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Hydrogen Tech World

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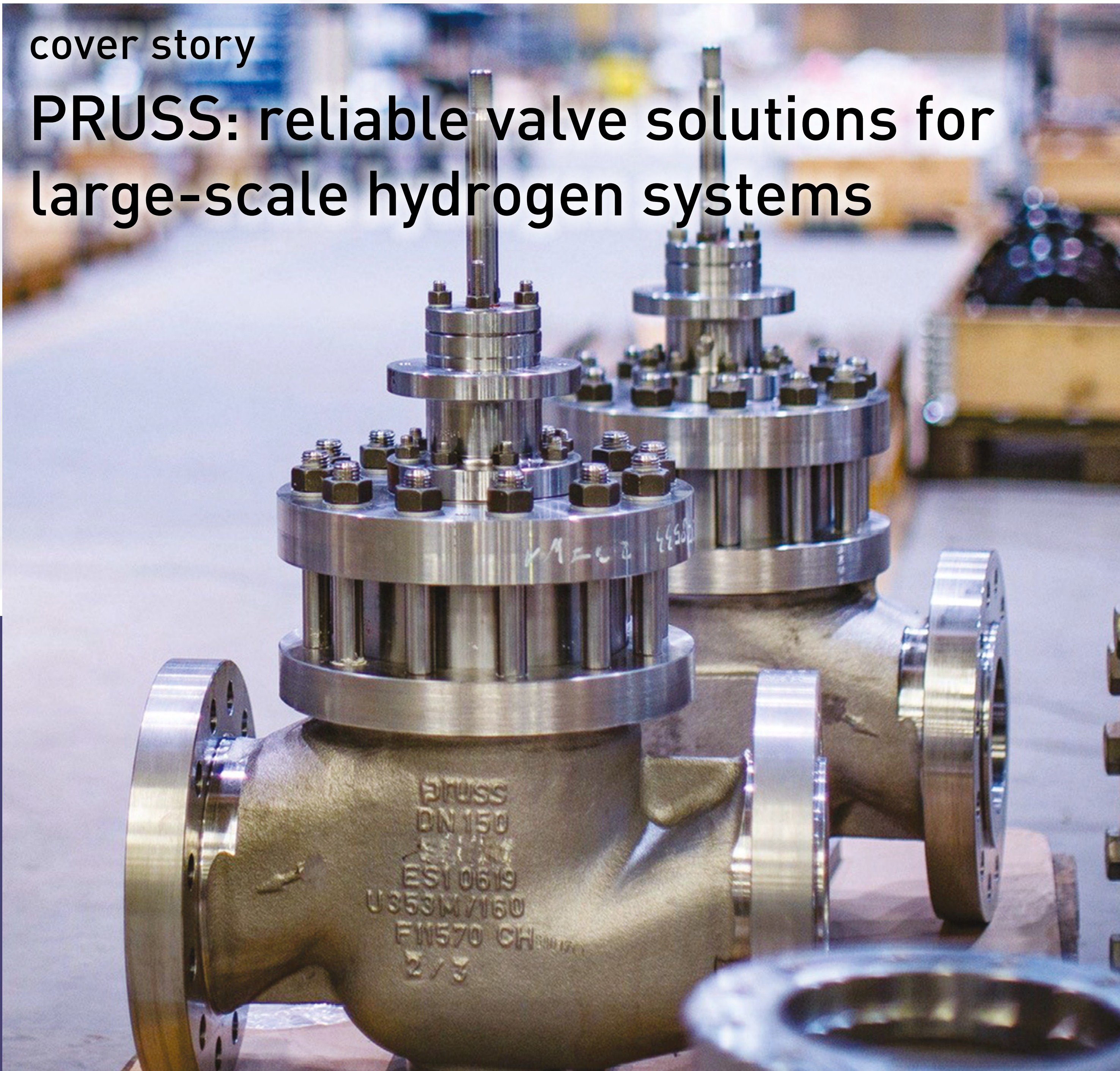
cover story

PRUSS: reliable valve solutions for large-scale hydrogen systems



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Contents

Powering sustainability together

Spring has arrived, and along with it, one of the busiest periods in the trade fair calendar. If you are reading these lines holding in your hands a printed version of this magazine, then you have made it to the inaugural Hydrogen Tech World Expo and Conference, in which case I hope to meet you in person. Nothing beats face-to-face contact!

Green hydrogen is the most promising route to decarbonising (primary) steel production, making the steel industry one of the major future markets for green hydrogen. To tap into these synergies, the Hydrogen Tech World Expo & Conference has been paired with the Green Steel World Expo & Conference, bringing key stakeholders from both sectors together to network, do business, and exchange knowledge and ideas. Encapsulating this mission is our new slogan: *Powering sustainability together!*

As always, it is with great pleasure that I present to you a new issue of the Hydrogen Tech World magazine. Some of the contributors to it will also be speaking at our event in Essen. Among them is Carlos Bernuy-Lopez, who works as a senior consultant in power-to-X and hydrogen technologies at Ramboll. Many of you may know Carlos from LinkedIn and Twitter, where he regularly posts about the role of hydrogen in the renewable energy mix. In his article, he provides a useful comparison of the four main water electrolysis technologies – alkaline, proton exchange membrane, solid oxide, and anion exchange membrane – as well as an analysis of their impact on the levelized cost of hydrogen (LCOH).

The cover story features PRUSS, a globally trusted supplier of control valves and actuators for various industrial sectors. Recognising the role of hydrogen in the future energy landscape and leveraging decades of expertise in flow-control solutions for hydrogen service, PRUSS now provides an extensive range of valve products for large-scale systems used in water electrolysis, hydrogen transport, storage, and industrial applications. To learn about the company's latest projects and developments, we talked to Wilfried Drehmel, CEO of PRUSS.

Other topics receiving special attention in this issue include hydrogen transport technologies in general and the liquid organic hydrogen carrier (LOHC) technology based on benzyl toluene in particular; the design, testing and certification of hydrogen cylinders; compatibility of metals with hydrogen gas; cryogenic valves for liquid hydrogen service; and technologies for hydrogen leak detection in industrial settings.

Looking ahead, mark your agenda for 14 & 15 May 2024, when the second edition of the Hydrogen Tech World Expo & Conference will be held. In my capacity as editor of this magazine and HTW conference manager, I am always on the lookout for quality content and speakers, so do feel encouraged to contact me at m.matosec@kci-world.com if interested in sharing your knowledge and experience with our rapidly growing Hydrogen Tech World community.

Wishing you much reading pleasure,

Matjaž Matošec
Editor-in-Chief

Industry Update

HAV Hydrogen obtains DNV AiP for containerised H2 system for ships

HAV Hydrogen has received Approval in Principle (AiP) from DNV for its deck-based containerized hydrogen energy system for ships, which has been developed to fast-track the commercial use of hydrogen as ship fuel.

The Zero Emission Pod system is a turnkey, standalone power pod where all support and safety systems as well as electrical power management are included. By using 200 kW hydrogen fuel cells, the system is flexible and can provide 1,000 kW within the footprint of a standard 20 container. By combining multiple containers, using larger modules or dedicated space below deck, multi-megawatt energy systems will also be available.

Installed effect can be used for the main propulsion systems, or for additional power supply on board the vessel to comply with green operation standards. Output effect will be dimensioned to provide optimal zero emission power in desired operating situations, sailing patterns and vessel type.

Quayside, the hydrogen system can ensure sufficient green power supply to the vessel, which does not need to rely on onshore charging infrastructure to achieve zero emission status.

The system is designed for operation in air temperatures between –20 to +35°C and seawater temperature from 0°C to +32°C.

HAV Hydrogen will be ready to start manufacturing of the Zero Emission Pod hydrogen containers during the second half of 2023, aiming for the first deliveries in 2024.

Ebara develops world's first liquid hydrogen booster pump

Ebara Corporation has developed what it claims to be the world's first liquid hydrogen booster pump for use in hydrogen-fired power generation. The company plans to launch its newly developed product to the market later this year.

In thermal power generation, a liquid hydrogen booster pump is required to supply hydrogen from the storage tank to the hydrogen gas turbine. Ebara began with product development in 2019, as part of a project funded by the New Energy and Industrial Technology Development Organization (NEDO). Using this liquid hydrogen prototype pump, the company, in October 2022, conducted a test with liquid hydrogen at -253°C at the JAXA Noshiro Experimental Station. Favorable results led to designing a large flow rate booster pump.

Electriq and Zenith to build solid hydrogen carrier production plant

Electriq and Zenith Energy Terminals have announced a partnership to build the world's first manufacturing plant of Electriq Powder – a solid hydrogen carrier, in the Port of Amsterdam, the Netherlands.

Electriq Powder acts like daily used detergent powder, simplifying storage, transport, and use of hydrogen in last mile, off-grid and backup applications. According to Electriq, it features superior safety and energy density, compared to compressed and liquefied hydrogen. The release of hydrogen from the powder and conversion into electricity is done through a proprietary, compact release unit.

The agreement includes the production of green hydrogen using renewable energy generated by Zenith's on-site wind turbines.

"This plant is the first of its kind in the world and will serve our customers in the Benelux market", said Baruch Halpert, Executive Chairman and CEO of Electriq. "The Netherlands is an early adopter of hydrogen as the fuel of the 21st century, and we see this Electriq Powder plant as a key enabler to leverage this in innovative, safe and industrial manner."

Electriq is currently working on further expanding its powder manufacturing capacity, to drive its planned expansion into worldwide markets, by creating similar partnerships in other geographical locations.

Emerson BM6X series slam-shut valve certified for hydrogen service

Bureau Veritas Italia has approved the Emerson BM6X series slam-shut valve for use in applications with up to 100% hydrogen and pressures up to 100 bar. The certification confirms the verification of material suitability, based on seal tests performed at the Emerson production plant in Bologna, Italy.

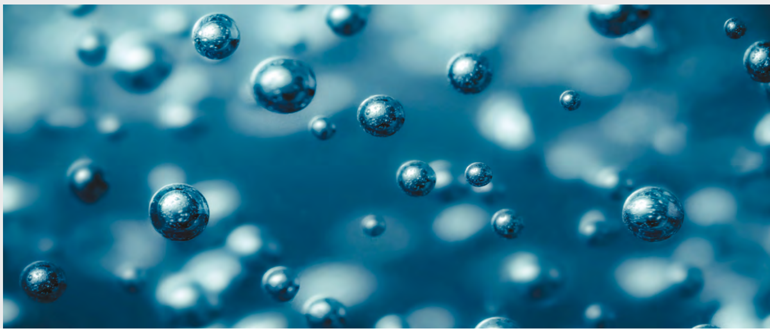
The Emerson BM6X series slam-shut valve has multiple applications throughout gas transmission networks, regulating stations, and end use infrastructure. For example, natural gas transmission and distribution companies can blend hydrogen into their distribution systems, reducing emissions when the blended mixture of hydrogen and natural gas is burned in homes for cooking, heating and other uses. Industrial end users can reduce emissions by using a mix of hydrogen and natural gas as fuel for turbines used for power generation.

Agfa to expand production capacity for its Zirfon membranes

Agfa has announced that its Board of Directors has validated the investment for a new industrial unit for the company's Zirfon membranes for green hydrogen production, next to further investments in growing the current facility.

The unit will be installed in existing buildings at the company's site in Mortsel, Belgium. When completed, the unit will be able to produce up to an equivalent of 20 GW per year of electrolyzer capacity for the production of green hydrogen. The design of the unit will also allow later extension.

Pascal Juéry, CEO of Agfa-Gevaert, said: "Customers all over the world appreciate our in-house developed Zirfon membranes for their unparalleled productivity and extreme reliability. With them, they are able to produce four times more hydrogen than with a conventional membrane. The leading Fraunhofer Institute also independently confirmed that our Zirfon membranes are the most cost-effective technology for hydrogen production via alkaline electrolysis. Our membranes have been selected for large scale hydrogen projects by the leading players in the industry. The new production unit will allow us to play a central role in the advent of the hydrogen economy and to be ready for the expected further increase in customer demand."



Ceres to validate its SOEC technology with Bosch and Linde Engineering

Ceres Power Holdings has signed contracts with Linde Engineering and Bosch to start a collaboration to validate the performance, cost, and operational functionality of its SOEC technology. The companies plan to prepare a two-year demonstration of a 1 MW SOEC system, starting in 2024 and to be located at a Bosch site in Stuttgart, Germany. Its aim is to showcase that the technology provides a highly efficient pathway to low-cost green hydrogen, which has a significant role to play in harder-to-decarbonise industrial sectors.

Ceres has committed £100 million for the development of its SOEC technology. Its first 100 kW electrolyser module is currently on test and initial results are providing confidence that this technology can deliver green hydrogen at <40 kWh/kg, around 25% more efficiently than incumbent lower-temperature technologies.

Nel takes FID to expand its production capacity in Connecticut

Nel has taken the final investment decision to expand the production capacity at its PEM electrolyser manufacturing facility in Wallingford, Connecticut. The expansion will bring annual production capacity towards 500 MW in 2025. The investment cost is estimated at approximately NOK 260 million.

"This is an important milestone for Nel," said Håkon Volldal, CEO of Nel. "With this expansion, we will increase PEM production capacity substantially and simultaneously reduce stack cost and improve stack efficiency.

