GLOBAL HYDROGEN REVIEW

Autumn 2022

WHY THE FUTURE IS HYDROGEN?

The Honeywell approach to accelerate the energy transition.

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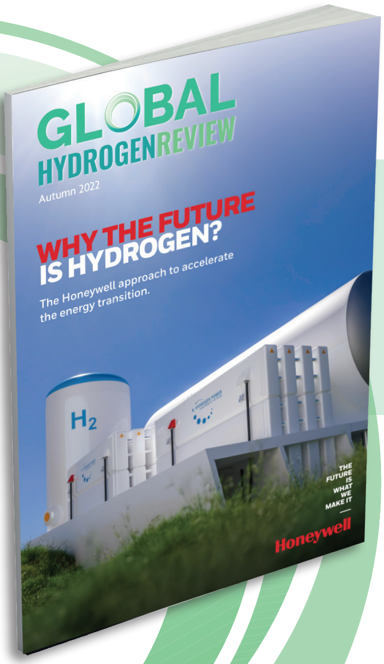

This month's front cover

The road to clean hydrogen production begins with operational efficiency. Proven, industrial-grade software is critical for establishing proper data infrastructure and supporting intelligent operations. Optimising operations through data-driven decision making will put hydrogen producers on a sustainable, low-carbon path to achieving a net zero future.

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COMMENT

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The *Global Hydrogen Review* team recently exhibited at ACHEMA – the giant trade show for the international process industries, which took place in Frankfurt, Germany. It was great to be back amongst the industry, and to catch up with friends and colleagues. Walking around the show, it was also striking to see the acceleration of the hydrogen sector. Hydrogen technology and solutions were proudly on display at many of the exhibition booths, and the burgeoning sector formed a key part of the congress agenda. Indeed, day one of ACHEMA was dedicated to the hydrogen economy, with a series of presentations covering topics including process analytics, modular automation, compression and much more, as well as a special highlight session devoted to the topic of unlocking hydrogen's future potential.

This session saw interesting presentations from Jürgen Nowicki, Executive Vice President and CEO of Linde Engineering, and Robert Schlögl, Director of Inorganic Chemistry, Fritz-Haber-Institut of Max-Planck-Society, as well as a heated panel discussion. A key takeaway from this session was that it is necessary to start thinking pragmatically about the hydrogen economy. While it is clear that green hydrogen will have a key role to play in the world's future sustainability strategy, Mr Nowicki stressed that we shouldn't focus too heavily on the colour of hydrogen at this stage. Current electrolyser technology is small scale and the process of building up the necessary infrastructure will take some time. Another hurdle for green hydrogen is that there is currently not enough renewable energy to make it viable on a large scale. As such, Mr Nowicki warned that the industry risks wasting time if it holds out for the green hydrogen revolution (and simply continues with its old – heavily CO_2 emitting – processes in the meantime). Instead, he suggests that we should look to provide hydrogen – regardless of its colour – as quickly as possible, and in sufficient quantities, to enable the industry to get going. And while we are laying the foundations for the sector, we can ensure that the path forward is as green as possible into the future.

Global Hydrogen Review is an open house to the entire rainbow of hydrogen production. And just like trade shows including ACHEMA and Gastech – where you can register for a free subscription to *Global Hydrogen Review* at stand 15N60 – we aim to provide a platform for a wide-ranging discussion of the technological innovations that will help to drive the hydrogen sector forward, regardless of colour. This issue of *Global Hydrogen Review* is packed full of detailed technical articles covering a range of topics including digitalisation, pipelines, turboexpanders, decarbonisation of the maritime sector and, of course, blue and green hydrogen production. If you have a take on the advancement of the hydrogen sector, we want to hear from you too. Please reach out using the contact information on the left of this page.

And don't forget to register for your free space at our *Global Hydrogen Conference.* Taking place on 16 November, this virtual conference will include a number of presentations from key industry players, as well as live Q&A sessions and networking opportunities. Turn to p. 57 and scan the QR code to secure your free space at the show.

THE KEY TO BUILDING SUCCESSFUL VALUE CHAINS

Jørg Aarnes, Energy Systems at DNV, Norway, explores key trends in hydrogen production, transport and end use.

