

# END-USE SAFETY

## SMART CONTROLS IN HYDROGEN APPLICATIONS

This section examines safety in hydrogen's diverse applications, industrial processes, power generation, fuel cell mobility and heating in our homes. It looks at case studies where leaks, explosion, fire or equipment failures can occur, and shows how smart control systems are keeping users safe. The section also discusses the importance of hands-on training, public education and stakeholder engagement in building trust.



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### Smart Controls to Protect People and Assets

Safety is of paramount importance in the hydrogen value chain: from production through distribution and storage to the end-user applications. For end user applications involving gaseous hydrogen, the hazards range from high pressure to the explosive potential of hydrogen. Other storage modes, such as liquid hydrogen and conversion to ammonia introduce cryogenic and toxic hazards.

Nobody should get hurt, and assets must be protected through the energy transition. In addition to industrial applications, the introduction of hydrogen into passenger vehicles and homes must be managed with due regard to public concerns and scientific principles. Smart controls must be built into hydrogen application equipment. Safety must be engineered in from the outset.<sup>1</sup>

### Production to Application in Energy Systems

**Hydrogen – roots in industry and now entering public life:** Hydrogen has been used for decades in industrial applications, as shown in Figure 1. It is a key ingredient of ammonia and fertilizers. Low-sulphur liquid fuels for cars, buses and aviation are produced using hydrogen. Flat glass, semiconductors and vegetable oils require hydrogen in sophisticated manufacturing processes.

The need to mitigate climate change is driving defossilisation of energy systems. This is making hydrogen relevant for domestic and commercial applications where it has not been used before. It is breaking out of industrial applications to uses where the general public will come into contact with this potentially hazardous chemical.