"Last year we opened the world's first fully automated alkaline electrolyser plant in Herøya, Norway. Now we will industrialize the PEM platform, and the expansion in Wallingford is an important first step."

The development of the ~500 MW PEM production line will be a substantial contributor to further expansion plans in the US, where developing a quality production concept is crucial for preparing Nel's planned Gigafactory.

The planned Gigafactory will have a potential of up to ~4 GW production capacity, distributed between both PEM and alkaline. Volldal said that the company is considering three attractive options in three different states and that the final decision is to be made shortly.

LONGi launches new generation of alkaline electrolyzers

LONGi Hydrogen, a wholly owned subsidiary of China's solar giant LONGi Green Energy Technology, has launched its new generation of alkaline electrolyzers.

Electricity price and energy consumption per unit of hydrogen production are the two variables that contribute to the highest sensitivity of the levelized cost of hydrogen (LCOH). The company claims that full-load DC power consumption of alkaline and PEM electrolysers currently is in the range of 4.5–4.6 kwh/Nm³. The full-load DC power consumption of ALK Hi1 can be as low as 4.3 kwh/Nm³. It is even lower for ALK Hi1 Plus, down to 4.1 kwh/Nm³, or even as low as 4.0 kwh/Nm³ when the current density is 2,500 A/m².

This means a comparative reduction of DC power consumption by more than 10%. According to LONGi, for every 0.1 kwh/Nm³ reduction in DC power consumption, depending on the number of system utilization hours, the LCOH can be reduced by 1.8%–2.2%, which translates to a reduction of the initial investment of hydrogen production equipment by 10% to 25%.

New JV to accelerate electrolyser capacity development in Nordics

Everfuel and Hy24, which manages the world's largest clean hydrogen infrastructure fund, have created a joint venture (JV) to finance the accelerated development of electrolyser capacity across the Nordics. Everfuel will own 51% of the JV and the Hy24-managed Clean H2 Infra Fund will own 49%.

The JV's first investment is to acquire the HySynergy Phase 1, 20 MW green hydrogen production plant in Fredericia, Denmark. The JV will further benefit from Everfuel's pipeline of hydrogen projects as they are matured to final investment decision and transferred to the JV, subject to predefined criteria.

The HySynergy Phase 1 electrolyser is expected to commence commercial operations in the second quarter of 2023 and will contribute to significant decarbonization of industrial processes at the adjacent Crossbridge Energy Refinery. HySynergy will also offer a competitive supply of green hydrogen as zero-emission fuel for clean mobility. In December 2022, HySynergy Phase 2, 300 MW, green hydrogen plant was granted IPCEI funding of EUR 33.1 million to support the construction of the first of three 100 MW electrolysers.

EvolOH to build 3.75 GW AEM electrolyzer plant in Massachusetts

U.S. cleantech company EvolOH has announced that it will build a manufacturing plant in Massachusetts for the fabrication and assembly of its anion exchange membrane (AEM) electrolyzer stacks.

The proprietary compact cell-stacking and high power-density design used in EvolOH's NautilusTM series stacks was created for high-speed manufacturing using low-cost materials that only require domestic supply chains and no precious metals.

The company claims that its electrolyzers provide the lowest capital and operating costs for green hydrogen production when operated using pure water. With power ratings up to 5 MW (2 tonnes per day) for a single stack, and 50 MW (20 tonnes per day) for a single containerized module, EvolOH's stacks are designed for large-scale power-to-hydrogen facilities.

The Massachusetts plant will be called EvolOH's Manufacturing Center of Excellence and will combine development facilities and staff with a single line of EvolOH's high-speed manufacturing process. When fully operational, this facility will have a capacity for up to 3.75 GW per year of electrolyzer stacks, making it the largest in the world. Facility work will begin later this year, with manufacturing to commence in 2025. EvolOH's second manufacturing plant, planned to break ground in 2026, will have the capacity to make up to 15 GW per year of electrolyzer stacks.

DNV launches second phase of offshore hydrogen pipelines JIP

DNV has launched Phase 2 of H2Pipe, a joint industry project (JIP) aiming to develop a new code for the design, re-qualification, construction and operation of offshore pipelines to transport hydrogen – either pure or blended with natural gas.

DNV started the first phase of H2Pipe in 2021: an initial test program looking into potential degradation of steel pipe mechanical properties was carried out to fill gaps in existing knowledge and to explore various test parameters as a preparation and narrow down the number of variables for the main test program planned for Phase 2. The first revision of the guideline was delivered to participants the same year. The guideline is currently at a high level, and more work is needed to develop more specific acceptance criteria.

Phase 2 of H2Pipe will last two years. It will consist of a comprehensive experimental test program to enhance the understanding of the governing hydrogen embrittlement mechanisms and how hydrogen affects the integrity of the line pipe material. In addition to the experimental test campaign, Phase 2 will also include tasks such as a feasibility level design of offshore hydrogen pipelines and a risk assessment study to look at safety aspects of offshore hydrogen pipelines. The primary outcome of Phase 2 of the JIP is expected to be a detailed guideline offering specific guidance for use in design and re-purposing of offshore pipelines for hydrogen transport.

Weichai launches high-power metal-supported SOFC with 92.55% CHP

Weichai has announced the global commercialization of its high-power metal-supported solid oxide fuel cell (SOFC), which has achieved a record-breaking combined heat and power (CHP) efficiency of 92.55% for high-power SOFC systems.

According to the company, the latest generation of metal-supported SOFC technology has outstanding advantages such as low operating temperature and strong resistance to thermal shocks compared to traditional electrolyte-supported and anode-supported technologies. Its product, which has been demonstrated in the Weichai Fuel Cell Industry Park and the Weifang Energy Group, accumulating more than 30,000 hours of operation, has overcome the technical difficulties of operating temperatures from 800°C to 600°C. The system's number of start-stop cycles is more than four times that of international competitors, and its start-up speed is more than three times that of international competitors, the company claims.

Weichai's SOFC is suitable for multiple applications such as industrial parks, buildings, and data centers, and can provide green and low-carbon solutions for distributed energy and microgrids.

The product has passed 39 certification tests for the European CE certification by TÜV SÜD.

H2Pro, Sumitomo to partner on green hydrogen and ammonia production

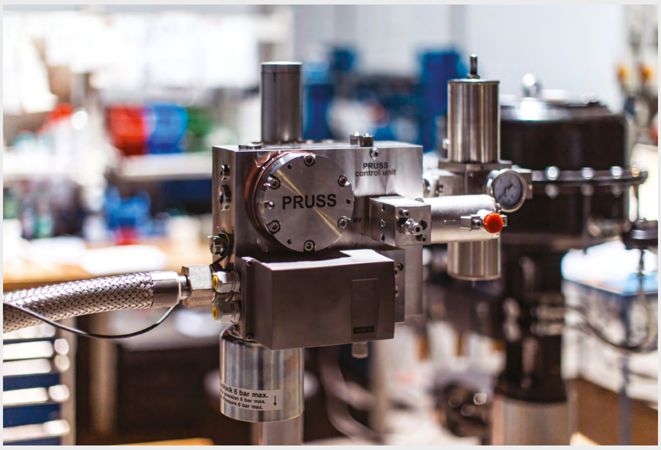
Israeli cleantech company H2Pro has announced its agreement with Sumitomo Corporation to partner on a variety of green hydrogen initiatives. Under the agreement, Sumitomo will integrate H2Pro's E-TAC electrolyzers at the hundreds of MW scale, primarily for use in green ammonia projects.

PRUSS: reliable valve solutions for large-scale hydrogen systems

Established in 1889, PRUSS is a globally trusted supplier of control valves and actuators for various industrial sectors. Recognising the role of hydrogen in the future energy landscape and leveraging decades of expertise in flow-control solutions for hydrogen service, PRUSS now provides an extensive range of valve products for large-scale systems used in water electrolysis, hydrogen transport, storage, and industrial applications. To learn about the company's latest projects and developments, we talked to Wilfried Drehmel, CEO of PRUSS.

By Matjaž Matošec

Founded by innovator and entrepreneur Waldemar Pruss, the Hanover-based company has flourished over time, evolving from a small family business into a household name among a long list of industrial giants. Although the company has established a solid reputation for quality and reliability, it remains committed to growth and innovation. Since our first conversation with Mr. Drehmel eight months ago, PRUSS has won six major contracts for the supply of valves for gas-fired power plants, made significant progress in developing a maintenance-free fuel gas metering valve for pure-hydrogen service, increased its



workforce by 15%, and put into operation a new machining centre.

Vast experience with hydrogen

PRUSS has a wealth of experience in the manufacture of hydrogen-service valves, with a track record spanning decades. "We began developing our expertise in hydrogen in the 1970s, so hydrogen is nothing new for us," says Mr. Drehmel.

The thermodynamic, chemical, and physical properties of hydrogen place unique demands on process equipment, requiring special material and design solutions to ensure safe operation. "While molecular hydrogen is relatively inert and therefore not corrosive, atomic hydrogen can cause cracking in certain metals, with highly stressed pressure-bearing components being particularly prone to hydrogen embrittlement, which is a risk that we take very seriously," explains Mr. Drehmel.

"Another challenge is the size of hydrogen. As one of the smallest elements, it can diffuse through many materials considered air-tight or impermeable to other gases, which calls for special sealing solutions," continues Mr. Drehmel. "To meet the demanding tightness requirements for hydrogen-service valves, we are able to use metallic seals for high-temperature applications, with our meticulous material selection process being supported by rigorous testing conducted in-

> *"We began developing our expertise in hydrogen in the 1970s, so hydrogen is nothing new for us."*

house and in accordance with a range of industry-recognised standards."

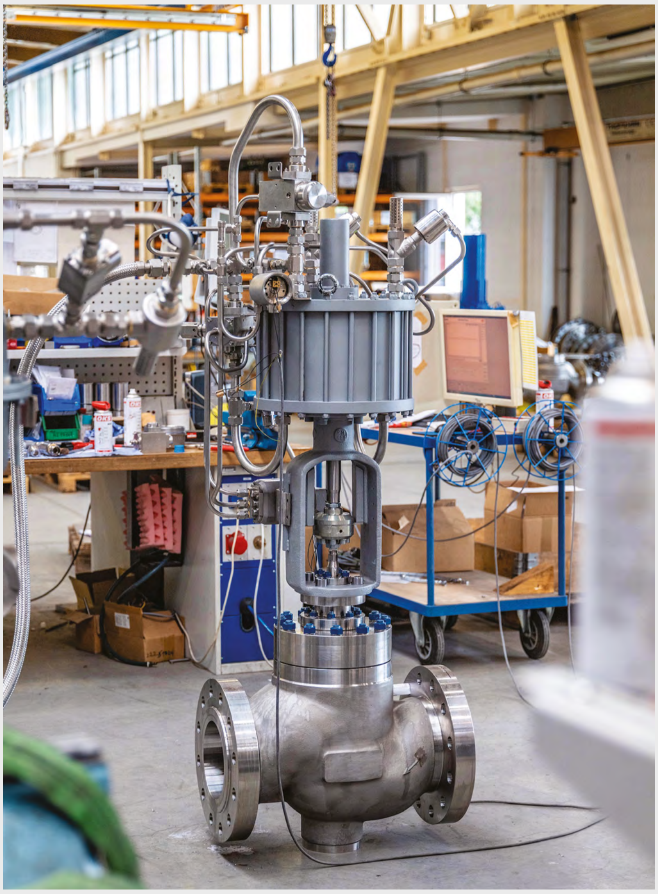
Comprehensive solutions

The power generation industry is a vital market for PRUSS, with significant potential for growth. "Wherever flow media such as oil, cooling water, steam, condensate, or gas must be controlled, shut off, secured or diverted, PRUSS can provide a solution – regardless of the application," says Mr. Drehmel. "We manufacture valves in all sizes and various materials, designed for temperatures of up to 720°C and operating pressures of up to 600 bar. To make the package complete, we also manufacture the corresponding pneumatic, hydraulic, and electro-hydraulic actuators."

Compared to other types of thermal power stations, gas-fired plants are characterised by relatively high efficiency, faster response time, lower capital costs, shorter construction times and lower carbon emissions. Another advantage is the fact that hydrogen could eventually replace natural gas as a fuel for combined-cycle gas turbines. While most existing gas-fired plants will require modest to moderate equipment modifications to run on a mixture of natural gas and hydrogen, a growing number of new plants are designed to be hydrogen-ready so that they can switch to the cleaner fuel as soon as the hydrogen supply, cost and pipeline infrastructure allow it.

First projects already underway

PRUSS has recently received multiple orders for valves and actuators from pioneering projects in Europe and Asia-Pacific that aim to generate power using hydrogen, either in its pure form or mixed with natural gas.



"Currently, we have orders for six projects, two for pure (100%) hydrogen and the remaining four for up to a 70% hydrogen blend," explains Mr. Drehmel. "The two 100% hydrogen projects are for testing purposes at existing plants, while the other four are for large-scale new installations, the largest of which has an output of more than 590 MW. These projects are currently being developed for customers who plan to initially operate their plants using natural gas but want the option to blend it with hydrogen in the future.

