and hard to achieve. Therefore, making hydrogen essential to support the EU's commitment to reach carbon neutrality by 2050 and the global effort to implement the Paris Agreement. Furthermore, it recognises the commercial opportunities of the hydrogen economy, citing Europe's strengths and advantages within clean hydrogen technologies manufacturing and the opportunities of a global development of clean hydrogen as an energy carrier.

Developing a vibrant and growing renewable (Green) hydrogen production and usage economy is clearly seen as the urgent priority. But this requires development and investment (Cumulative investments in European green hydrogen could be up to EUR 180-470 billion by 2050). But if the hydrogen value chain does develop as planned it could employ up to 1 million people, directly or indirectly. While green hydrogen is seen as the ultimate source, it will be necessary to satisfy demand in the near future with grey hydrogen.

There is an international dimension to the full potential of a global hydrogen economy and in particular the European Commission wants to actively strengthen EU leadership in international fora for technical standards, regulations and definitions on hydrogen.

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21 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/926744/hydrogen-advisory-council-inaugural-meeting-minutes-200720.pdf

European aligned bodies with an international remit include:

EURAMET - The European Association of National Metrology Institutes

EURAMET is the Regional Metrology Organisation (RMO) of Europe. Its members are the National Metrology Institutes (NMI) in Europe. It works with them to meet their national requirements and to encourage and support work in fields such as research in metrology, traceability of measurements to the SI (International System of Units) units, international recognition of national measurement standards and related Calibration and Measurement Capabilities (CMC). Established to enhance the benefits of metrology to society and to develop and disseminate an integrated, cost effective and internationally competitive measurement infrastructure for Europe.

Assisting EURAMET in achieving its aims is CIPM MRA. et The Comité International des Poids Mesures (CIPM, which promotes world-wide uniformity in units of measurement) sponsored the creation of a Mutual Recognition Scheme (CIPM MRA) to underpin and formalize technical competence of its signatory National Metrology Institutes and Designated Institutes.

One of the main routes to achieving this is through the European Metrology Programme for Innovation and Research (EMPIR). EMPIR coordinates research projects in this space and enables European metrology institutes, industrial and medical organisations, and academia to collaborate on a wide variety of joint research projects within specified fields: including industry, energy and the environment.

EMPIR follows on from the successful European Metrology Research Programme (EMRP), which has now been completed.

Fuel Cells and Hydrogen Joint Undertaking (FCH JU)

This is a public/private partnership supporting research, technological development and demonstration activities in fuel cell and hydrogen energy technologies in Europe. It aims to accelerate the commercialisation and successful market entry of these to help achieve carbon emissions reductions targets. The European Commission is a founding member of FCH JU, along with the industrial and research arms of Hydrogen Europe. FCH 2 JU is the second generation of FCH JU.

Within the FCH JU, the Regulations, Codes and Standards Strategy Coordination (RCS SC) Group is crucial for the market deployment of FCH systems plays a critical role. There is a recognised lack of harmonized standards and codes across Europe and globally and these gaps are a major barrier for the commercialization of hydrogen technologies. The RCS SC Group aims to:

- Develop science-based, fit-for-purpose European and international standards that promote and enable market deployment by providing the technical requirements to build public confidence
- Establishing compliance/certification criteria within the EC and UN regulatory framework

And much of this is to be done by establishing an approach to enhance European participation and influence in European and international regulations, codes and standards fora, including inputs to Annual Union Work Plans for Standardisation.

MetroHyVe

The hydrogen industry currently faces the dilemma that they must meet certain measurement requirements (set by European legislation) but cannot do so due to a lack of available methods and standards. The aim of the MetroHyVe project is to ensure that these measurement challenges do not prevent global uptake of hydrogen vehicles to the automotive market.

Hydrogen Europe

The European association represents the interests of the hydrogen industry and its various stakeholders. Membership includes national trade associations, research institutions and industry stakeholders. One of Hydrogen Europe's key outputs is HyLAW, a project that aims to identify the relevant regulations and standards across Europe that are relevant to the uptake of hydrogen technologies and approaches. Crucially it seeks to identify discrepancies, gaps and challenges and to remove (or harmonise) these barriers to commercial market entry.