From very little demand today, hydrogen and derivatives such as ammonia will account for 5% of world energy demand by mid-century, according to DNV's new 'Hydrogen Forecast to 2050'.[1]

To meet the targets of the Paris Agreement, the most likely forecast for the uptake of hydrogen and derivatives would need to triple, with governments backing urgent, significant policy interventions to scale hydrogen to meet around 15% of world energy demand by mid-century. However, from DNV's research and the 5% demand that has been forecast, there are already many lessons to learn about the value chains that will connect and scale hydrogen as an energy carrier.

This article explores key trends in hydrogen production, transport and end use, focusing on the lessons learnt for building successful value chains on the path to enabling societies to embrace the urgent decarbonisation opportunities presented by hydrogen.

Competitiveness and ability to scale are crucial

Competitiveness is crucial to determining successful value chains. This includes competition within and across hydrogen production, transport and end use, but more crucially taking an energy systems perspective to evaluate how hydrogen value chains compete with other technologies, such as electrification.

This is not just about linking production to consumption; it also involves considering energy efficiencies and losses, economics, greenhouse gas emissions, and geography — in terms of both location for transport, and resources such as natural gas and renewable energy for production.

The ability to scale is also essential. Hydrogen supply needs to grow together with demand, which generally requires a gradual pathway that avoids economic, technical and system risks. This will require the management of safety risk and public acceptance, innovation to bring down costs, and the employment of policies to make hydrogen projects competitive and bankable.

One of the key questions is: when will the world move from hydrogen projects to a hydrogen economy? Most large hydrogen projects within the next decade will likely require offtake agreements and a full value chain perspective to get off the ground. A hydrogen economy, however, requires flexible value chains that mix and match options in production, transport and end use. This will be underpinned by enabling infrastructure, certification and standards to ease trade and interoperability, and by flexibility mechanisms – such as hydrogen blending – to balance supply and demand.

Hydrogen value chains for energy use are in their infancy

Hydrogen is already a large and thriving industry, however it is not low-carbon hydrogen production and energy use that is thriving today. Global demand for non-energy hydrogen is around 90 million tpy (2020). To put this into perspective, DNV forecasts that demand for hydrogen as an energy carrier will not reach this level until the early 2040s.

The hydrogen currently produced comes from coal or natural gas without carbon capture, producing emissions greater than the carbon dioxide (CO_2) emissions of France and Germany combined. It is produced at or close to where it is consumed, predominately used in fertilizer or for chemical feedstock, and is used by relatively few large industrial users.

This is wildly different from the low-carbon energy use value chains of the future. For hydrogen to play a meaningful role as a strategic decarbonised energy carrier, new value chains and the development of hydrogen markets will be required. Many different hydrogen value chains will develop. This is partly due to the versatility of hydrogen: it can be produced from coal, natural gas, grid electricity, or dedicated renewables; it can be stored, transported and used in its pure form, blended with natural gas, or converted to derivatives such as ammonia; and it can be consumed across a range of industries and applications, including maritime shipping, heat production, road transport and aviation.

This, of course, has significant costs. DNV forecasts that global spend on producing hydrogen for energy purposes from now until 2050 will be US$6.8 trillion, with an additional US$180 billion spent on hydrogen pipelines, and US$530 billion on building and operating ammonia terminals.

Hydrogen production: managing cost in the shift to low-carbon

Hydrogen will undergo a shift to low-carbon production. The major factors determining this are the level of emissions and cost (both of the production method and its competition). Scaling renewable energy generation and carbon capture and storage (CCS) is also essential to enabling the production of low-carbon hydrogen.

Green hydrogen will increasingly be the cheapest form of production in most regions. By 2050, DNV forecasts that 72% of hydrogen and derivatives used as energy carriers will be electricity-based, and 28% blue hydrogen from fossil fuels with CCS, down from 34% in 2030. Some regions with cheap natural gas will have a higher blue hydrogen share.

Grid-based electrolysis costs will decrease significantly towards 2050, averaging around US$1.5/kg by then – a level that in certain regions will be matched by green hydrogen from dedicated renewable electrolysis, and by blue hydrogen. The global average for blue hydrogen will fall from US$2.5/kg in 2030 to US$2.2/kg in 2050. In regions with access to cheap gas, such as the US, costs are already US$2/kg. Globally, green hydrogen will reach cost parity with blue within the next decade.