"We are currently working on obtaining type approvals for our new valve version, which will be used in these projects. The project scope includes hydraulically actuated fuel gas control valves for all burner stages and the relevant emergency shut-off valves, which are pneumatically actuated. To implement these projects, we need to run an endurance test and conduct detailed characteristic testing, which is currently being done in-house."

Cutting-edge flow control technology

As one of the key suppliers to large gas turbine companies, it is no surprise that PRUSS is at the forefront of innovation of flow control equipment for gas turbine applications.

"In the past few years, we have developed special fuel gas control valves with emergency shut-off function for hydrogen service in gas turbines," says Mr. Drehmel. "These products meet ultra-high, Class VI leakage requirements – even after an endurance test of 20,000 cycles under operating conditions. Furthermore, our valves are available with rangeabilities of up to 350:1, allowing exceptionally precise flow control. What this means in practice is that they are also able to control the ignition phase, which in turn means greater reliability and efficiency as well as lower investment and installation costs."

Another recent product development is a fuel gas metering valve for pure hydrogen service, which has been designed to provide maintenance-free operation for at least five years. This valve is currently undergoing endurance testing.

Valves for large-scale electrolysers

PRUSS offers a diverse product portfolio to meet flow control needs throughout the hydrogen value chain, from green hydrogen production plants to pipelines and underground storage facilities. Its valve solutions for hydrogen service include process valves for water electrolysis, gas-liquid separation, pressure control and safety shut-off valves for various applications, and blow-off and anti-surge valves for compressor protection. Both static seals and moveable sealing parts are designed in such a way that all these valves are in principle maintenance free, decreasing operational costs and preventing downtime.

As large-scale electrolysers are becoming a reality, some of the processes associated with green hydrogen production may have to

PRUSS is represented in more than 60 countries across the globe

be optimised. One such process is the gas-liquid separation, for which PRUSS offers a fitting valve solution. Mr. Drehmel provides more detail: "The hydrogen gas coming out of the PEM electrolyser stack still contains a certain amount of water, which must be let out of the system. Currently, this is mainly done via cyclonic separation, but this process leads to significant pressure losses, making it uneconomic for large-scale electrolysers. A more efficient alternative is to collect this water in a header that works like a condensate trap and then drain it. This requires an abrasion-resistant blowdown valve, which is a product that we have supplied in thousands for use in steam power plants."

Sustaining quality and growth

To meet the ever-growing demand for its products, PRUSS has recently added 15 new employees to its workforce. At the end of last year, the company also put into operation a state-of-the-art machining centre, which has been seamlessly integrated into its existing CNC machine park. This centre enables the company to produce a great variety of complex components fully automatically, resulting in a 30% increase in efficiency and 300% increase in capacity.

The company's global network of sales and service partners is also expanding and now represents PRUSS in more than 60 countries. "We provide customer support wherever needed," says Mr. Drehmel. "This can be done on-site by accredited service teams of our representatives, by our in-house specialists or remotely. Whether for commissioning, regular shutdown service, emergency operations or spare parts recommendations, our highly qualified service team is available at any time."

Finally, PRUSS regularly exhibits at various industry trade shows worldwide to showcase its products and forge new business partnerships. The next opportunity to meet Mr. Drehmel and his team will be on 4 and 5 April at the Hydrogen Tech World event in Essen, Germany. Visit the PRUSS stand F16 to learn more about their products and services!

Hydrogen transport technologies: the key to a global hydrogen economy

A sustainable hydrogen economy can only succeed through safe and affordable storage, transport, and distribution of hydrogen. For this purpose, several technologies are available such as gaseous hydrogen (GH_2), liquid hydrogen (LH_2), ammonia, liquid organic hydrogen carriers (LOHCs), and pipelines – each with their respective advantages, disadvantages, and areas of application. Compared to other storage and transport solutions, the LOHC technology based on benzyl toluene offers promising synergies for industrial off-takers and has huge benefits in terms of safety and handling.

By Dr. Peter Gless, Senior Business Development Manager, Hydrogenious LOHC Technologies

Today, and even more so in the future, many countries will depend on hydrogen imports to meet their huge demand in the energy, mobility, and industrial sectors. Green hydrogen, produced from renewable energy sources such as solar and wind, is particularly essential to drive the decarbonization of these sectors.

Unfortunately, not all countries have the capacity to produce renewable energy and green hydrogen in the quantities required, making long-distance transport even more critical to establishing a global hydrogen economy. At the same time, the properties of molecular hydrogen make it a very difficult commodity to store and transport, as it is extremely volatile and even explosive. The question of which technology can 'tame' this particular energy source and allow for its safe and cost-efficient transport and storage is of utmost importance.

Non-pipeline methods for hydrogen transport, such as in the form of GH_2, LH_2, ammonia or bound to an LOHC are usually easier to scale, faster to implement and more flexible when faced with challenging transport conditions, while pipeline-based transport is expected to be more cost-efficient in the long term, but also has unique challenges to deal with.

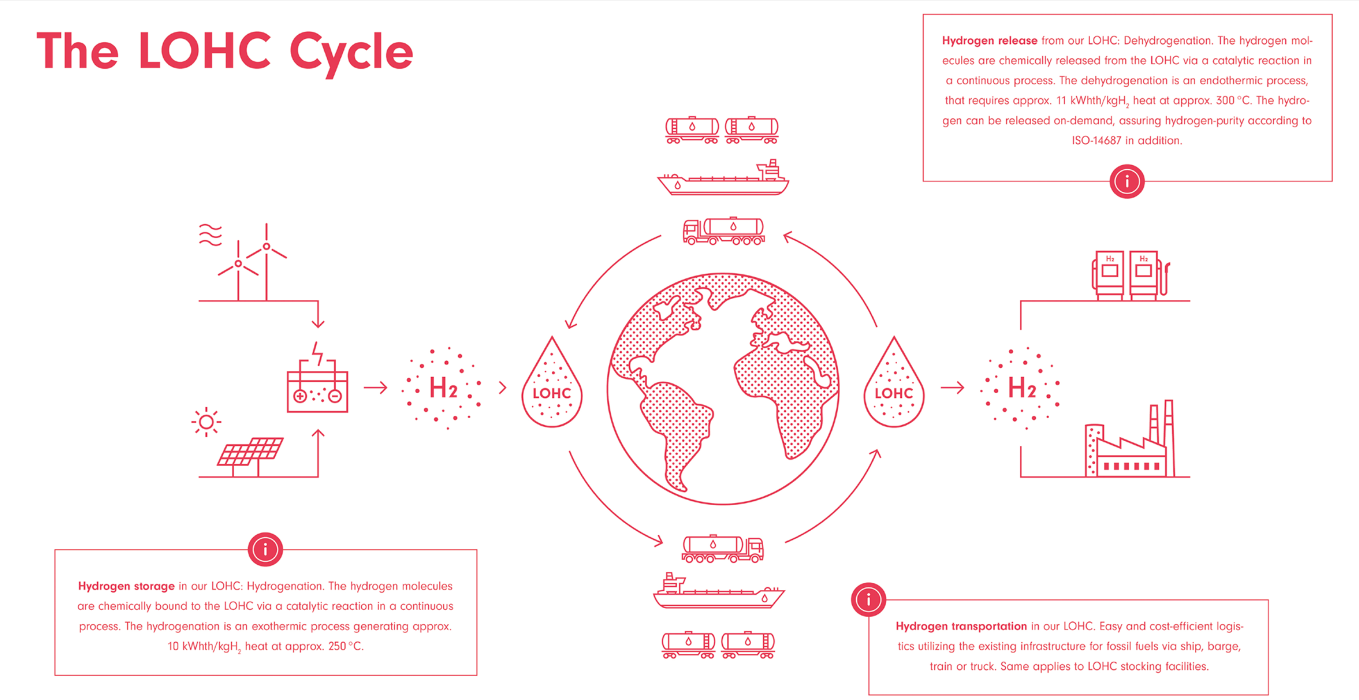
However, the LOHC technology based on benzyl toluene stands out among the other hydrogen transport technologies, not only in terms of safety, flexibility, and cost efficiency, but also when examining possible synergies with industrial off-takers.

Hydrogen transport with LOHC

LOHCs are organic carrier liquids that can chemically bind hydrogen (hydrogenation) and release it again when needed (dehydrogenation). Stored in the LOHC, the hydrogen can be transported much more easily and safely to its destination. After the hydrogen is released from the LOHC, the carrier material is not consumed but instead shipped back to the hydrogen production site and re-used for the next hydrogen transport.

There are several possible LOHCs, such as carbazole, toluene/methylcyclohexane (MCH), dibenzyl toluene or benzyl toluene. The latter has particularly positive properties as a hydrogen carrier, since it is a non-explosive, flame-retardant thermal oil with a lower hazard potential than diesel, is already well established in the industry as a heat conductor oil and is also very stable compared to other LOHCs.

LOHC based on benzyl toluene (LOHC-BT) does not require low temperatures or high pressure and can be



The LOHC cycle with benzyl toluene. Image © Hydrogenious LOHC Technologies

transported over long distances in the existing liquid fuel infrastructure. It also shows no boil-off (hydrogen losses), not even during long periods of time. Hydrogen purity according to ISO-14687 is ensured. By using the existing infrastructure, LOHC-BT is also particularly fast and cost-effective to implement, and the local workforce for handling of liquid fuels can be leveraged, which in turn helps securing jobs. The flexibility of the technology favours diversification of import routes – transport via tank ships, barges, railroad and tanker trucks is possible.

Especially when seaports and barge ports are involved as transshipment points for the onward transport of hydrogen to off-takers, the LOHC-BT is advantageous due to its relatively low hazard potential compared to, for example, the highly toxic ammonia, which is considered to be very problematic in the urban environment of ports close to cities such as Amsterdam, Rotterdam or Hamburg.

Benefits of LOHC for industrial applications

An advantageous characteristic of the LOHC-BT technology lies in the chemical process itself: while the hydrogenation (storage of hydrogen in the LOHC) is an exothermic process that produces excess heat energy, the dehydrogenation (release of hydrogen from the LOHC) is an endothermic process – it requires additional energy in the form of heat.

This opens up synergies on the hydrogen production side, where the excess heat from hydrogenation could for example be fed into local heat grids or used for seawater desalination. On the off-taker side, heavy industry with a lot of process heat could leverage this excess energy for the dehydrogenation of the hydrogen from the LOHC-BT.

Steel mills are among the industry off-takers that can particularly benefit from the LOHC-BT technology: they not only need green hydrogen as a form of carbon-neutral energy source but also molecular hydrogen with high purity for their production processes. LOHC-BT can easily be stored at the off-taker site for releasing hydrogen on demand, which is key for industrial use. Steel mills also have a lot of excess heat that could be integrated in the LOHC-BT dehydrogenation process, lowering the total cost of ownership.

Hydrogen transport technologies compared

When comparing different hydrogen transport technologies, it quickly becomes clear that there is no one perfect solution for all applications. Since each transport technology has specific advantages and disadvantages depending on the application, an agnostic approach in terms of technologies is essential. In addition to the above-mentioned LOHC technology, several solutions are currently in focus of the public discussion.

Compressed hydrogen (CH_2) stored in suitable pressure vessels (e.g., pressure cylinders) is already widely used today as a transport technology as well as for mobility. However, it is only cost-effective for very short distances, and the energy input for compression is relatively high, making it unsuitable for international import/export on an industrial scale.

Hydrogen liquefied at -253°C (LH_2) has a high storage density, is being researched intensively and is already being used in some areas (e.g., automotive and aerospace industries). However, the considerable energy input and high technical expenditure for liquefaction, storage and transport are a challenge, especially for large-scale transport over long distances. LH_2 requires complex infrastructure and costly thermal insulation. At the same time, boil-off, i.e., evaporation of hydrogen during transfer and storage, is difficult to avoid.

Ammonia (NH_3) is used in large quantities in the fertilizer industry. In the future, green hydrogen can be stored in the form of NH_3 and then transported on ocean-going ships approved for chemicals. After transport, the hydrogen molecule can be separated from NH_3 by means of cracking.

However, due to its high toxicity and corrosive properties, ammonia is a very hazardous substance that can only be transported and stored with considerable effort and cost. Long-distance transport of hydrogen in the form of NH_3 to end users is thus made much more difficult. Separating hydrogen from NH_3 also requires a lot of energy at high temperatures, and the cracking technology needed for separation does not yet exist on a large industrial scale. The released hydrogen would also have to be extensively processed to obtain corresponding degrees of purity.

Artist's impression of a 1.5 tpd hydrogen LOHC release plant, as planned to be built in Rotterdam, the Netherlands, in 2025/2026. Image © Hydrogenious LOHC Technologies

Pipeline-based transport of gaseous, compressed hydrogen makes it possible to transport a large amount of energy relatively safely. For this purpose, either new pipelines must be built, or existing natural gas pipelines must be upgraded. The construction of new pipelines is accompanied by very high investments and a tendency towards negative social acceptance. Converting existing natural gas pipelines must be examined for each individual case. The availability of the necessary compressors for large-scale hydrogen transport is still being researched, and the connection of new consumers is not always possible.

The construction of a European 'hydrogen backbone' with mainly converted natural gas pipelines for example can advance a Europe-wide connection of hydrogen sources and consumers at a very low cost. However, it can only cover part of the projected transport demand for Europe, as not all sources and consumers can be linked without building new pipelines.