5.3.4 Netherlands

The Netherlands published their Hydrogen strategy in 2020. This built on the National Climate Agreement launched by government with businesses and other stakeholders. Both of these documents clearly identify Hydrogen as a significant technology and fuel that will help achieve the decarbonisation targets. They have initiated schemes and mechanisms to stimulate the hydrogen production market and also the potential demand side use cases, for example FCEVs and refuelling stations and a potential obligation for blending hydrogen (10-20%) into the natural gas network.

As a critical supporting policy to their Hydrogen strategy, maintaining an international strategy will continue to be a part of the Dutch approach. They will focus principally on Europe but also look to take part in global partnership initiatives.

With regards to standards, the Netherlands sees as a necessity, the need to work collectively with the European Union and fellow member states; seeking direct contact with the European Commission at every conceivable level. This is to influence and to achieve consensus on what European policy should be with regards common standards for sustainability, safety, quality and blending of hydrogen in gas grids. In addition, they participate in the Pentalateral Forum (Benelux, Germany, France, Austria and Switzerland). Within this, The Netherlands has taken the initiative to develop common approaches to critical issues such as standards, market incentives and market regulations ahead of the discussions in an EU context.

5.3.5 Germany

Germany's Federal Government published an ambitious National Hydrogen Strategy[22] in June 2020. While of national importance, it clearly sees a Hydrogen future being an internationally collaborative one.

It identifies, that due to the particular physical and chemical properties of hydrogen, the urgent need to develop a quality assurance infrastructure for hydrogen production, transport, storage and use. These cannot be tackled nationally but needs to be built up and networked at national and European level, particularly around metrology.

In particular, there is a need for scientifically accepted and regulated measurement methods and assessment criteria, and internationally accepted standards and technical standards; these will help build trust amongst the users. Germany sees the value to its economy and climate commitments in Hydrogen and understands the value to helping develop standards and policies. Leveraging the scale of the European Union is critical to the success of the hydrogen project and will play a pivotal role in shaping the basic international framework.

They plan to use their European Council presidency to take on an active role in setting up a market for hydrogen and establishing sustainability standards and to place a central focus on the framework for sector coupling and the development of an EU internal market for hydrogen.

Two specific measures of interest call for the "Advocacy for an international harmonisation of standards for mobility applications for hydrogen and fuel-cell-based systems (e.g. refuelling standards, hydrogen quality, official calibration, hydrogen-powered car type approval, licencing for ships etc" and "At European level, we want to set sustainability and quality standards in the field of hydrogen and PtX products, and thus to actively foster the establishment of the international hydrogen market. This includes support for the development of European regulations, codes and standards in the various fields of application which will form the groundwork for the international market and ensure that the market ramp-up in Germany takes place in line with the needs of the energy transition. In parallel to this, Germany will also intensify the dialogue on common standards with other countries in order to pave the way towards a universalisation in international organisations."

5.3.6 USA

Another country to publish a national hydrogen strategy in 2020 was the USA. It builds on work from the Department of Energy over the last 20 years and it states that aspects of a growing hydrogen economy can enhance the USA's energy security, resiliency and economic prosperity. It identifies Transport and Industrial heat as being two key use cases. While it acknowledges the opportunity of Hydrogen being distributed in the gas network it does not rank Domestic heating as highly as some other national approaches

While the US does not currently export hydrogen in significant amounts, the strategy recognises the potential of an international market in hydrogen and acknowledges the global initiatives that are driving decarbonisation.

Regarding standards it recognises that there are existing national and international standards that enable the safe usage of hydrogen today, with today's infrastructure. But as hydrogen infrastructure, production and usage increase, the state of existing regulations and standards currently limits hydrogen uptake. Certain standards may be unclear or not written with new uses of hydrogen in mind, therefore preventing the exploitation of the full benefits hydrogen can provide. The strategy calls for this standards and regulations to be updated if hydrogen is to have the opportunity to fulfil its potential. Within the USA there is a base framework but there are gaps, and it is critical that essential standards exist to cover the new and growing hydrogen applications. The National Institute of Standards and Technology (part of the US Department of Commerce) is leading on developing and improving international standards in this area, for example the OIML Recommendations mentioned above.

5.3.7 Japan

Japan launched the world's first national hydrogen strategy in 2017. Noting the structural challenges facing Japan's energy system; their energy security and self-sufficiency rate plus their CO2 emission reduction targets. Hydrogen is seen as a key plank in their bid to solve the riddle of the challenges above but also as a burgeoning economic sector in its own right. They identified several primary use cases for hydrogen, including Transport & Mobility, Industrial use and Domestic heating. They are encouraging technological and regulatory developments and reforms in these areas. In production, transport, distribution and refuelling.