Transport: cost and derivatives

The future of the hydrogen value chain will rely on developing infrastructure for low-cost distribution and delivery.

Cost considerations will lead to more than 50% of hydrogen pipelines globally being repurposed from natural gas pipelines, rising to as high as 80% in some regions, as the cost to repurpose pipelines is expected to be just 10 – 35% of new construction costs.

The long-distance transport of hydrogen requires substantial infrastructure investments, and there are considerable benefits to keeping transport distances as short as practicable. DNV forecasts that hydrogen will be transported by pipelines up to medium distances within and between countries, but almost never between continents. Ammonia is safer and more

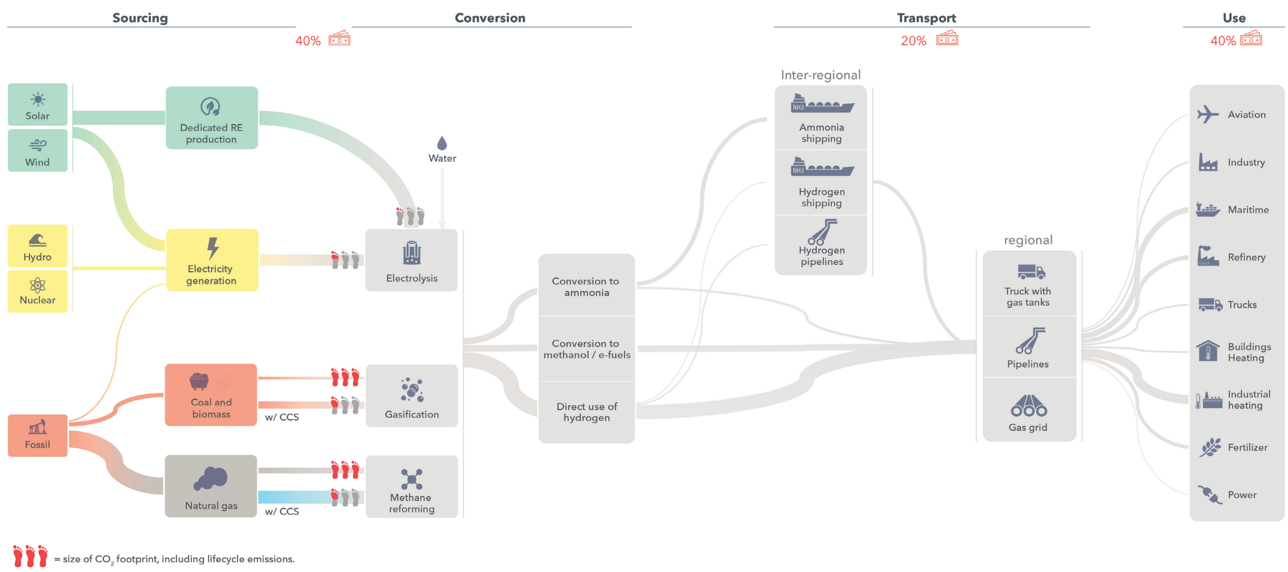

Figure 1. Hydrogen production and use flows in 2050 (the thickness of the flow lines approximates the volume of each flow indicating major production routes and end uses in 2050). Source: DNV 'Hydrogen Forecast to 2050'.

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convenient to transport, e.g. by ship, and 59% of energy-related ammonia will be traded between regions by 2050.

End use: prioritising hard-to-abate sectors

Hydrogen is expensive and less efficient than direct electrification in most cases. It makes sense to electrify the sectors that can be electrified, particularly in energy systems without extensive gas infrastructure.

In sectors that are difficult or impossible to electrify, such as in aviation, shipping, and high-heat industrial processes, hydrogen is desperately needed. In countries such as the UK, hydrogen will also see some use for heating buildings, as existing gas networks have the potential to deliver hydrogen to end users at lower costs than a wholesale switch to electricity.

Direct use of hydrogen will be dominated by the manufacturing sector, where it will replace coal and gas in high-temperature processes. These industries, such as iron and steel, are also where the uptake will first start, in the late 2020s.