Conclusion

Since the global transformation of energy systems as well as decarbonization of industry and mobility will require the export and import of cost-efficient, green hydrogen, a reliable and safe transport infrastructure for industrial volumes of hydrogen is a key factor for success. All the above-mentioned transport technologies will play their part in ramping up a global hydrogen economy and must be considered in the short and long term. LOHC-BT is one of these very promising solutions that offers a lot of benefits in terms of safety, handling, and flexibility. Its synergy with potential industrial off-takers that have a lot of excess heat energy, such as steel mills, underscores the importance of considering different hydrogen transport technologies on a case-by-case basis, in order to maximize the inherent advantages of each technology.

About Hydrogenous LOHC

Hydrogenious LOHC adds the missing link to high-performing hydrogen value chains globally. Based on its proven LOHC technology with benzyl toluene as carrier medium, Hydrogenious LOHC allows for flexible hydrogen supply to consumers in industry and mobility across the globe, utilizing conventional liquid-fuel infrastructure. Founded in 2013, its portfolio and that of its joint venture companies today includes stationary and mobile (on-board) LOHC-based applications. Hydrogenious LOHC Technologies, headquartered in Erlangen, Germany, offers – within an EPC partnership with Bilfinger – (de-)hydrogenation turnkey plants, operation & maintenance and LOHC logistics services. Hydrogenious LOHC Emirates, based in the United Arab Emirates and a joint venture with Emirates Specialized Contracting & Oilfield Services (ESCO), acts as the regional spearhead in the Middle East since the end of 2021. Hydrogenious LOHC Maritime, established in 2021 jointly with Østensjø Group and located in Norway, develops an emission-free onboard propulsion system with a promising LOHC/fuel cell solution for the global shipping industry. www.hydrogenious.net

Hydrogen cylinders: design, testing and certification

The cylinder plays a crucial role in the application of gaseous hydrogen. It is indispensable, regardless of whether it is used for stationary applications, mobile storage during transportation, or at the vehicle level. The search for a product that offers sufficient storage capacity and is constructed in a way that ensures safe handling of hydrogen is an ongoing process.

By Daan ten Have, Commercial Manager – Energy, Kiwa

The low energy density and molecular structure of hydrogen require it to be compressed to a significant pressure, which is one of the key challenges in designing a hydrogen cylinder. Meeting these difficult requirements with a product that has a limited number of components may not be easy, but it is crucial. So, what exactly are these requirements?

Strength

First of all, strength. The aim is to create a cylinder that is strong enough to withstand enormous pressure. Focussing on type IV cylinders, the laminate and its winding pattern rest as a sort of shell around the gas-tight inner part of the cylinder. This laminate is a combination of resin and fibre materials, and after processing, it should be able to withstand the forces and dynamics that a cylinder experiences throughout its lifespan.

Gas tightness

To ensure the safe containment of a gaseous energy carrier, a cylinder must be completely leak tight. However, due to the specific characteristics of hydrogen, as discussed in an article on permeation featured in the February issue of this magazine, achieving complete leak tightness can prove to be a challenge, too.

It may appear implausible, but there is always some extent of leakage present due to the permeation of the liner material. Typically, the liner is made of a blow-moulded material that is integrated into the cylinder's design, providing the necessary gas-tight properties of the product.

Elongation

The principle of elongation refers to the 'flex' of a cylinder, or the increase in internal volume when the cylinder is pressurised from atmospheric pressure to, for example, 700 bar. The most cost-efficient solution is a cylinder that is able to maintain strength and gas tightness with a minimal amount of fibre material. Of the few components that form a cylinder, the fibres are the most valuable part.

Load cycles

During the lifetime of a cylinder, it will be pressurised numerous times, causing stress on the material in a mechanical way and also being influenced by the dynamics of temperature increase and decrease. Fast filling, which is essential in vehicle applications such as cars, trucks, and buses, involves filling the cylinder with high flow and pressure while pre-cooling the gas to -40°C to prevent temperature increase inside the cylinder and ensure safe filling.

While the above summary touches on some of the key parameters and characteristics, there are of course many more details to elaborate on. But what happens when a cylinder manufacturer aims to introduce its product to the market? How can they ensure that the market and its users can trust in a safe and well-engineered design? The answer is testing.

Standards and homologation

Several standards are applicable throughout the market, each accepted or harmonized by a structure of testing, certification, and product control in various ways.

The applicable standard and test program depend on the geographical area where the cylinder will be marketed.

National standards are required for cylinders in emerging markets like China and India, and existing standards are mainly adopted as they have been in place for quite some time. The automotive market for hydrogen cylinders is by far the most established in terms of standardisation and adoption.

The North American market has its own method of certification and does not necessarily involve an independent party for certification and product control. However, the standard used (HGV 2) is well formed and extensive.

In the European market, the UN ECE R 134 is obligatory for vehicle-level certification, and a national authority is involved in certification and production control (conformity of production).

The structure for certification of cylinders in the transportation sector, with hydrogen as cargo, is organised differently. A notified body, accredited and qualified, is involved in the technical assessment of the design and production control.

In any case, extensive testing is required.

Testing

Returning to the requirements for a cylinder to be considered fit for use, let us have a brief look at the test methods used. Hydraulic testing is used to determine the strength of the cylinder. One of the first parameters required is the burst pressure of a cylinder to align the theoretical burst pressure (by means of software modelling) with the practical burst pressure.

Containarised test bays at one of Kiwa's testing facilities

The cylinder testing process is relatively simple yet critical for manufacturers to obtain initial data. The dynamic hydraulic load cycle test, which involves the ingress of a liquid into the cylinder, is essential and required by many standards. The test starts at a predetermined low pressure and gradually increases to an upper limit, which depends on the maximum allowable working pressure (MAWP), the standard used, and manufacturer requirements.

The number of load cycles can vary, but 30,000 cycles are common. To simulate the cylinder's lifetime, several external influences are added. Chemical exposure (automotive fluids), dropping from a height, impact tests, and even creating a flaw in the outer materials of the product are just some examples of what a cylinder endures during the test phase of certification. Additionally, low- and high-temperature testing is performed at -40°C and +85°C during the load cycle test.

Gas testing

Some standards require a hydrogen gas leak rate test to be conducted at working pressure. This test is static, meaning that the pressure remains constant and does not create any stresses on the material. The permeation is measured over a longer period of time, which can take up to 3–4 weeks.

During the simulation of the fuelling of a high-pressure hydrogen system the cylinder is pressurised with pre-cooled hydrogen for 500 pressure cycles at different temperatures, and intermediate permeation is measured. However, very few test laboratories can comply with these demanding parameters, especially as cylinders are increasing in size (>400 liters/700 WP).

When testing the cylinder for external influences, such as fire and high velocity impact, it is pushed to its limits.

For instance, when simulating a fire, the cylinder and its safety components must withstand a temperature of at least 800°C for 12 minutes without rupturing. The safety components must also ensure a controlled blowout.

In the high-velocity impact test (or shooting test), the cylinder is filled with gas and shot at to simulate the impact of a firearm. The cylinder must maintain its form after being hit, and any gas must blow out through the hole(s) caused by the penetration of the bullet.

Quality control by a third party

Certification or type approval can only be issued when the cylinder complies with the tests described in the appropriate standard and the quality of the product can be assessed and controlled.

A third party is involved in independently checking and controlling the production of the cylinders and quality management. The manufacturer is audited at pre-determined intervals to verify the quality management system. Additionally, the quality of the product is assured through batch testing of the produced cylinders using load cycle tests and burst testing.

New mobility and storage solutions

After considering all of the above, we can conclude that the hydrogen storage market is well defined in terms of safety, quality, production, and quality assurance. However, there is a constant learning curve throughout the market as new technologies, improvements in materials, and new applications emerge.

These new developments are continuously monitored and implemented in updated standards formed by all parts of the market, including manufacturers, legislators, users, and test facilities. All these stakeholders are involved in implementing these impulses in standardization.

Compatibility of metals with hydrogen gas

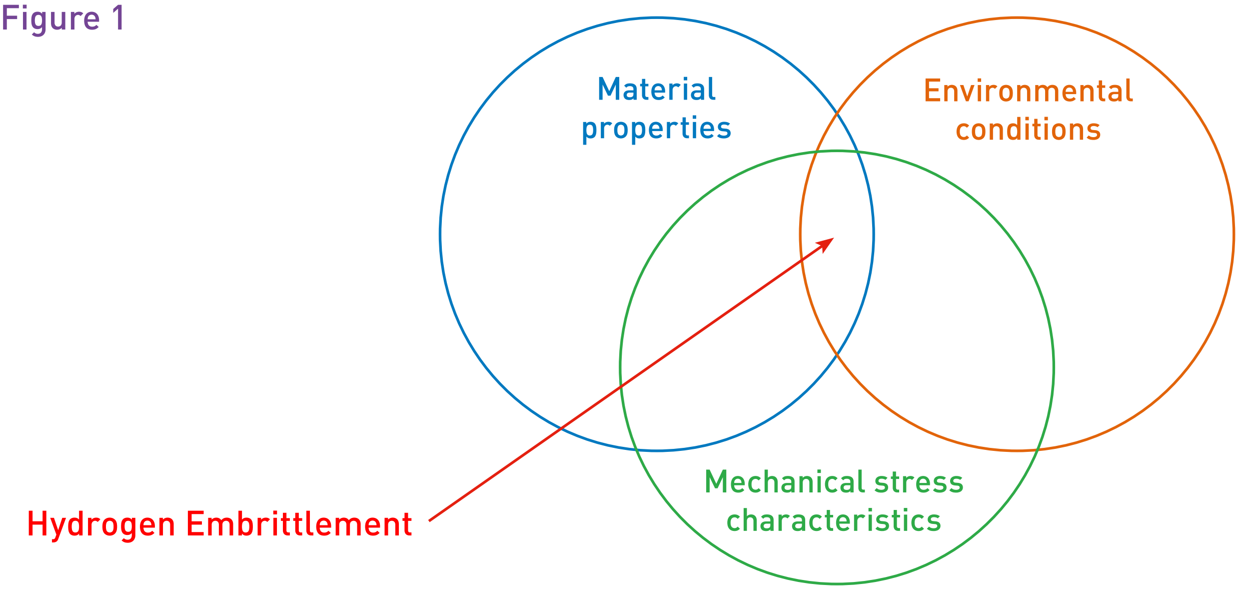
As hydrogen becomes more prominent in the portfolio of technologies for reducing carbon emissions, more attention has been directed towards its safe transport, storage, and end use. Most hazard scenarios involve the unintended release of hydrogen, which can result from improper design, assembly, or operation of hydrogen containment systems. One important aspect of design is the selection of materials, particularly those comprising the pressure boundaries of hydrogen containment components. From the perspective of unintended hydrogen release, materials selection is focused on two particular concerns related to hydrogen ingress: 1) hydrogen permeation rates in materials, which dictate the leak rates through pressure boundaries, and 2) the potential for hydrogen to degrade the mechanical properties of materials, which can lead to failure of pressure boundaries and sudden release of hydrogen. This article focuses on the second concern, and more specifically on the hydrogen-induced degradation of metals. In gaseous hydrogen environments at near-ambient temperatures, failure resulting from hydrogen-induced degradation of metals is typically referred to as 'hydrogen embrittlement'.

By Dr. Brian Somerday, Materials Engineering Consultant, Somerday Consulting, LLC

The potential for hydrogen embrittlement starts with the ingress of hydrogen into the metal. When hydrogen is in molecular form (H_2), it cannot enter directly into the metal since the hydrogen molecule size is greater than the 'free volume' between metal atoms. Consequently, hydrogen can only enter into metals that can catalyze the molecular hydrogen to dissociate into individual hydrogen atoms (H) on the metal surface. These hydrogen atoms can then enter and penetrate (diffuse) further into the metal by occupying the free volume between metal atoms. During this diffusion process hydrogen atoms can encounter metallurgical defects, and it is these hydrogen-defect interactions that lead to material degradation. These degradation events at the micro-scale are recognized as hydrogen embrittlement at the macro-scale by the formation of cracks. Such cracks can then propagate through the pressure boundaries of hydrogen containment components, leading to unintended hydrogen release. Since the dissociation of molecular hydrogen and diffusion of atomic hydrogen are time-dependent in nature, the formation and propagation of cracks are similarly time-dependent.

While the terms 'hydrogen embrittlement' and 'material compatibility' are often invoked interchangeably, the phenomenon of hydrogen embrittlement is not solely a material compatibility issue. This perspective is illustrated from the diagram in Figure 1, in which the circles represent three types of variables: material properties, environmental conditions, and mechanical stress characteristics. Hydrogen embrittlement is activated at the intersection of these three variable types, indicating that the phenomenon depends not only on material properties but also on environmental conditions and mechanical stress characteristics. In practical terms, a metal comprising the pressure boundary in a hydrogen containment component may function safely under one combination of environmental conditions and mechanical stress characteristics, but this same metal may suffer hydrogen embrittlement under a different combination of these variable-types.