[22] https://www.bmwi.de/Redaktion/EN/Publikationen/Energie/the-national-hydrogen-strategy.html

The hydrogen sector in Japan is growing and is projected to grow significantly, with particularly large increases in hydrogen refuelling stations expected.

Like other jurisdictions, Japan identified international development as a central tenet of their strategy. They are looking to lead international standardisation through all available international frameworks. Given their leading position in this area and their strong technological and manufacturing economy, they will be keen to ensure international standardisation to open up global markets.

5.4 Flow measurement challenges

5.4.1 Transport (Hydrogen Vehicle Refuelling)

Accuracy

Hydrogen Refuelling Stations (HRS) for vehicles come under regulation OIML R-139 (5.2 above). As shown in Table 2 below, new HRS must now meet class 2 (+/- 2% when initially certified, +/- 3% once in-service). Old and existing HRS must meet class 4 (+/- 4% when initially certified or +/-5% once in-service).

However, this could in theory result in a relatively large loss to the consumer when filling up their FCEV. For example, if filling up your tank for £50, you could be short-changed by £1.50 - £2.50. I.E., you're not getting as much fuel as you're paying for.

For comparison, the existing regulatory requirements for petrol and diesel is an 'at the nozzle uncertainty' of -0.5% to +1.0% ((at the minimum measured quantity of 5 litres as set out in OIML R 117). This asymmetry results in a slight bias in favour of the consumer and on a similar £50 fill could lose out by a maximum of just 50p.

It's reasonable to assume that customers will expect accuracy and would be used to the accuracy currently available when filling up with petrol or diesel. As shown, the OIML requirements below in Table 2 are looser than these though. Given that customer acceptance and indeed customer enthusiasm will be vital in driving the take-up of hydrogen technologies, they need to be on side and any of these potential worries addressed.

Table 4: The maximum permissible error (MPE) on mass indications, positive or negative, is given in the table below. (Source: OIML R 139)

Accuracy class		MPE for the meter **[in % of the measured quantity value]**	MPE for the complete measuring system **[in % of the measured quantity value]**	
			at type evaluation, initial or subsequent verification	in-service inspection under rated operating conditions
For general application	1.5	1	1.5	2
For hydrogen only	2	1.5	2	3
	4	2	4	5

Currently there is no method of verification available so trading standards cannot properly investigate any disputed volume deliveries. This is because the UK does not currently have the necessary equipment or skills to test fuel dispensers. Secondly, there is no traceability chain linked back to a physical primary standard for hydrogen.

Again, to compare with the current situation with petrol or diesel, if a consumer disputes the dispensed volume Trading Standards are fully equipped to investigate. They have the well-established equipment and skills to test fuel dispensers and there is a robust traceability chain linked back to the physical primary standards for liquid flow which are held by NEL.

Conditions and Uncertainties

In a typical HRS, vehicles are filled to 350 bar (cars and buses) or 700 bar (cars only). The measuring system includes precooling to -40ºC. These are tough and challenging conditions for a flow meter. Uncertainties vary according to the precise position of the meter within the measuring system. For example: if close to the compressor, the gas is at ambient temperature, stable pressure and a large dead volume[23]. But, if close to the dispenser, the temperature is more variable (ambient to -40ºC) and dead volume is minimised.

These uncertainties have been explored and corroborated in field test conducted by Air Liquide for FCH JU, (Air Liquide (FCH JU), 2019).

[23] Dead volume is the volume between the flow meter and the point of transfer into the vehicle

All of this is compounded by the lack of hydrogen calibration facilities. Thereby, demanding a method of flow meter calibration and a means of field verification at the refuelling station