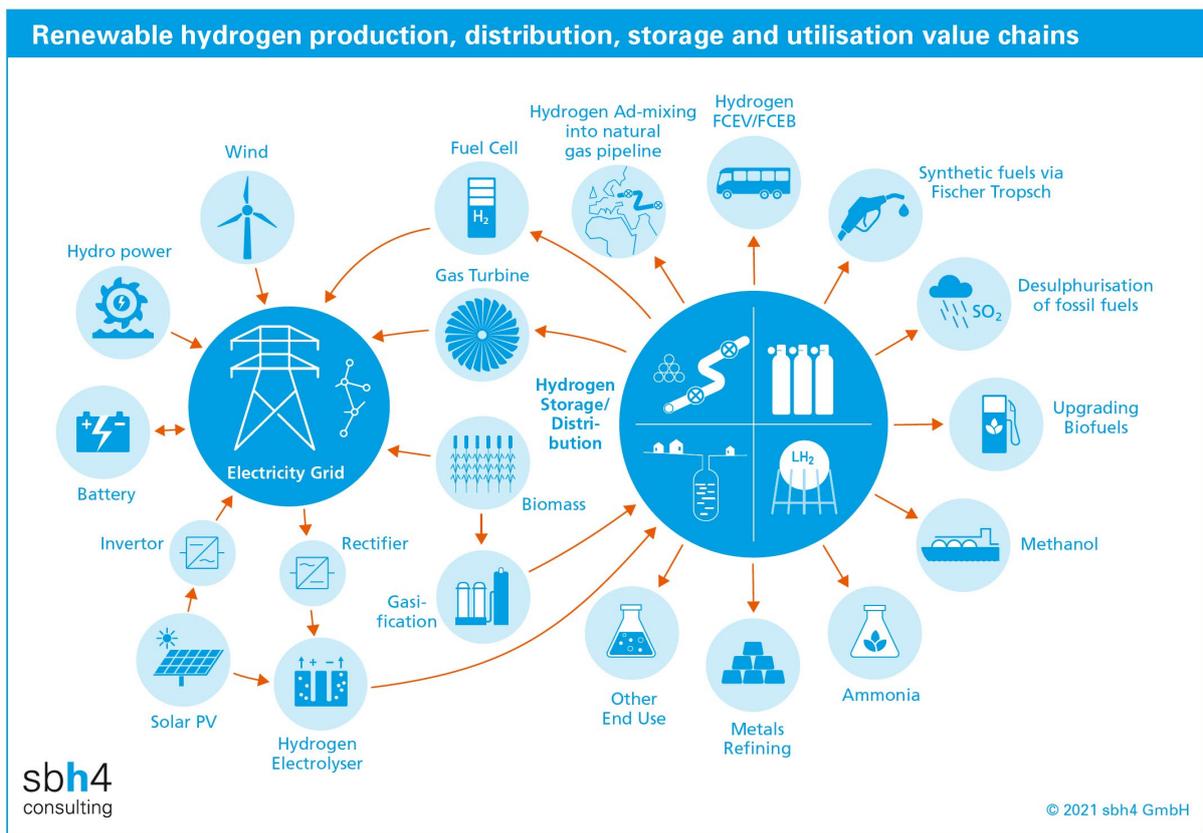


Figure 1. Hydrogen value chains showing end use applications

**The safety Imperative in end-user applications:** Roadside refuelling stations for gasoline and CNG are common. Electric charging points are also becoming prevalent. Alongside these, hydrogen refuelling stations for heavy trucks and passenger cars are being implemented. These are not staffed with technical experts who have had years of safety training and they are used by professional haulage drivers and members of the public. Safety must be designed into these facilities without relying on hydrogen safety expertise of the user.

The concept of blending hydrogen into natural gas distribution pipelines has been raised, with several pilot projects from Gail India and others to explore the issues that may arise.<sup>2</sup> This mixture of hydrogen and methane might be used in homes for heating boilers, or cooking on a stove. There are precedents for using flammable gases such as natural gas, town gas and bottled LPG in domestic and commercial buildings. Despite this, the introduction of hydrogen represents a change and smart control systems are required to ensure public safety.

**Emerging Innovations & Digital Enablers:** Digitalisation of safety monitoring networks has been achieved in refineries and power generation assets in the energy sector. Cabled and wireless communications link multiple sensors to control systems which can invoke mitigation such as closing valves to shut-off the supply of flammable gases.

Robust standards are in place to ensure the integrity of these functional safety systems. For use in industrial settings with hydrogen, they can be rated to safety integrity level 1, 2, or 3. The highest SIL, level 4, is generally used in nuclear power plants and aircraft. A higher SIL rating refers to a lower risk of a functional safety measure failing, when it is required. However, there is a high price to pay for the high-level SILs.

Domestic systems and cars must work at the intersection of safety and affordability. Mass production of sensors and other safety system components used in high-volume production of cars and heating boilers will enable this. But, the transition of hydrogen from the chemical industry to applications where the general public are involved requires a shift in the technologies used and the mindset of the teams designing these safety systems.

**Regulatory & Standards Landscape:** The industrial gases sector, led by international companies such as Air Liquide, INOX Air Products, and Linde Gas, has been at the forefront of handling hydrogen in industrial settings. Experts from these companies have united in their efforts to maintain rigorous safety standards to protect employees, industrial hydrogen users and the public. Their collective expertise has been consolidated by EIGA<sup>3</sup> into various documents.

The physical properties of hydrogen differ from other gaseous energy vectors that are in common use. Whilst all of these gases are flammable, the explosion, ignition and flame hazards of hydrogen are unique. Equipment that has been deployed to mitigate the risk of using natural gas will not be appropriate for hydrogen.

Application risk profiles, smart controls built into end-user systems, training and public engagement related to hydrogen use-cases raise key questions for the future deployment of hydrogen at scale.

The next sections explore these issues in detail, offering practical insights and actionable guidance for industry, regulators, and technology providers.

## Application risk profiles

### a) Industrial and chemical processes

The use of hydrogen in industry is common. Standard engineering practices and reliable equipment exist to mitigate the two risks of hydrogen gas: pressure and flammability.