Hydrogen derivatives such as ammonia, methanol and e-kerosene will play a key role in decarbonising the heavy transport sector (aviation, maritime, and parts of trucking), but uptake is only forecast to scale up in the late 2030s.

DNV does not foresee hydrogen uptake in passenger vehicles, and only limited uptake in power generation. Hydrogen for heating of buildings, typically blended with natural gas, has an early uptake in some regions, but will not scale globally.

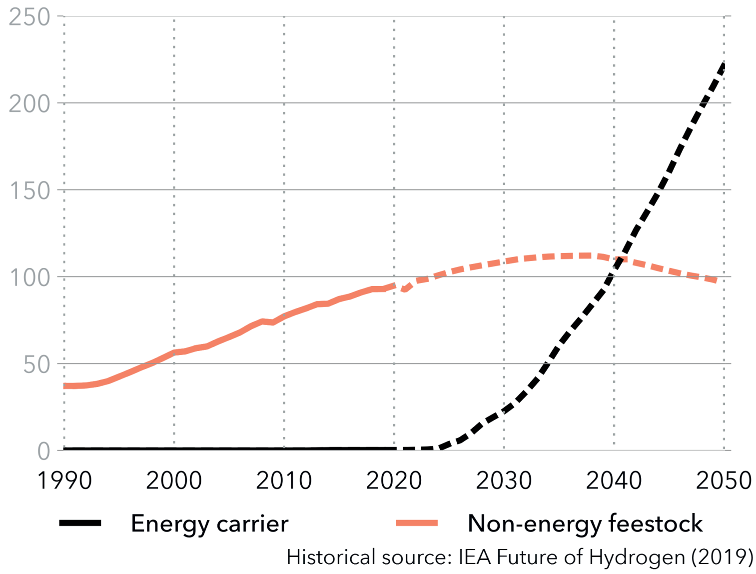

Figure 2. Global demand for hydrogen and its derivatives, by purpose (million tpy).

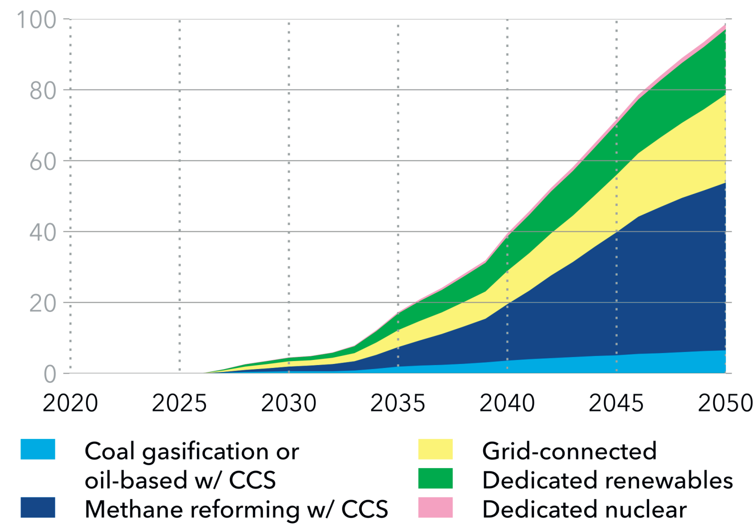

Figure 3. Global production of hydrogen derivatives as an energy carrier, by production route (million tpy hydrogen).

Managing safety risks

Safety (hydrogen) and toxicity (ammonia) are key risks. It is also important to manage both public perception risk and financial risk in order to ensure increased hydrogen uptake. Hydrogen is crucial for decarbonisation, and safety must not become its achilles heel. DNV is leading critical work in this regard: hydrogen facilities can be engineered to be as safe as or safer than widely-accepted natural gas facilities.

Safety measures must be designed into hydrogen production and distribution systems, and these need to be properly operated and maintained throughout their life cycles. The same approach must extend to the hydrogen carrier, ammonia, which will be heavily used to decarbonise shipping. There, toxicity is a key concern, and must be managed accordingly.

Managing investment risk

Hydrogen investment is intrinsically linked to wider energy investment trends. While increased risk in fossil fuels is driving significant capital to look for a new home in the energy transition, it is not necessarily the case that this capital will flow into hydrogen.