Flow meter calibration method

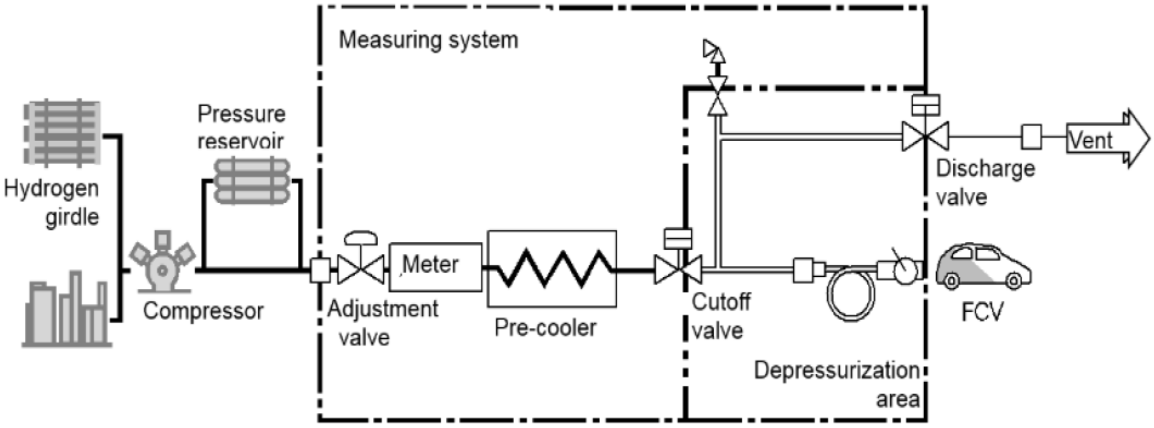

Figure 15: "Typical" configuration of an HRS measuring system (Source: MetroHyVe)

Coriolis meters are the preferred meter type used in refuelling stations. To meet the demand for proper calibration, NEL have investigated an alternative calibration method using nitrogen/air, matching mass flow rate and density. These featured separate tests to account for temperature and pressure and were conducted in collaboration with METAS, CESAME and RISE to test meters from the three manufacturers used in European HRSs

These calibration tests showed errors within acceptable limits and good reproducibility between facilities. Showing that alternative fluids to hydrogen can be used for the meter calibration but that field verification is still necessary

5.4.2 Domestic and Industrial Metering

There are some particular properties of hydrogen that pose challenges to accurate and safe metering. These are:

- Increased Flow Rates for pure hydrogen (compared to natural gas). The flow rate of 20 m^3/hour for hydrogen compared to 6 m^3/hour for natural gas means that existing flow meters can be over-ranged, resulting in possible measurement errors and the potential for increased wear/failure of mechanical meters.
- Lowest Gas Density which is 8 times lower than natural gas
- High speed of sound, 3 times higher than natural gas

Much of the focus of the hydrogen trials to date has been on safety. This is a critical area, but the accuracy of gas meters needs to be fully investigated, both at blended and at 100% hydrogen levels.

Given the volumes of hydrogen that are forecast to be transported in the gas networks, and used by industrial and domestic consumers, there needs to be high confidence in the accuracy of the meters. There are likely to be many transfers in custodianship, and many economic actors involved from production to final consumption. As the cash registers of the system, the metrology needs to be accurate.

As described at length in this report there are a number of different meter types available. Currently, there are three main types of meter used in the domestic and industrial distribution networks. These are:

- Diaphragm: but there might be increased errors from internal leakage.
- Ultrasonic: but there might be increased errors from signal attenuation, timing resolution.
- Thermal Mass: Might be well suited to changes in the fluid.

To explore the possible uncertainties, there is an urgent need for new test data because data for existing natural gas usage may not be relevant.

The UK's Designated Institute for Flow and Density Measurement, NEL, has been involved in a number of initiatives to establish new Test facilities and programmes. These include:

- Hydrogen Test Facility for Domestic Gas Meters
  - Designed for pure hydrogen, funded by Northern Gas Networks (Q1 2019)
  - Design revised to allow testing with blends e.g. (hydrogen with natural gas or nitrogen)
  - Build and commission Q4 2020
  - Flow rates 0.1 to 38 m^3/hr, 0 to 100% hydrogen

- Measurement Uncertainty ±0.3% @ 95% confidence

- EMPIR JRP "Flow metering of renewable gases" NEWGASMET
  - Started in June 2019
  - NEL will assess the suitability of CEN/TC 237 standards for ultrasonic and thermal mass flow meters when used with renewable gases (biogas, hydrogen, mixtures etc…)
  - Test programme includes accuracy testing 2 types of domestic gas flow meter with 100% hydrogen