Figure 1



Although the diagram in Figure 1 is qualitative, it can still serve as a guide to identify variables that must be considered when assessing the risk for hydrogen embrittlement. In the material properties space, variables such as material strength, alloy-element composition, and metallurgical features can all affect the potential for hydrogen embrittlement. One prevailing trend across all classes of metals is that higher-strength alloys are more prone to hydrogen embrittlement than lower-strength alloys. In the context of Figure 1, this means that hydrogen embrittlement can be activated in higher-strength alloys for more combinations of environmental conditions and mechanical stress characteristics compared to lower-strength alloys. A practical extension of this concept is that managing hydrogen embrittlement by modifying environmental conditions or mechanical stress characteristics may be less effective for hydrogen containment components fabricated from higher-strength alloys. One example of a higher-strength alloy that can be encountered in components employed for hydrogen containment is 17-4 PH stainless steel. There are documented cases of components fabricated from 17-4 PH stainless steel that have failed in gaseous hydrogen service.[1]

In the mechanical stress characteristics space in Figure 1, one important consideration is the time-variation of mechanical stresses on metals in hydrogen containment components. Specifically, the activation of hydrogen embrittlement can depend on whether the applied mechanical stress is constant or whether it repeatedly cycles between maximum and minimum levels. For example, as mentioned previously, lower-strength alloys tend to be more resistant to hydrogen embrittlement than higher-strength alloys. However, this trend is most consistent when applied mechanical stresses are constant. Certain lower-strength alloys may not exhibit hydrogen embrittlement under constant mechanical stress, but when the same alloys are subjected to cyclic mechanical stress, then hydrogen embrittlement may be promoted. In addition to the time-variation of mechanical stresses, the absolute magnitudes of mechanical stresses can dictate the activation of hydrogen embrittlement. In particular, geometric discontinuities in containment components can give rise to elevated mechanical stresses, and in turn these sites promote the formation of hydrogen embrittlement-related cracks. A real-world case study of how mechanical stresses can govern the activation of hydrogen embrittlement is the spate of failures that occurred in steel hydrogen transport cylinders throughout Western Europe in the 1970s. Two prominent factors that contributed to these hydrogen embrittlement-related failures were cyclic mechanical stresses resulting from filling/discharging operations and localized mechanical stress concentration at the base of the cylinders.[2]

The final space in Figure 1 is environmental conditions, and here two of the primary variables influencing the activation of hydrogen embrittlement are gas pressure and temperature. As hydrogen gas pressure increases, hydrogen ingress into metals becomes more extensive so the potential for hydrogen embrittlement is enhanced concomitantly. Such enhanced hydrogen embrittlement susceptibility does not continue indefinitely as gas pressure increases since the severity of hydrogen-induced material degradation reaches a limit. Regarding temperature, the potential for hydrogen embrittlement is typically highest at near-ambient conditions. As temperature decreases, hydrogen diffusion becomes slower, which can limit the extent of hydrogen penetration into metals. At higher temperature, although hydrogen diffusion is accelerated, there is less interaction between hydrogen and metallurgical defects. As a result, at both lower and higher temperatures, hydrogen-induced material degradation is less severe.

The high-level view encapsulated in Figure 1 can guide various approaches for assessing the risk of hydrogen embrittlement in hydrogen containment systems. In some scenarios, simply identifying key variables associated with a hydrogen containment component may be sufficient to assess the risk of hydrogen embrittlement. For example, a component fabricated from lower-strength steel and subjected to constant mechanical stresses at typical design levels is unlikely to suffer hydrogen embrittlement.

Another way the concepts in Figure 1 can be helpful is when the successful field experience of hydrogen containment systems serves as a reference for evaluating the hydrogen embrittlement potential in other systems considered for hydrogen service. Here, the guidance from Figure 1 is to determine whether the three variable types associated with the system in question may enhance the potential for hydrogen embrittlement relative to the system with successful field experience. For example, assume the two systems are identical in the material properties and environmental conditions spaces, but the system with successful field experience was only subjected to constant mechanical stresses while the system in question is expected to experience cyclic mechanical stresses. In this case, the successful field experience cannot provide confidence that the system in question is safe from hydrogen embrittlement.

About the author

Dr. Brian Somerday is currently a Materials Engineering Consultant with Somerday Consulting, LLC., a member of the Hydrogen Safety Panel, and routinely supports activities at the Center for Hydrogen Safety. He has 25 years of experience in mechanical metallurgy with a focus on environmental effects on fracture and fatigue of structural alloys. Brian has published extensively on the topic of hydrogen-assisted fracture and fatigue in structural alloys, including co-authoring the *Technical Reference for Hydrogen Compatibility of Materials* (www.sandia.gov/matlsTechRef/) and co-editing the two-volume set *Gaseous Hydrogen Embrittlement of Materials in Energy Technologies* (Woodhead Publishing, 2012).

Similar reasoning must be applied in circumstances when hydrogen embrittlement potential in containment systems is evaluated based on data from materials testing in hydrogen gas. In this approach, it is imperative that properties of materials as well as environmental conditions in the testing relate to the hydrogen containment system in a conservative fashion. One specific example of the need to apply materials testing data in this judicious manner is represented by the 300-series stainless steels. For these steels, the potential for hydrogen embrittlement is highest at temperatures just below typical ambient conditions. Thus, in a containment system fabricated from 300-series stainless steel that operates at -50°C, the risk of hydrogen embrittlement cannot be reliably evaluated based on testing this steel in hydrogen gas at room temperature.

In summary, when assessing the potential for hydrogen embrittlement in containment systems, it is essential to consider the three variable types featured in Figure 1. Although there are numerous specific variables that populate the spaces depicted in Figure 1, the following list represents one variable from each space that deserves particular attention:

- **Material strength.** When procuring containment components that are not explicitly certified for gaseous hydrogen service, it is advisable to review the list of materials in the product drawing to identify any higher-strength alloys, such as 17-4 PH stainless steel, that raise concerns for hydrogen embrittlement.
- **Time-variation of mechanical stresses.** When containment components are subjected to cyclic mechanical stresses, the most effective means to account for hydrogen embrittlement is through quantitative analysis. These methods couple stress analysis of components with data from materials testing in hydrogen gas. Examples of such approaches are in the American Society of Mechanical Engineers (ASME) codes for stationary pressure vessels (ASME Boiler and Pressure Vessel Code, Section VIII, Division 3, Article KD-10) and for pipelines (ASME B31.12).
- **Hydrogen gas pressure.** For many metals, hydrogen embrittlement can be activated in gaseous hydrogen even at very low pressures (for example, 1 bar or less). For this reason, it cannot be assumed that there is a threshold pressure below which containment systems are safe from hydrogen embrittlement for all combinations of material properties and mechanical stress characteristics.

References

[1] *Journal of the Society of Materials Science, Japan* 69.5 (2020): 395–400.
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About the CHS and HSP

Founded in 2018, the Center for Hydrogen Safety (CHS) is a non-profit, unbiased, corporate membership organization promoting the safe operation, handling, and use of hydrogen and hydrogen systems across all installations and applications. CHS has more than 100 global member organizations and 14 strategic partners and utilizes best practices, lessons learned, education resources, conferences, webinars, workshops, and working groups to develop and share hydrogen safety knowledge. Visit www.aiche.org/chs.

A trusted and highly respected resource, the Hydrogen Safety Panel (HSP) is a pioneer in reducing knowledge barriers to hydrogen fuel cell deployment and enabling timely technology adoption by cities and communities. Building on its diverse knowledge, rich experience, and technical objectivity, this not-for-profit expert panel utilizes safety reviews, research, information dissemination, and training to help government agencies, industry and other stakeholders ensure that hydrogen is safely stored and handled. Visit https://h2tools.org/hsp.

Industrial perspective on liquid hydrogen valves

Storage and transportation of hydrogen in liquid state offers several advantages. Liquid hydrogen (LH_2) has a higher density and requires a lower storage pressure compared to gaseous hydrogen. However, hydrogen turns into liquid at -253°C, which brings its own challenges. The very low temperature as well as the risk of flammability make it a challenging medium. Stringent safety measures and reliability are thus a must when designing valves for this application.

By Fadila Khelfaoui and Frédéric Blanquet, Velan

LH_2 applications

Currently, LH_2 is being used and explored in various special applications. The aerospace industry uses it for rocket launching and transonic wind tunnels. Under the umbrella of big science, LH_2 is essential in superconductivity applications, particle accelerators and nuclear fusion. Recently, with increasing demand for sustainability, LH_2 has become of interest as a source of fuel for heavier trucks and ships.

Valves play an important role in the successful operation of these applications. Reliable and safe operation of valves that form part of the LH_2 supply chain ecosystem (production, transport, storage, and distribution) is a necessity.

Working with LH_2 is not easy. There are numerous challenges associated with it. Leveraging 30 years of field experience and technical expertise in supplying high performance valves down to -272°C, Velan has been involved in pioneering projects and is unequivocally well positioned to meet the LH_2 challenges.

Design challenges

Pressure, temperature, and hydrogen concentration are the primary factors when determining valve design risk assessment. For optimum valve performance, design features and material selection are of utmost importance. There are challenges to be overcome when handling LH_2. One such challenge is the deleterious effect of hydrogen on metallic materials. Combined with the very low temperature, valve materials need not only to withstand the attack of hydrogen molecules (some degradation mechanisms are still a subject of debate in the scientific community) but must also be able to perform at that temperature for a long service life. The current knowledge of non-metallic material compatibility with hydrogen is still limited. This gap in knowledge must be taken into consideration when selecting sealing materials.

Tight sealing is another key design performance criterion. Under thermal gradients resulting from temperature differentials of up to 300°C between the LH_2 and the surrounding environment (at room temperature), different valve components expand and contract by varying amounts. This discrepancy can result in detrimental leakage of critical sealing surfaces.

Sealing tightness at the stem is another design consideration. The transition from cold to warm generates a heat flow. Ice may form in the warmer section of the bonnet cavity, compromising the stem sealant and thus the operability of the valve.

The -253°C temperature demands optimal insulation technology for the valves to maintain LH_2 at this temperature and minimize hydrogen losses via boil-off. Any heat transfer to the liquid causes hydrogen to evaporate and leak. Furthermore, a break in the insulation causes oxygen condensation. Any contact between oxygen and hydrogen or other combustible material will increase the likelihood of fire hazard. Therefore, when considering the susceptibility of valves to the risk of fire, the valve design must be explosion-proof and include a fireproof actuator, instruments, and wiring, in conformance with the most stringent certifications. This will ensure that the valve will function safely during a fire.

Pressure buildup is another potential issue that may render the valve inoperable. The accumulation may occur when liquid is trapped in the valve cavity, and under certain conditions of heat transfer and vapor formation. In the case of high differential pressure, cavitation and/or noise can occur, which will damage the valve prematurely and result in unacceptable process failures.

By considering these aspects regardless of the process conditions, appropriate design features are integrated into the design process, thus providing a safe and reliable operation.

Other key design challenges are related to environmental issues such as fugitive emissions. Hydrogen has unique characteristics: small molecular size being colorless, odorless, and explosive. These characteristics make zero leakage an absolute necessity.

Velan engineer providing support at the Westcoast hydrogen liquefaction plant in North Las Vegas

Valve solutions

Regardless of their functionality or type, all valves in LH_2 service must meet certain common requirements. These include the use of appropriate construction materials that ensure structural integrity at very low temperatures, as well as materials that are inherently fire safe. Similarly, the sealing and packing materials used in these valves must also meet these basic requirements.

Austenitic stainless steel is a preferred material for LH_2 valves. It offers excellent impact strength, minimal heat loss, and can handle steep temperature gradients. Other materials are also available that are compatible with hydrogen but depend on the process conditions.

Besides the choice of materials, other design details such as extending the stem with a gas column protect the sealing packing from the effects of extremely low temperature. In addition, the stem extension can be supplemented with a thermal collar to avoid condensation in the insulated area.

Unique features tailored to each valve design offer enhanced technical solutions to different challenges.

Special process applications utilizing Velan valves down to -272°C

Butterfly valves

Velan provides two different designs of butterfly valve: double- and triple-offset metal seated valves. Both designs provide bi-directional flow capabilities. They are designed with disc rotation geometries to ensure tight shut-off sealing. Trapped cavities are eliminated.

In the double offset, an exceptionally tight shut-off is achieved with eccentric disc rotation combined with a unique sealing system, VELFLEX. This patent technology overcomes even high temperature fluctuations.

The triple-offset disc rotation geometry, TORQSEAL, ensures that the disc seal contacts the body seat only at the final shut-off position without rubbing or galling, providing a torque-generated resilient seat with sufficient wedging effect to ensure a uniform seal contact around the entire circumference of the valve seat when the valve is closed. The resiliency of the seal allows self-adjusting of the valve body and disc to prevent the risk of jamming during temperature transients.

A reinforced stainless-steel shaft is furnished for high cycles and smooth operation at very low temperature.

The VELFLEX double offset valve design allows for easy and quick in-line maintenance. Thanks to the side cover, free access to the seat and disc for inspection or maintenance is possible without disassembly of actuators, and no special tools are required.

Control valves

Velan has a quite unique portfolio of control valves for low-temperature applications designed for temperatures down to -272°C and working pressures up to PN70.

The valves used are bellows seal globe control valves, with angle and/or straight patterns. Proprietary design features and material are developed for reliable and safe operation. Valves can be fitted with a tight double shell or jacket enabling vacuum insulation. Valves are manually or pneumatically operated, depending on the on-site applications.