Over-pressure in equipment can lead to catastrophic failure and a massive release of hydrogen. Powerful explosions and intense fires can be the result. Avoiding over-pressure is achieved using mechanical relief valves which vent hydrogen to prevent mechanical damage. In the vent header, hydrogen must not be allowed to mix with air or other oxidant gases before it is released to the atmosphere either directly or through a flare or gas scrubber.

If hydrogen does leak from a high-pressure source, it can be detected rapidly using various techniques. Fixed gas detectors use sensors to identify the presence of a flammable gas and are located close to likely leak points such as valves and pipe flanges. However, the gas detector relies on the leaked hydrogen gas passing over the sensor. Wind direction changes can suppress the signal meaning potentially explosive hydrogen gas leaks are not detected.

To support gas detection, flame detectors can be installed. They are immune to wind direction changes, but are only activated after a leak has been ignited. Hydrogen burns with an inorganic flame: no CO<sub>2</sub> is present. Furthermore, the unburned hydrogen is also an inorganic molecule. This means that conventional flame detectors which rely in the Infra-Red (IR) signatures of

methane and CO<sub>2</sub> molecules are not suitable for hydrogen. Innovative flame detection equipment operating in other IR and ultraviolet (UV) wavelengths is required for hydrogen flames.

### b) Hydrogen pipelines

Moving hydrogen from an industrial production location to end user application locations can be achieved in many ways. The most cost-effective mode for high volumes of hydrogen is to use a pipeline network. The same concept is true for natural gas transmission and distribution.

Hydrogen is a tiny molecule and has the ability to attack and embrittle steel in ways that methane cannot. The grade of steel, pressure of the pipeline and the operational regime of the pipeline pressurisation and depressurisation are all governed by this property of hydrogen to embrittle steel.<sup>4</sup>

Safety precautions begin with the selection of an appropriate grade of steel, or by coating the internal walls of the pipeline to avoid direct contact of hydrogen with the pipeline material. Additionally, mechanically activated overflow protection valves are used. These automatically close if a pipeline is ruptured to minimise the amount of flammable gas that will be released.

In addition to good engineering practices and mechanical devices, smart controls are also used. High-tech sensors can detect sudden pressure drops and send signals through digital control systems to close valves in the pipeline network.

### c) Hydrogen mobility

Pressure is the major risk in hydrogen mobility applications. To ensure there is sufficient fuel storage capacity on a fuel cell electric vehicle hydrogen is stored at 700 bar on board cars and trucks in custom-engineered carbon-fibre tanks.

In the event of a fire on the fuel-cell-electric vehicle (FCEV), the pressure in the storage tank will increase as it heats up. If it explodes due to overpressure, it will seriously injure, or kill the occupants of the car or the haulage vehicle cab.<sup>5</sup> To prevent this, the hydrogen storage tanks are fitted with a thermal pressure relief device (TPRD) which vents hydrogen in a safe direction away from the vehicle occupants in the event of a fire near the fuel tank. This smart control TPRD operates in a similar way to water sprinklers in a hotel or commercial building.