- EMPIR JRP "Metrology for Decarbonising the Gas Grid"
  - Proposal submitted, would start in June 2021
  - NEL leading WP1: Flow Metering
  - Test programme for domestic gas meters, 100% H 2 and H 2 /CH 4 mixtures (up to 20% H 2
  - Includes existing meters and meters developed for use with hydrogen
  - Study of how calibrations transfer between nitrogen and hydrogen
  - Also includes CO_2 flow metering for CCS

6 Liquid hydrogen

6.1 Use Cases

Gaseous hydrogen has a very low volumetric energy density. As shown in the chart below, hydrogen has high energy density by mass but low by volume. It is more economically efficient to store or transport energy at higher volumetric energy densities where possible. Therefore, gaseous hydrogen is typically pressurised and compressed for storage. To achieve even greater volumetric energy densities, hydrogen can be liquefied.

However, as with other cryogenic liquids, the process of liquefaction is relatively energy demanding and hence there are non-trivial cost associated with this. Hydrogen has a critical temperature (the temperature above which a gas cannot be liquefied by pressure alone) below -230°C. So requires considerable processing through heat exchangers as well as pressurisation to liquefy. Once in a cryogenic liquid state, the hydrogen can be stored or transported (in containment vessels). In the absence of a pipeline network, liquid hydrogen could be the most economical way of distributing large quantities of hydrogen to the end user. However, further energy is required to do this effectively over medium to long terms; without active refridgeration to maintain the low temperature, liquid hydrogen can boil off and require venting. There is scope for lighter weight liquid hydrogen storage, due to the fact that it is stored at atmospheric pressures and does not require as much structural strength. Commercially viable lighter weight storage vessels are being researched and developed.

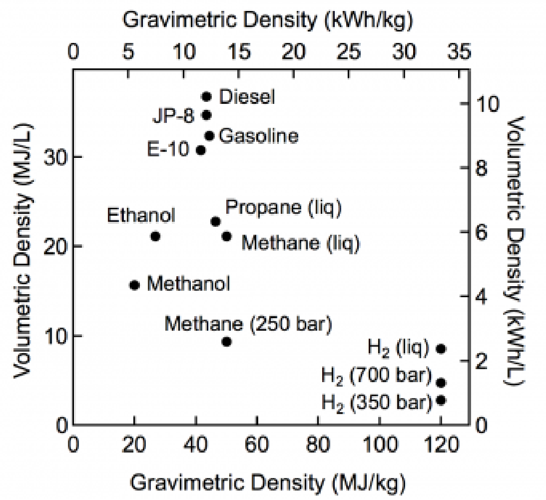

Figure 16: Comparison of specific energy (energy per mass or gravimetric density) and energy density (energy per volume or volumetric density) for several fuels (Source: EERE)

There are currently limited fuel applications for liquid hydrogen (other than as a rocket propellent). There is some development in liquid hydrogen fuel cells, but these are in concept stage rather than commercially available. However, the value of liquid hydrogen as a store and vector is high and may be key to wider success of the hydrogen economy.

Japan and Germany have identified the potential need to import hydrogen to achieve decarbonisation targets, and both are supporting further work into improving the techniques of liquefaction, storage and transport of liquid hydrogen. For example, Japan, as part of their Hydrogen strategy, will work to develop international hydrogen supply chains. To contribute to this to this effort, they will demonstrate a liquefied hydrogen supply chain by the mid-2020s with a view to commercialisation around 2030.

6.2 Metrology Considerations

The main physical characteristics that are most challenging for the metering of liquid hydrogen are the extreme cold temperatures and the susceptibility to phase change when operating near its critical point (from even minute changes in temperature or pressure). In addition, the typical features of liquid hydrogen (when compared with other general liquids) are low viscosity, large latent heat and small density, compared with other general liquids.

Coriolis technology (see 4.6 above) is the most widely used meter type for liquid hydrogen. These meters are well understood within the hydrogen, chemical engineering and oil and gas sectors; having been successfully used with liquefied natural gas (LNG) and liquified nitrogen, and test rigs are available to calibrate these meters with these fluids. However, further investigation is required to investigate any potential influences on accuracy when metering at much lower temperatures; for example, liquid hydrogen at 20K. Analysis and comparison of calibrations with liquid nitrogen and with liquid hydrogen will help determine any influence due to the fluid temperature.

As with gaseous hydrogen there is considerable research and development into suitable metrology and thermal mass and differential pressure meters types have potential too.