Safety relief valves

The safety relief valves are specially designed for overpressure protection of liquefied helium lines in superconductivity applications. This is achieved by a magnetic safety device developed specifically to protect containers and pressure shells against overpressure of compressed fluids at ambient temperature or during a very low temperature discharge. In the event of a local temperature increase, called 'quench', the valve opens in less than 80 ms. Initially supplied for liquefied helium, it can be adapted to hydrogen applications.

Qualification and approval

Tests are performed in accordance with the most stringent customer requirements. Protection against explosion is required in conformance with ATEX, KOSHA, NAMUR standards as per the applicable legislations. Some customers require local certifications, such as KGS in Korea, or NK in Japan.

Today, there is still no specific standard for valves in hydrogen service. Working groups to define this standardization are being set up to accelerate the deployment of 'green' hydrogen on a commercial scale. TÜV has issued a standard, but no customer is implementing it yet.

Field experience

In the past, Velan has supplied control valves for hydrogen liquefaction plants in the USA (Westcoast project, North Las Vegas) and in South Korea (SK project, Ulsan) and is currently manufacturing valves for the Woodside project (Ardmore, Oklahoma).

In the field of aerospace, Velan has supplied butterfly valves for the launch pad of Ariane rockets in Kourou (French Guiana) and control valves for the Indian space program.

Future of LH_2

Currently, LH_2 is gaining popularity as a clean fuel and a sustainable form of energy. Although it holds much promise, the deployment of LH_2 on a large scale worldwide is still a challenge. With proven engineering expertise and hydrogen field experience, Velan is ready to be a part of the solution.

About the authors

Fadila Khelfaoui is a professional engineer with 25 years of combined experience in materials engineering and coatings. She joined Velan Canada in 2016 as Corporate Engineer, Metallurgy. She holds a Ph.D. degree in materials science and engineering and is a registered Professional Engineer in Quebec.

Frédéric Blanquet has 34 years of experience in the valve industry. He has been responsible for cryogenic market at Velan France for the past 19 years.

Electrolysis technologies and LCOH: current state and prospects for 2030

Water electrolysis (WE) is key to decarbonising hard-to-abate industries such as fertilizers and steel. Four main technologies – alkaline (AWE), proton exchange membrane (PEM), solid oxide electrolysis cells (SOEC), and anion exchange membrane (AEM) – can be found in the market, each with its own advantages and disadvantages. This article provides a short review of these technologies and analyses their impact on the levelized cost of hydrogen (LCOH).

By Carlos Bernuy-Lopez, Senior Consultant – Power-to-X and Hydrogen Technologies at Ramboll

Introduction

Green hydrogen is poised to play a crucial role in addressing many of the climate challenges we face in the coming years, including the need to reduce greenhouse gas emissions and achieve our climate targets. For instance, if we only consider the current use of hydrogen in the European Union (EU), which is mostly grey hydrogen derived from the steam reforming of natural gas, over 220 metric tons (Mt) of carbon dioxide equivalent (CO_2eq) could be avoided, which accounts for 8% of the EU's total emissions. In addition, green hydrogen is key to decarbonising hard-to-abate industries such as steel manufacturing, which is responsible for emitting over 200 Mt of CO_2eq, or 7% of total EU emissions. Therefore, the EU has set an ambitious target through RePowerEU to produce around 20 Mt of renewable hydrogen by 2030, which could help eliminate a significant portion of these emissions associated with grey hydrogen use and steel production.

The cleanest manner to produce green hydrogen is through electrolysis, which splits water molecules into hydrogen and oxygen in a device called electrolyser. If the electricity powering the electrolyser comes from renewable sources, the process is fully green. Therefore, the more available and affordable renewable energy makes green hydrogen a very competitive solution to both replace grey hydrogen and manufacture green steel. However, the cost of both electricity and electrolysers determines the cost competitiveness of green hydrogen projects, impacting the so-called levelized cost of hydrogen (LCOH). The LCOH takes into consideration both capital and operating expenditures (CAPEX and OPEX) of a certain green hydrogen project and is expressed in €/kg or $/kg.

As key equipment in green hydrogen projects, electrolysers have a major impact on the LCOH, along with the electricity price. Different electrolysis technologies can be used for water electrolysis, each with different characteristics in terms of CAPEX and OPEX. These are alkaline water electrolysis (AWE), proton exchange membrane (PEM) water electrolysis, solid oxide electrolysis cells (SOEC), and anion exchange membrane (AEM) water electrolysis. For all of them, CAPEX is heavily influenced by the materials used, while the electrical efficiency of each technology determines the OPEX associated with carrying out the electrochemical reaction. This article will review the main characteristics of these technologies as well as the key materials forming part of the different electrolyser types. Finally, the article will present LCOH values for state-of-the-art examples of each technology in 2023, as well as expected LCOH values in 2030, based on future projections of electricity prices and improved CAPEX and OPEX for each technology.

Alkaline water electrolysis

Alkaline water electrolysis (AWE) is the most mature electrolysis technology, which uses a liquid electrolyte (KOH). The main characteristics of AWE, along with the current LCOH values that can be obtained with two commonly used reference electricity prices (€60 and €40/MWh), are presented in the first column of Table 1. Both large stacks and systems can be achieved with the use of pressurized alkaline technology: stacks as large as 5 MW with an output pressure of 100 kg/h and systems close to 1 GW. In terms of CAPEX and OPEX, an average CAPEX for an AWE system is around €500/kW or €25,000 kg/h, and the average OPEX is around 54 kWh/kg, with a stack lifetime of 80,000 h.[3,4]

Regarding the materials used in AWE, both pure Ni and Ni-plated carbon steel are the more common materials, with the use of some expensive and rare-earth metals such as Ru or Ir being significant in some of the solutions offered in the market. Recent calculations made by the International Energy Agency estimate that AWE uses around 800 kg/MW of Ni.[5] Pure Ni and Ni-plated carbon steel are used as components of different parts in the electrolyser stack, such as bipolar plates and electrode supports, or even as catalysts in the case of Ni. Ni-plated carbon steel is intended to replace pure Ni in all components where less harsh conditions allow that, and as the

Table 1. State-of-the-art characteristics of different electrolysis technologies and LCOH values based on the CAPEX and OPEX values specified. A system is defined as equipment including stacks, power electronics and balance of the system components (gas separators, electrolyte tanks, etc.), and excluding balance of plant.

2023					
Parameter	Units	AWE	PEM	SOEC	AEM
Critical raw materials	**Chemical elements**	**Ni, Ru, Ir**	**Pt, Ti, Ir**	**Co, Ni**	**Ni**
Stack size	MW | kg/h	5 | 100	1 | 17	0.04 | 1	0.0025 | 0.043
Maximum system size	GW	1	1	0.05	N/A
Average system efficiency	kWh/kg	54	60	40	N/A
Average degradation	h	80,000	60,000	20,000	5,000
Average system CAPEX	€/kW | €1,000 per kg/h	500 | 25	750 | 44	800 | 32	N/A
LCOH with electricity price €60/MWh	€/kg	4.6	5.4	4.3	N/A
LCOH with electricity price €40/MWh	€/kg	3.2	3.9	3.19	N/A

quality of the Ni coating over carbon steels is improved. Balance-of-system components, such as electrolyte tanks or gas separators, are mainly made of Ni-plated carbon steel, but due to the corrosion characteristics of the electrolyte, some stainless-steel components may also be needed. In addition, stainless steel is also used for system tubing. Finally, non-expensive catalysts such as Raney Ni, but also Ni, Fe and/or Cu-containing alloys, are the more common materials used as catalysts. In some cases, the use of Ru and Ir can also be found, allowing the operation of the stack at higher current densities, leading to smaller footprints, although without much improvement in electrical efficiencies.

As can be seen from Table 2, with the expected projections for 2030 and lower renewable electricity prices (€15 and €30/MWh as reference), the LCOH can already be quite interesting, and the improvement is much more significant when OPEX (both electricity consumption and durability) is improved. Therefore, it seems an interesting approach to focus less on reducing costs when a good CAPEX level is reached (€300–€400/kW) and instead to improve both electricity consumption and degradation of the AWE stacks. High-quality Ni coatings on carbon steel components leading to lower Ni content will result in good CAPEX levels. Likewise, longer component durability will lead to lower OPEX and, therefore, lower LCOH. Finally, achieving higher electrical efficiency and cost-efficient catalysts with larger surface area will bring electricity consumption down, which will contribute to improving the LCOH (lower OPEX), even without such favourable electricity prices.

PEM water electrolysis

Proton exchange membrane water electrolysis (PEMWE) is characterised by having a solid electrolyte and by operating at much higher current densities, resulting in a significantly smaller system footprint. With a relatively high output pressure of ca. 30 bar, it produces high-purity hydrogen (99.999%). The second column of Table 1 summarizes the main characteristics of this technology, as well as the LCOH calculations for electricity at both €60 and €40/MWh. Rather large stacks can also be achieved, with current sizes averaging 1 MW and 17 kg/h of produced hydrogen. Lower footprints of 25 kg/h per m^3, compared to 7 kg/h per m^3 in the case of AWE, can be achieved. These large stacks in hydrogen output and small footprints allow PEM manufacturers to currently reach system sizes in the GW range. In terms of CAPEX, PEMWE is about 50% more expensive on average than AWE. This value is €750/kW or €44,000 kg/h, and has slightly higher electricity consumption on average than AWE (56 kWh/kg) as well as a shorter stack lifetime on average (60,000 h).[3,4]

Regarding the materials, PEM is the more demanding technology in terms of raw materials, as it uses large quantities of Ti, Pt, and Ir. Ti is used in some of the stack components, such as bipolar plates and porous transport layers (PTLs), due to its good performance and stability in the service conditions (high potentials in acidic media). Pt and Ir are used as catalysts to carry out the high-demanding electrocatalytic reaction in acidic media, with loads of Ir and Pt about 0.3 kg/MW and 0.7 kg/MW respectively.[5] In addition, Pt is also used as a coating for some of the Ti components described above (mainly PTLs). One of the main advantages of PEM technology is the use of fewer balance-of-system components, as no electrolyte tanks or gas separators are needed. However, the use of stainless steel for system tubing is still necessary, as is the case with AWE technologies.

As in the case of AWE, Table 2 shows the projections for CAPEX, OPEX and the LCOH of PEMWE for 2030. It is expected that there will be a considerable decrease in CAPEX as coated stainless steel components will be able to replace Ti components in both bipolar plates and PTLs. In addition, a decrease in catalyst loading will be achieved for both Pt and Ir due to improved manufacturing techniques that will lead to catalysts with a much larger surface area. This will also improve both electrical efficiencies and durability, decreasing the OPEX. The expected projections for CAPEX and OPEX (€500/kW, 50 kWh/kg and €18,000 per kg/h) will also allow this technology to produce hydrogen with a competitive LCOH.

Solid oxide electrolysis

Solid oxide electrolysers (SOECs) are characterised by their ability to operate at

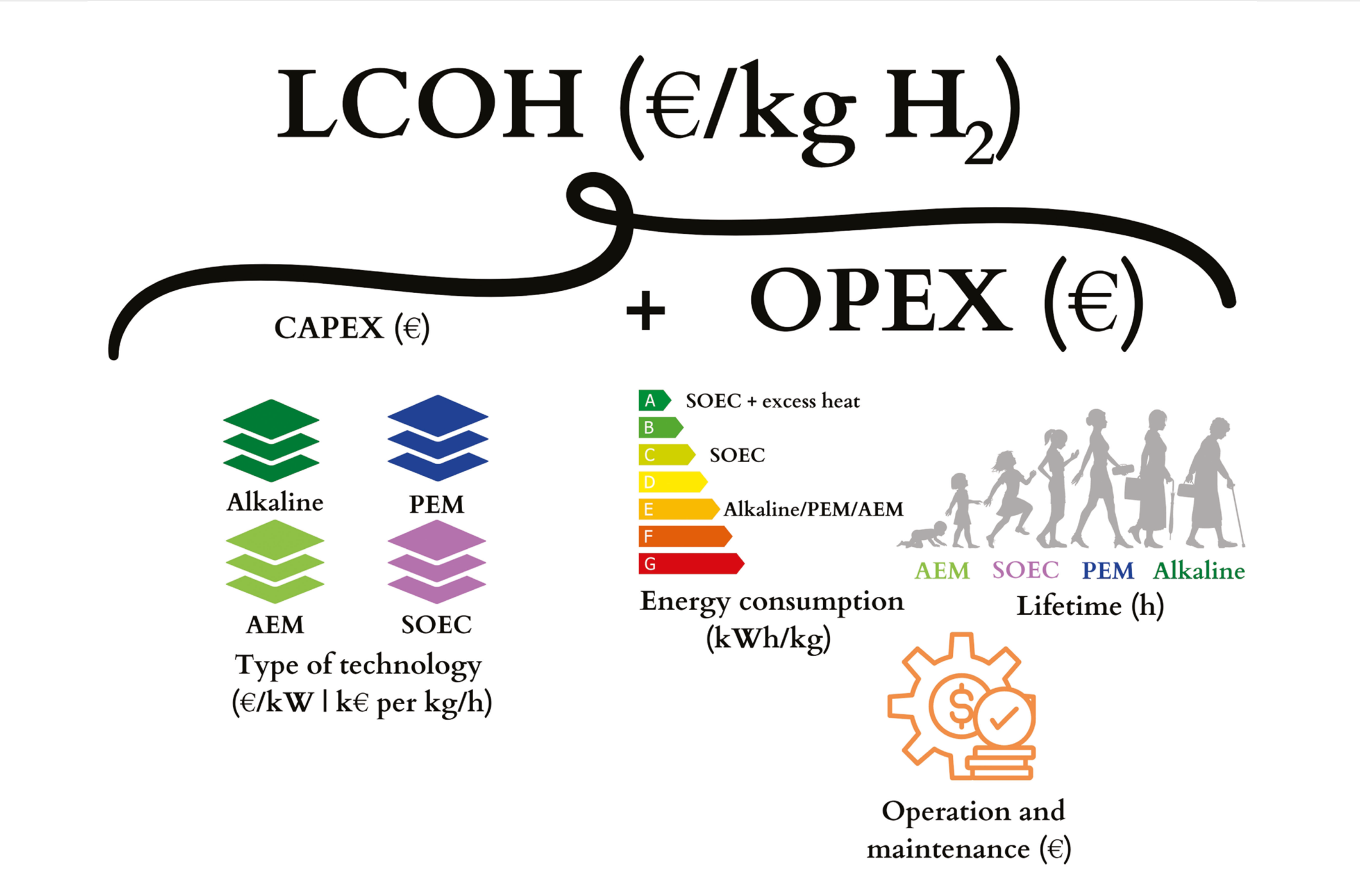

Table 2. Projected characteristics of different electrolysis technologies for 2030 and LCOH values based on the CAPEX and OPEX values specified