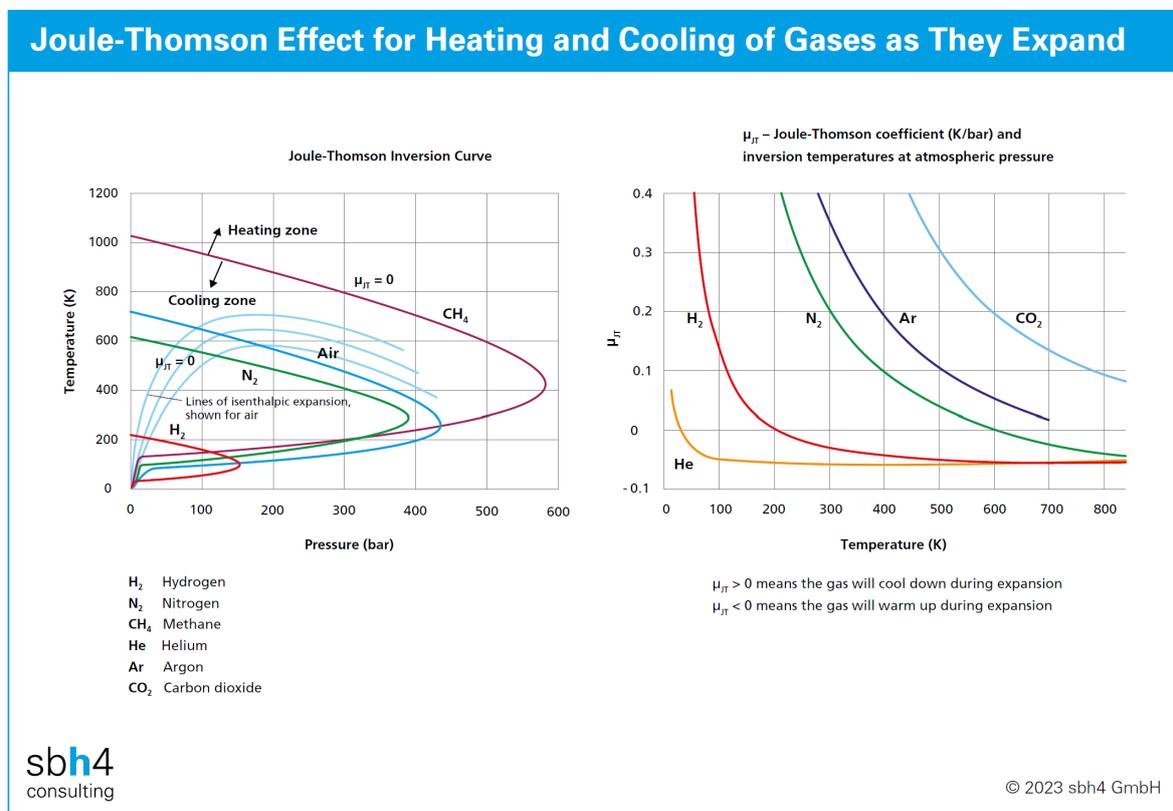


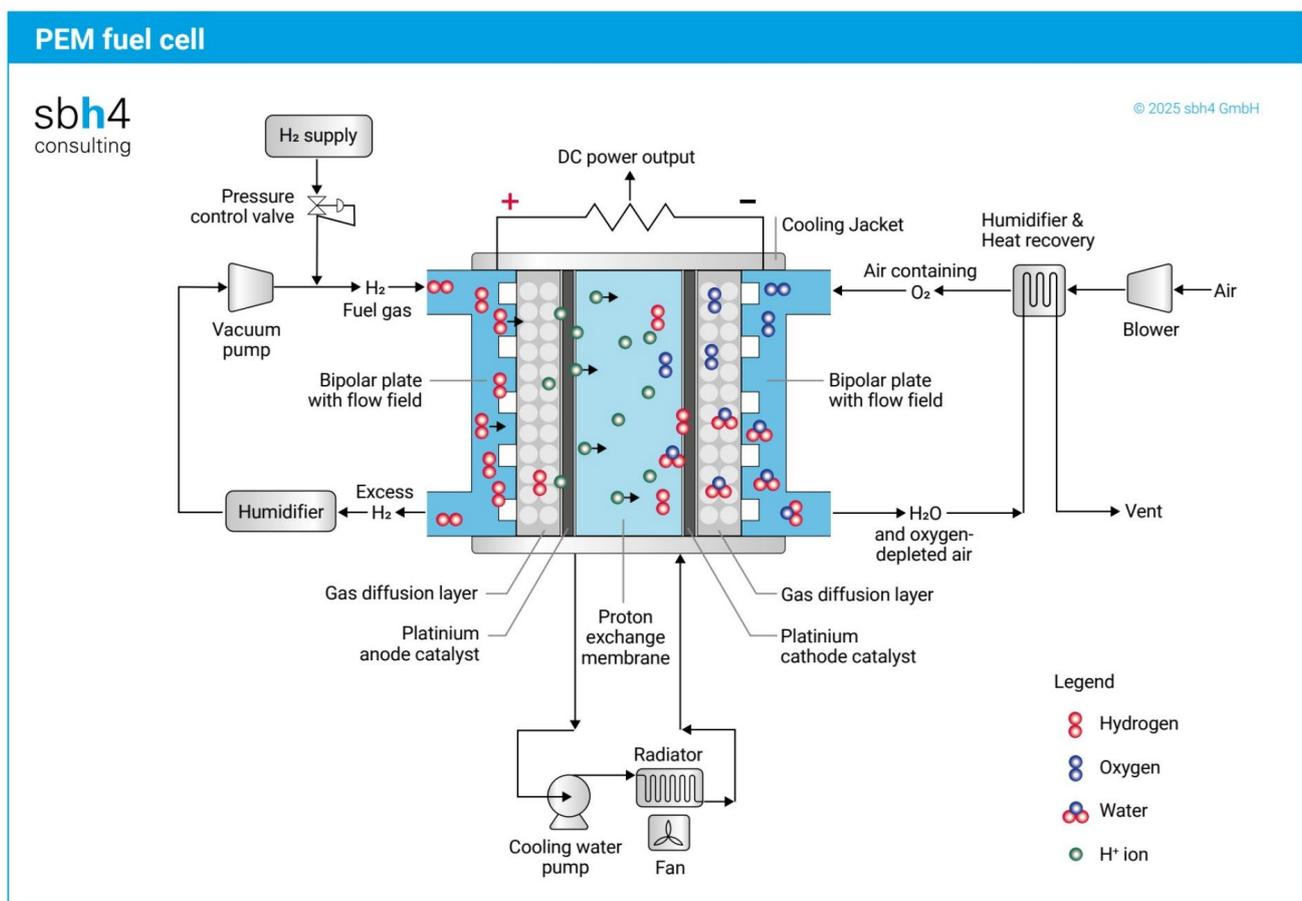
Figure 2. Joule-Thomson expansion of hydrogen and other gases

To decant hydrogen into FCEV's tank, hydrogen is stored at the refuelling station (HRS) at up to 1,000 bar. A release of hydrogen from this pressure can heat the gas instantaneously to above its auto-ignition temperature due to combination of adiabatic expansion, friction and the Joule-Thomson effect. This heating can result in a flame or explosion. Joule-Thomson expansion of natural gas and air are used to liquefy these gases. As shown in Figure 2, when hydrogen is released from a very high pressure to the atmosphere it heats up, rather than cooling down. Therefore, there is no cooling effect to counteract the other heating mechanisms.

**d) Fuel cells for onsite heat and power**

Fuel cells, as shown in Figure 3, are commonly used in Japan and South Korea to convert natural gas to heat and power. They are typically used in blocks of residential flats, hotels, and offices. In the future, the same concept will be used with hydrogen as the fuel to replace natural gas and de-fossilise this energy system.

Modern data-centres which enable the internet, cloud computing and AI are also keen to decarbonise their operational footprint. Some are looking to use large hydrogen-fed fuel cells for this purpose.



**Figure 3.** Fuel cell process layout

Hydrogen can be delivered to these end-user locations by truck. These trucks store up to 1 tonne of high-pressure hydrogen. It is common for the hydrogen trailer to be de-coupled from the tractor unit and be connected to the end user site by a high-pressure hose. When the trailer is empty, a full trailer of hydrogen is delivered and the truck tows away the empty one for refilling.

The consequences of towing a hydrogen trailer away whilst it is still connected to the data centre would be catastrophic. To mitigate this, there is an electronic cable attached to the gas hose. If the trailer is erroneously towed away whilst it is still connected to the data centre, the electrical cable is broken. The loss of this electrical connection drives smart control systems to close valves on the truck and the end-user site to minimise the amount of flammable hydrogen that can leak.