7 Review findings

7.1 Summary

As described above, there is considerable interest and increasing momentum regarding hydrogen as key enabler of decarbonisation. Countries or supranational organisations will have differing hydrogen strategies featuring varying emphases of different use cases or trajectories of growth. However, all major economies see a role for hydrogen in their economies. The precise route maps or business models owe a lot to vested interests and existing infrastructure within these jurisdictions. Some, such as the UK, eye the possibility of nationwide pipeline distribution to homes and industries combined with green hydrogen production and domestic usage and export. While others, like Germany and Japan, see the need for hydrogen imports and therefore are exploring the long-distance transport of cryogenic hydrogen. And those with large existing oil and gas sectors place an importance on the role of blue hydrogen in their particular decarbonisation journeys.

All, though, agree that there will be a strong international market in production and consumption technologies. Therefore, there needs to be an international harmonisation of a range of standards including those for flow measurement. As the cash registers of the future hydrogen economy there has to be total user acceptance and confidence in the accuracy of hydrogen metering.

7.1.1 Transport

A truly international sector, with considerable cross-border traffic flows and international exports and imports of vehicles. Therefore, the challenges the UK is facing with regards accuracy and reliability of flow measurements in hydrogen refuelling stations (HRS) are identical to those being faced elsewhere. Therefore, there is a need to continue with the international collaboration projects currently being conducted to explore the best ways to test and calibrate flow meters within HRSs, and provide traceable measurement in deployed HRS. The physical characteristics of hydrogen, the variability of temperature and pressure in measuring systems, and the absolute need for consumer confidence and enthusiasm make the harmonisation of flow measurement standards essential.

7.1.2 Domestic & Industrial

The UK can thank its industrial past and geological good fortune for its far-reaching natural gas transmission and distribution network. There is a real opportunity here. That is to repurpose the natural gas grid to store and transport hydrogen. Either as a blend or as 100% hydrogen. This report has identified a number of schemes and pilots that are exploring the feasibility of hydrogen (having been transported by the natural gas network) being used in domestic and industrial settings.

Many of these have focussed firstly on the safety of hydrogen, which is the right thing to do. There now needs to be a real drive to understand the accuracy of, and establish standards for, the metering of the hydrogen blends and pure hydrogen. Like transport this is an international endeavour. For although this is GB's gas network, many of the meter manufacturers are based overseas, and the network is physically connected to other networks in Ireland, Scandinavia and continental Europe.

There is an urgent need to identify and harmonise flow measurement standards, and test and calibration techniques.

7.2 Actions needed on hydrogen flow measurement

As a lead organisation of the National Measurement System (funded by BEIS), NEL has already been acting to ensure that the UK's needs for hydrogen flow and density measurement are met. Existing actions and others identified through this report are set out below:

1. The UK Government, working with industry, should publish a National Hydrogen Strategy as soon as possible (at least by the end of 2021) and ensure that the vital importance of harmonised standards, including for flow measurement is given clear priority.
    a. And as an interim measure there needs to be a growing clarity about the role of hydrogen in the long-awaited Energy White Paper.
2. The UK Government needs to provide Physical Primary Standards for hydrogen for the UK to ensure that a traceable and suitably accurate measurement chain exists.
    a. This is essential to enabling domestic and international trade and markets – you can't sell what you can't measure.
3. The UK Government needs to help the relevant bodies develop the correct regulatory regime and documentary standards.
    a. Tight enough to ensure control, relaxed enough to enable affordable and technologically feasible. compliance

4. Supported by BEIS, the UK's Designated Institute for Flow and Density Measurement (NEL) needs to help industry to implement flow measurement in compliance with regulations and documentary standards.
    a. For example, today such support is in place to help industry meet the OGA's fiscal regulations in the North Sea for oil and gas production; we will need to do likewise for hydrogen and CCS.
5. The UK Government and relevant agencies need to develop a full engagement programme allowing them to participate fully in all relevant international hydrogen metrology and standards fora.
    a. Leadership in this area will provide considerable confidence and clarity to the sector as a whole.
    b. Being at the table is essential and being there early and leading the conversation is even better. This will help the UK's progress to net zero, enhance clean growth and facilitate global standards that are well suited to UK's commercial success in the global marketplace.

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Corporate Headquarters
10 Bressenden Place
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SW1E 5DN
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