2030					
Parameter	Units	Alkaline	PEM	SOEC	AEM
Critical raw materials	Chemical elements	Ni	Pt, Ir	Co, Ni	Ni
Stack size	MW | kg/h	20 | 432	10 | 216	0.5 | 13.3	0.1 | 2
Maximum system size	GW	>1	>1	1	0.1
Average system efficiency	kWh/kg	50	50	38	55
Average degradation	H	100,000	80,000	80,000	20,000
Average system CAPEX	€/kW | €1,000 per kg/h	200 | 9	400 | 18	400 | 15	400 | 20
LCOH with electricity price €30/MWh	€/kg	2.2	2.4	1.9	2.7
LCOH with electricity price €15/MWh	€/kg	1.2	1.4	1.1	1.7

high temperatures (i.e., 500–850°C), making them the most efficient technology of all. Additionally, they are made of cheap and abundant materials (i.e., ceramic oxides). The third column of Table 1 shows the main characteristics of this technology, together with LCOH calculations for electricity at both €60 and €40/MWh. Compared to PEM and AEM, SOECs use much smaller stacks due to the difficulty in scaling up high-quality and reliable ceramic technology. However, these systems can already achieve the MW scale, allowing for their deployment and further development. The main advantage of SOECs over other electrolysis technologies is their much higher efficiency. They operate at the thermoneutral point (1.23 V), resulting in stack efficiency very close to 100%. An average electricity consumption value for SOECs when feeding steam water at 150°C is 40 kWh/kg and 45 kWh/kg when heating of water is considered.[3,4] In terms of current LCOH values, this technology offers the best values due to much lower OPEX, even with its shorter lifetime, as its stack replacement is much cheaper than for AEM or PEM technologies.

SOECs are made of cheap and abundant materials, namely ceramic oxides containing inexpensive and readily available materials such as Zr, Fe, Mn, stainless steels. There are also other materials, such as Ce or Y, that are less abundant but still cost-effective and readily available. Special mention must be made of both Ni and Co as both materials are used quite extensively, which could be an issue. However, the current use of Ni and Co is only 200 and 25 kg/MW, respectively, which is four times less than in alkaline technologies in the case of Ni.[5] The use of high temperatures is another material concern as more advanced stainless steels need to be used since the operating temperature is higher (i.e., >750°C) in both stack components and hot boxes. However, recent developments show a trend in decreasing the operating temperature below this critical level (<700°C), where cheaper stainless steels can be used.

The table highlights the immense potential of this technology as it can enable us to achieve the cost level of €1/kg of hydrogen by 2030, even with relatively high electricity prices. This is due to the possibility of attaining electrical efficiencies close to 95% if excess heat is supplied to the system. The expected decrease in CAPEX and OPEX (€400/kW, €15,000 per kg/h, and 38 kWh/kg), along with increased durability and larger systems, will help to achieve LCOHs close to €1/kg.

AEM water electrolysis

Anion exchange membrane (AEM) water electrolysis is the least developed of the

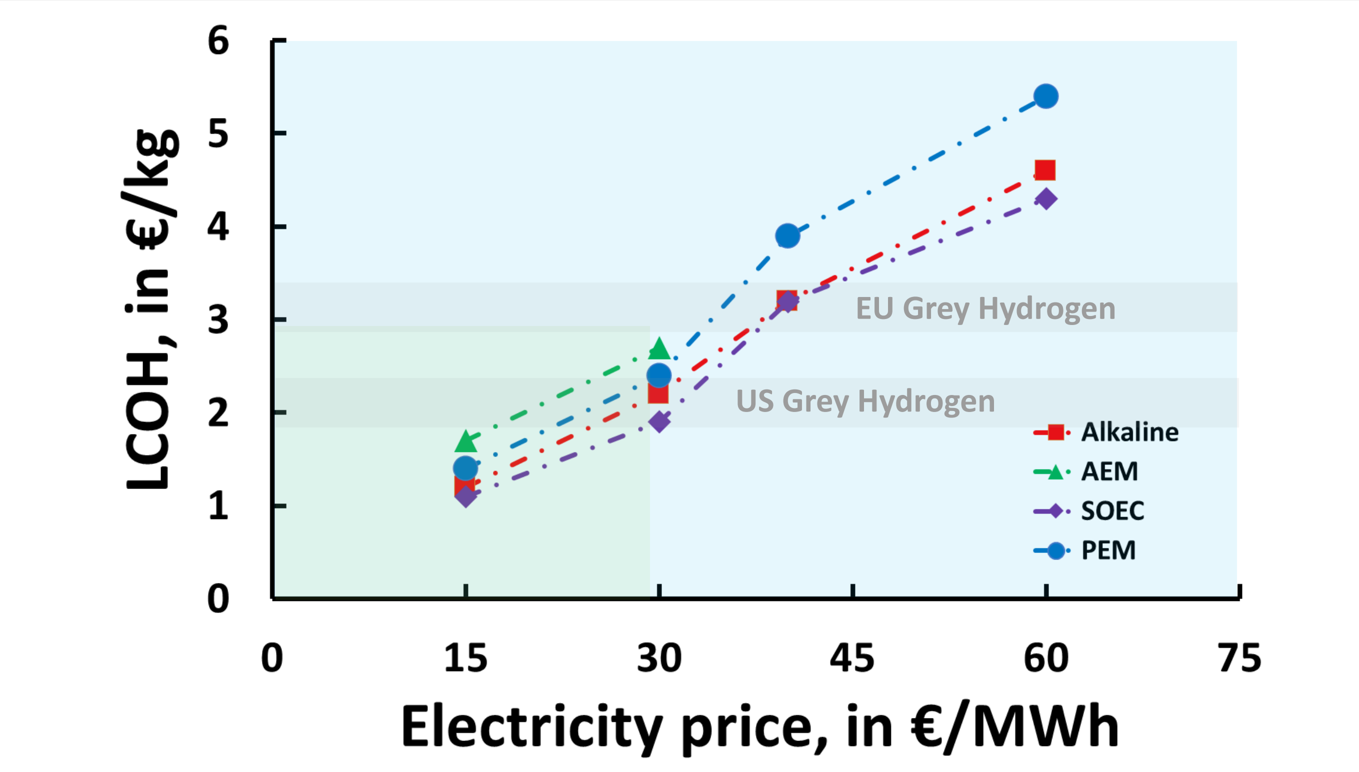

Fig. 1. LCOH for different technologies at different electricity prices, based on data from Tables 1 and 2

electrolysis technologies discussed in this article, although it has large potential to contribute significantly to the overall picture. It is a membrane technology, like PEM, but operates in an alkaline medium, allowing for the use of inexpensive materials and resulting in a smaller footprint. The main characteristics of this technology, including its efficiency and electricity consumption, are presented in the last column of Table 1. The table, however, does not show the CAPEX and OPEX values for AEM electrolysers, as there are currently very few companies in the market selling AEM electrolyser products, and the author of this article wishes to present only significant average values for all electrolysis technologies.

Regarding materials, the main advantage of AEM is the use of abundant and cost-effective materials in most of the components. Only excessive use of Ni as the main component could jeopardise the competitiveness of this technology. A current limitation of AEM technology is the lack of cost-effective and long-lasting membranes suitable for use in an alkaline medium. However, rapid developments are being made in this area, which is expected to make AEM a viable solution in the medium term. This is reflected in the promising projections for AEM technology in terms of LCOH, as shown in Table 2.[3]

LCOH considerations and value chain

As mentioned at the beginning of this article, electrolysis technologies are an essential component in determining the final LCOH for a green hydrogen project. Figure 1 summarises the LCOHs achievable by using different electrolysis technologies, based on a set of reference electricity prices, both currently and projected for 2030. Encouragingly, all four technologies discussed can reach the LCOH target of less than €2/kg by 2030, which would make green hydrogen competitive with the lowest-cost grey hydrogen currently available in both Europe and the US. This is crucial to achieving the ambitious hydrogen production goals by 2030.

For example, to produce 10 Mt of green hydrogen in the EU, 650–750 GW of electrolysis capacity would need to be installed, depending on the technology employed. A higher penetration of SOECs would potentially reduce this capacity requirement. However, manufacturing several hundred GWs of electrolysers within the next seven years is an optimistic target, given that the current manufacturing capacity worldwide is estimated at only 20 GW. Therefore, the success of achieving our climate goals will depend on the contribution of every manufacturer across all technologies. Fortunately, this represents a great opportunity for developing new industries, economic growth, and job creation as we transition away from fossil fuels.

Conclusion

Four electrolysis technologies can currently be found in the market: alkaline, PEM, SOEC, and AEM. In this article, the current state of the art and challenges, as well as the technological and price developments expected to occur by 2030, have been presented. Based on this analysis, significant growth in deployment of these technologies can be expected in the coming years.

Alkaline technologies are likely to be used in projects that have fewer electricity price restrictions, little space limitations, and low renewable variabilities, such as large, GW-scale industrial projects connected to hydropower. On the other hand, PEM technologies are better suited for projects with high renewable variability and limited space, such as offshore projects. SOEC are ideal for projects with excess heat and lower demand for hydrogen, such as projects in the steel and fertilizer industries, 50 to 100 MW in size.

Even greater deployment of green hydrogen projects can be expected in 2030 and beyond, characterised by lower CAPEX and OPEX, and consequently lower LCOH. This progress will be driven by further reductions in renewable electricity costs and advancements in electrolysis technologies.

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About the author

Carlos Bernuy-Lopez holds a PhD in Material Science from the University of Liverpool and currently works as a senior consultant in power-to-X and hydrogen technologies at Ramboll. His expertise of more than 17 years spans both technology (fuel cells and electrolysers) and application know-how (steel, ammonia, and e-fuels). Prior to joining Ramboll, he first worked at various universities and research centers across Europe and Japan, and subsequently moved to industry, where he led R&D as well as business development projects at steel companies such as Alleima (previously Sandvik Materials Technology) and H_2 Green Steel. Carlos also possesses several years of experience providing project management guidance, including coaching PhD and Master students as well as summer interns. Passionate about green hydrogen and knowledge sharing, he regularly posts on LinkedIn and Twitter about the role of hydrogen in the renewable energy mix.

Hydrogen gas safety standards and best practices Part 2: detection technologies

Part 1 of this series addressed the safety considerations and challenges with industrial storage of gaseous hydrogen. Part 2 focuses on the most up-to-date technologies and best practices to be used when implementing a robust hydrogen leak detection system for an industrial facility. New technologies are continually being developed to deliver faster and more reliable detection. However, all have strengths and weaknesses that should be considered in the context of the specific application before implementation.

By Milad Eskandar, Daniel Brosig and Matt Russell, Gas Cleaning Technologies LLC, and John Boyle, John Boyle Consulting LLC

Leak sensor types and efficacy

Detecting leaks is not only important to minimize hydrogen losses, but also to prevent potential fires or explosions, especially indoors, due to its wide flammability limit range and low ignition energy. Various types of hydrogen sensors and leak detector technologies exist, and while none of them provide perfect detection, a combination of different technologies along with routine inspections is the best way to ensure safe operation.

The National Fire Protection Association (NFPA) requirements call for the detection of gaseous hydrogen inside hydrogen equipment enclosures (HEE) that include hydrogen generation, compression, or processing equipment. This detection must be interlocked to the mechanical ventilation system and initiate ventilation at a rate of 0.0051 $m^3/sec/m^2$ (1 $scf/min/ft^2$) of floor area in the enclosure when the hydrogen concentration is measured at a minimum of 0.4 vol%. Alternatively, mechanical ventilation can be continuously running and not be linked with the hydrogen detection system. The detection system must also be linked to the emergency shutdown system (ESS); detection of hydrogen at 1 vol % (25% of its lower flammability limit [LFL]) or higher must result in the activation of the ESS.[1] There are no other requirements for hydrogen detection from NFPA. However, standards vary from country to country and state to state. Care should be taken to ensure local norms and standards are being followed.