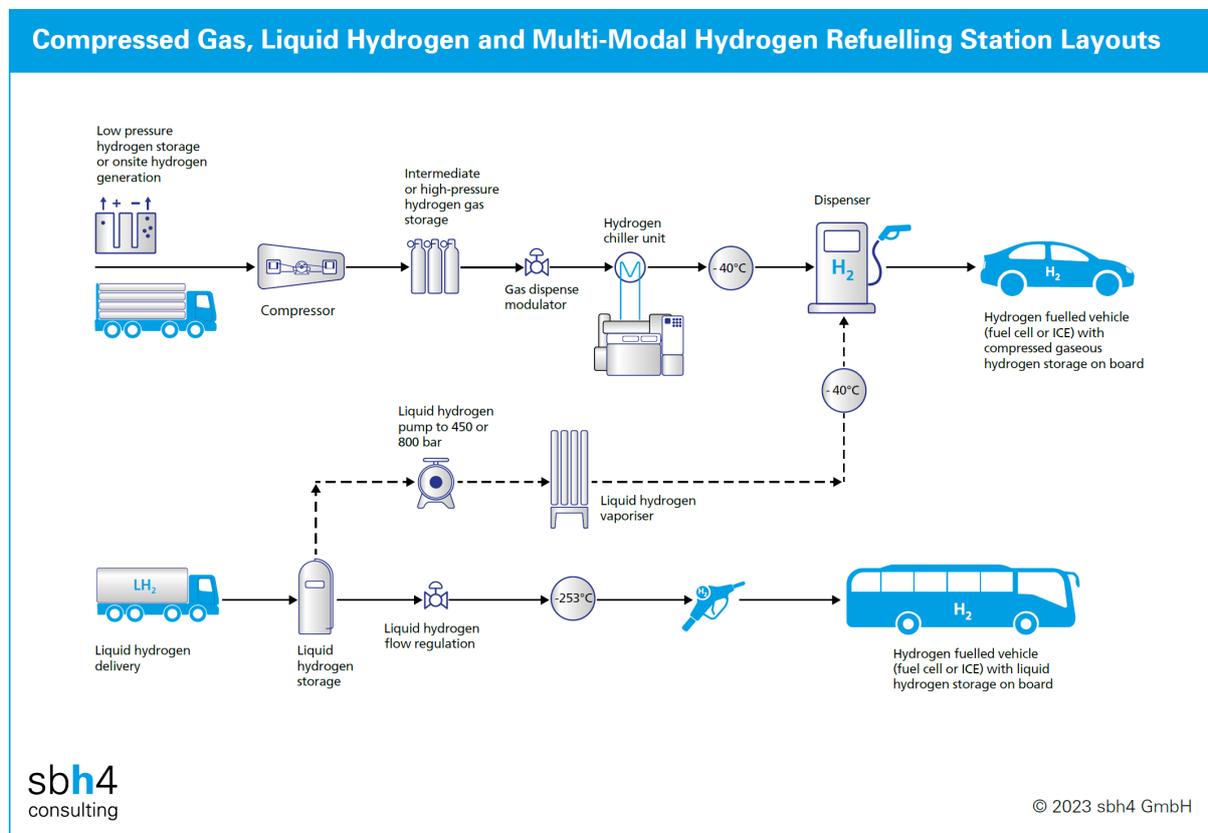
## Safety training

Training is essential for mechanical, electrical, instrumentation, process and civil engineers involved in designing hydrogen systems. They must understand the unique properties of hydrogen such as its very high flame speed, low ignition energy, and low density to design appropriate installations and equipment.

Blast walls must be built with appropriate civil engineering standards to contain the energy of an explosion. Electrical equipment must be spark free to avoid introducing an ignition source. Processes and operations must be designed to minimise the amount of hydrogen stored at a location.

Experts from the oil and gas sector, chemicals plants and power generation will have a good basic foundation in safe engineering practices. However, they must be trained in the specific hazards and mitigation techniques related to hydrogen.

Multiple standards exist in this area, such as the ISO 22734-1:2025 which covers ‘Hydrogen generators using water electrolysis’.<sup>6</sup> This standard makes recommendations about parameters to measure and the corresponding smart controls and safety measures that can be invoked.



**Figure 4.** Gaseous and liquid hydrogen refuelling station architecture

By focusing on training for the experts who design hydrogen systems and smart controls around them, it will be possible to build emerging hydrogen infrastructure such as hydrogen refuelling stations, as shown in Figure 4, and end-user equipment such as fuel cell electric vehicles in a robust way. This will eliminate the need for complex training for end users, who will often be members of the public without any knowledge of the hazards associated with hydrogen.

## Public acceptance

The hazards of electricity in the home are severe, yet it is common for children to use electrical devices such as computers and radios. When drivers fill their motorcycle at the gas station, there is always a risk that flammable vapours will ignite. Despite this known hazard, some drivers use their mobile phones whilst refilling with gasoline.

In these established cases, people have been de-sensitised to the risk through frequent exposure. In the past, nothing happened... so the assumption is that everything will be OK today.

Hydrogen is a new energy vector for the public. Fear of the unknown is a key psychological factor to address. Honesty, empathy and smart controls to reduce the likelihood of incidents are the keys to ensuring public acceptance.

In the early days of the hydrogen economy, communication is the main tool to garner public acceptance. As more prolonged safe exposure to takes place, the perception of hydrogen will align with gasoline, natural gas and electricity – energy vectors that we handle with very little conder on a daily basis.

### Next-gen safety trends for end-use safety

Early hydrogen leak detection on board the buses, trucks, trains and cars will mitigate the hazard of using hydrogen as a fuel. To achieve this, a specification for an on-board hydrogen sensor has been proposed which specifies that the sensor react to the leak within seconds.<sup>7</sup> Sensors to achieve this ultra-fast response are being developed.<sup>8</sup> A smart control system incorporating such a device can respond to a leak and automatically close valves on the hydrogen storage tanks to minimise the amount of gas that has leaked.

Many leak detection systems rely on chemical reactions in sensors to identify a leak. However, many different gases can trigger a response. For example, a catalytic bead sensor will detect many flammable gases including methane, carbon monoxide and hydrogen. In some use-cases, such as an industrial steam methane reformer, or a domestic boiler running on a blend of natural gas and hydrogen, these three gases can present at the same location.

A limitation of the commonly used, and cost-effective catalytic bead sensor is that it requires a reaction between the fuel gas (hydrogen) and oxygen (from air). To detect a hydrogen leak in an inert background gas such as nitrogen, sonic leak detection or a different type of sensor technology must be used.

Sonic hydrogen leak detection listens for the characteristic signature of a gas as it rapidly flows from high to low pressure.<sup>9</sup> These devices are increasingly being integrated into smart control systems alongside chemical gas detectors and flame detectors.

Speciation of the hydrogen leak, separate to the other flammable gases is complex. A new generation of MEMS-based sensors is being developed precisely of this purpose to enable a higher degree of granularity in smart control systems.<sup>10</sup>

### Conclusions & Future Outlook

Hydrogen has been around for decades, and will be here for centuries in chemical and industrial applications. Questions remain regarding the range of emerging use cases in which hydrogen can cost-effectively be deployed.

Safety equipment, procedures and smart controls exist. When these are properly implemented by people with appropriate training, each economically viable hydrogen application can be implemented without concern.

Thankfully, economics can drive the selection of the most appropriate end-user applications without the complication of needing to ask additional questions about the readiness of safety systems.

However there remains the challenge of aligning public perception with the scientific basis for declaring hydrogen systems as 'safe'.

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