Hydrogen gas point detectors are useful to be placed in indoor locations or near storage areas where hydrogen can accumulate. A good rule of thumb is to place this type of sensor in the highest draft-free location in the room or enclosure, 30 cm (12 in) or more below the ceiling to avoid elevated temperatures.[1] These sensors can also be used outdoors when combined with hydrophobic screens to protect from rain. It is important to note that point sensors do not measure hydrogen concentration over an area but only in the immediate vicinity where the sensor is located as they rely on diffusion of hydrogen towards the sensor. In outdoor and well-ventilated areas, hydrogen concentration is likely to be highly diluted by air; therefore, it may not be possible for point detectors to adequately identify a leak. For this reason, it is recommended that point sensors be placed as close as possible to potential leak sources in these situations. Most point sensors also require routine calibration with standard gas mixtures.

Commonly found types of hydrogen point sensors include:

- Electrochemical
- Metal oxide (MOX)
- 'Pellistor' or catalytic bead
- Thermal conductivity

In addition to point detectors, fixed ultrasonic leak detectors can help identify leaks in high-pressure systems (usually above 7 bar) by identifying anomalies in ultrasonic sound waves attributed to gas leaks. These sensors usually have a spherical radius in which they can detect leaks and can be useful for outdoor storage tanks, short pipelines, or use areas. As background noise can affect the performance of these detectors, care should be taken to ensure appropriate placement.

To pinpoint the leak source more accurately and to detect leakages that fixed sensors may miss, operators should perform routine inspections with handheld sensors. Many types are commercially available, including handheld versions of the above-mentioned sensors, usually equipped with vacuum pumps to get an accurate measurement of hydrogen in the area the device is pointed towards. Portable ultrasonic leak detectors are also available and provide audio-visual feedback when nearing the source of a leak. Thermal imaging can detect leaks based on temperature differences between the leaking gas and its immediate surroundings. This method can be used from moving vehicles, helicopters, or portable handheld systems and is capable of inspecting several miles or hundreds of miles of pipeline per day.[2]

In addition to area detection and routine inspections, the use of a visual indicator can be beneficial to identify leaks more easily. Commercially available hydrogen detection

Fig. 1. Gas detector located outdoors in a hydrogen use area

tapes wrapped around joints and fittings change color when in contact with diatomic gaseous hydrogen. This can be especially useful during commissioning or in areas that may experience high levels of vibration increasing the possibility for a leak. Special care should be taken as some detection tapes may show a false positive if they come in contact with hydrogen sulfide.

In the case of a hydrogen fire, a flame camera or sensor with an audiovisual alarm can notify personnel of a problem area and trigger emergency shutdown and/or evacuation procedures. Hydrogen flames are often invisible or difficult to see with the human eye, especially in daylight or artificial light. Flame cameras designed for hydrogen flame detection monitor radiation emitted by the flame in the ultraviolet (UV) and infrared (IR) spectral bands. These cameras are appropriate for indoor or outdoor use and multiple cameras can be strategically installed to ensure full visual coverage over the area in which hydrogen is being stored and transported. These cameras usually have a wide field of view (~130°) and a range of less than 20 m (65 ft).

Odorization potential

Because hydrogen is an odorless gas, adding an odorant into a gas stream will make the gas smell and can allow for humans to detect the presence of the gas even at concentrations well below flammability levels in order to ensure their own safety and potentially help identify possible leaks. Odorants allow for the detection of leaks in positions where it may be difficult to place detectors. Commonly used with hydrocarbons for the past century, odorizers allow for an early warning system before flammable levels are reached.[9] Gas odorization is, in most countries, a legal or regulatory requirement that specifies that natural gas in air must be readily detectable by odor at a concentration of 20–25% of

Fig. 2: Common leak detectors used in hydrogen systems. Catalytic bead point sensor (top left)[3], ultrasonic area leak detector (top middle)[4], handheld electrochemical sensor with pump (top right)[5], handheld ultrasonic leak detector (bottom left)[6], handheld thermal imaging leak detector (bottom middle)[7], UV/IR flame camera (bottom right)[8].

the LFL. However, there are no regulations for the use of an odorant in hydrogen systems.[10] As a safety measure it can still be beneficial to introduce an odorant in certain industrial situations.

Odorant selection is strongly based on the density and vapor pressure of the gas being odorized. Ideal odorants should have certain physical and functional properties, including[11]:

- Low odor detection threshold
- Suitable detection intensity
- Little or no olfactory fatigue
- Distinguishable from smells of daily life
- Characteristically unpleasant
- Low boiling point
- Low corrosivity
- Low toxicity

Conclusion

It is important to note that the technologies and standards discussed in this article only account for a small representation of the extensive information available to draw upon when designing a system. Detailed technical information regarding hydrogen sensors or leak sensors should be obtained directly from their respective suppliers, and experimental technologies should be field tested and only used in addition to redundant backup proven technologies. Personnel should be professionally trained to perform routine maintenance and inspections, while properly documenting findings. The strictest standards should be followed from the National Fire Protection Association, the Compressed Gas Association, the Environmental Protection Agency as well as any local agencies.

This article is for information purposes only and should by no means be used as the basis for design and engineering. As safety technologies and standards continue to change based on the growing understanding of hydrogen systems, the hydrogen detection technologies with best proven track record should be given priority, while most up-to-date standards should be routinely reviewed and followed.

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Since 1995, Gas Cleaning Technologies (GCT) has built a reputation as a responsive, technology-driven organization with a proven record of high-quality, specialized gas cleaning and energy solutions delivered to industries around the world. GCT's decarbonization solutions range from industrial process energy-intensity audits, green fuel conversion and waste heat recovery to hydrogen production and CO_2 capture technologies. With professionals specialized on process engineering, field testing, technology development and integration, GCT serves clients across the globe from five locations: Dallas, Chicago, Vancouver, Singapore and India. For more information, visit www.gcteng.com or contact us at brosig@gcteng.com.

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Hydrogen Tech World

Conference Timetable

4 April	Speaker	Company	Presentation title
9:25	Welcome by Matjaž Matošec, Hydrogen Tech World Conference Manager		
9:30	Luc Graré	Lhyfe	A roadmap to enabling green hydrogen to decarbonize industry and transport
10:00	Carlos-Bernuy Lopez	Ramboll	On the path to low Levelized Costs of Hydrogen (LCOH): electrolysis technologies considerations
10:30	Alexander Spiess	Hynamics Deutschland	Developing large-scale hydrogen projects – uncertainties and challenges (from real-life projects)
11:00	**Coffee break**		
11:15	Thijs de Groot	HyCC	Challenges and opportunities in scaling up alkaline water electrolysis
11:45	Paul Dainora	thyssenkrupp nucera	Large-scale water electrolysis for decarbonized and other hard-to-abate industries
12:15	Jan Schmidt	Hystar	Developing the world's most efficient PEM electrolyser
12:45	**Lunch**		
13:45	Michael Schulz	Siemens Energy	Optimization of compression solutions for (green) hydrogen
14:15	Achim Heiming	Alfa Laval	The role of efficient heat transfer in hydrogen production
14:45	Angela Philipp	Alleima	Duplex stainless steel in heat exchangers for alkaline electrolyzers
15:15	**Coffee break**		
15:30	Margery Ryan	Johnson Matthey	Platinum group metals: an enabler for hydrogen, not a barrier
16:00	Eduard Ametller	HABONIM	Hydrogen service – an unprecedented benchmark for valve technology: challenges & solutions
16:30	Jamie Frew	12 TO ZERO	Floating wind, hydrogen and the green steel: entwined technologies propelling a low-carbon future
17:30-19:30	**Networking Reception**		

5 April	Speaker	Company	Presentation title
9:30	Catherine Gras	Storengy	Hydrogen storage in salt caverns – the Hypster project
10:00	Christian Kosack	Uniper Energy Storage	HyStorage – investigating the influence of hydrogen mixtures on a porous reservoir
10:30	Robin Lane	Gravitricity	Developing a flexible underground hydrogen storage solution
11:00	**Coffee break**		
11:15	Gregor Ziemann	H-TEC SYSTEMS	Accelerating the adoption of hydrogen: reducing the Levelized Cost of Hydrogen by going large scale
11:45	Christian Schnitzer	Evonik	Efficient AEM electrolysis with DURAION® membranes
12:15	Christian von Olshausen	Sunfire	SOEC electrolysis – the game changer for industrial applications
12:45	**Lunch**		
13:45	René Peters	TNO	The development of offshore hydrogen production to enable further growth of offshore wind in the Netherlands
14:15	Frank Sowa	DMT Group / HydroHub	Ammonia as hydrogen carrier – how to increase efficiency of hydrogen reconversion?
14:45	Peter Gless	Hydrogenious LOHC Technologies	LOHC technology – an important building block for flexible and demand-oriented hydrogen supply to decarbonize the steel industry
15:15	**Coffee break**		
15:30	Yannick Dandois	Vinçotte, member of group Kiwa	From electricity to hydrogen: the impact of electrolyzers on process safety risks
16:00	Thomas Gallinger	TÜV SÜD	H2-ready? Product and plant quality assessment by third parties
16:30	Hans Jonk	Gasunie Energy Development	Hyperlink: developing a hydrogen network in North-West Germany

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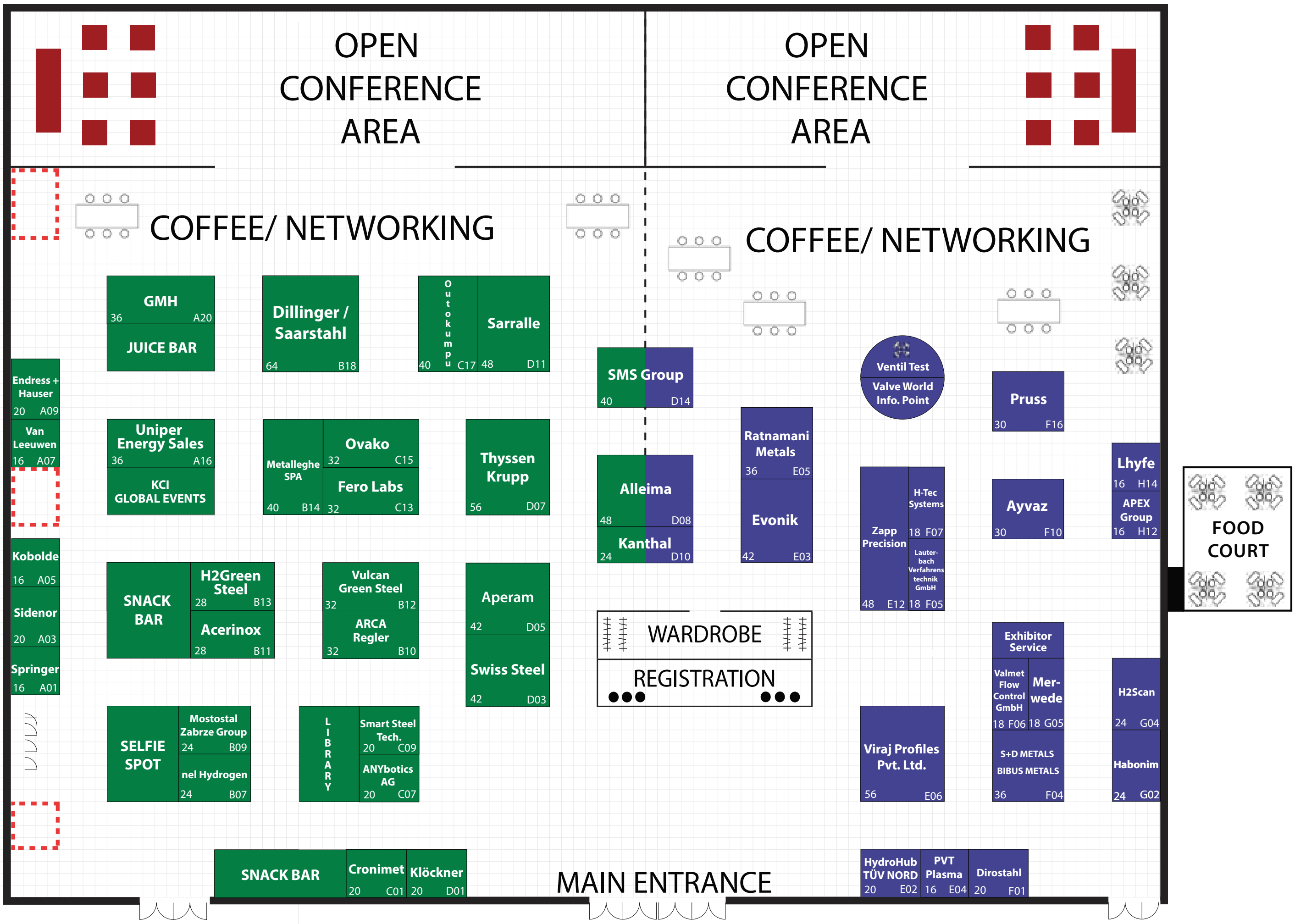

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