Capital will only flow into projects that are bankable. Energy companies and investors need to ensure that hydrogen projects offer a balance between risk and return. This requires long-term stability, certainty, and line-of-sight, which can be strengthened by business models and long-term agreements, the regulatory environment, government support, partnerships, and technological innovation.

The market's maturity is also essential, with investment risk reduced by greater certainty of demand – now and in the future. An ever-present worry for companies investing in hydrogen production is where the demand will come from, at what level, and crucially, when. The core issue is that from a financing perspective, hydrogen opportunities are currently long-term, low-return, and seemingly high-risk.

Greater policy interventions needed to scale hydrogen

The foreseen low and late uptake of hydrogen suggests that for hydrogen to play its optimal role in the race for net zero, much stronger policies are needed to scale beyond the present forecast, in the form of stronger mandates, demand-side measures instilling confidence in offtake to producers, and higher carbon prices. The policies and regulations set to have the most impact on scaling hydrogen can be split into six categories:

- National strategies, with timelines and targets, are the first step to creating a stable planning horizon and certainty for stakeholders. The second step is to establish more costly fossil-energy carriers until hydrogen value chains become economically-viable.
- Technology-push policies are needed to advance technologies along the entrepreneurial and technology development cycle – from R&D and piloting, to scaling up. Government funding programmes with investment grants/loans to CAPEX will be the dominant early-stage form of support.
- Demand-pull policies are needed to create demand for renewable and low-carbon hydrogen in new applications, and for the established non-energy hydrogen industry to switch from unabated fossil fuels. Government funding programmes are also available to hydrogen consumers to cover CAPEX required to convert process technology and equipment for use in hydrogen applications. This alleviates the ever-present worry about where the demand will come from, at what level, and crucially, when, for companies investing in hydrogen production.
- Fiscal policies, such as carbon pricing, pass on carbon costs to emitters, encouraging the use of low or zero-carbon hydrogen. They are needed to stimulate innovation and close the cost gap between conventional unabated fossil fuel-based technologies and new hydrogen-based technologies. New market-based instruments, such as contracts for difference (CfD), can help lower operational costs and provide predictable terms for both producers and end users.
- Certification schemes are key to scaling the hydrogen economy and fostering international trade. One of the key aspects is the carbon intensity of the hydrogen produced, in order to guarantee that the hydrogen is in fact contributing to decarbonisation targets being met. Certification of hydrogen would give both producers and consumers the confidence – and ability to show – that a switch to hydrogen will support their decarbonisation efforts.
- Standards provide clarity and harmonisation on the technical and safety aspects of hydrogen needed to ensure secure and reliable supply. International collaboration is pulling government and industry players together, facilitating harmonisation and the exchange of best practices.

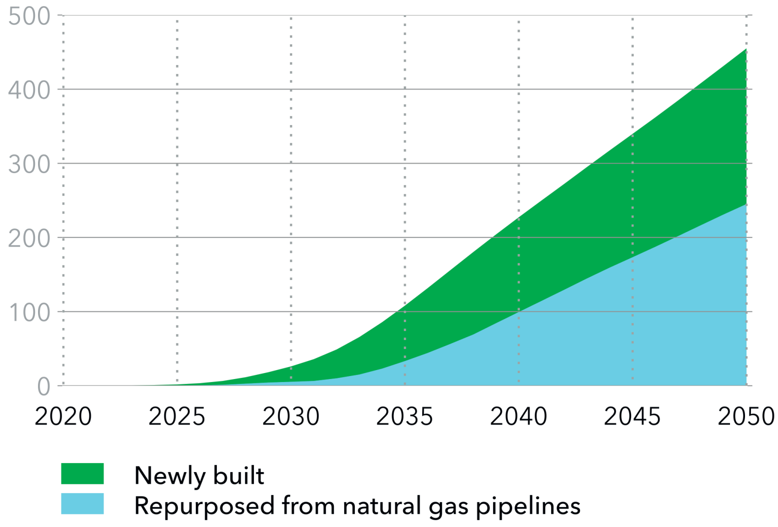

Figure 4. Global hydrogen pipeline capacity (TW-km).

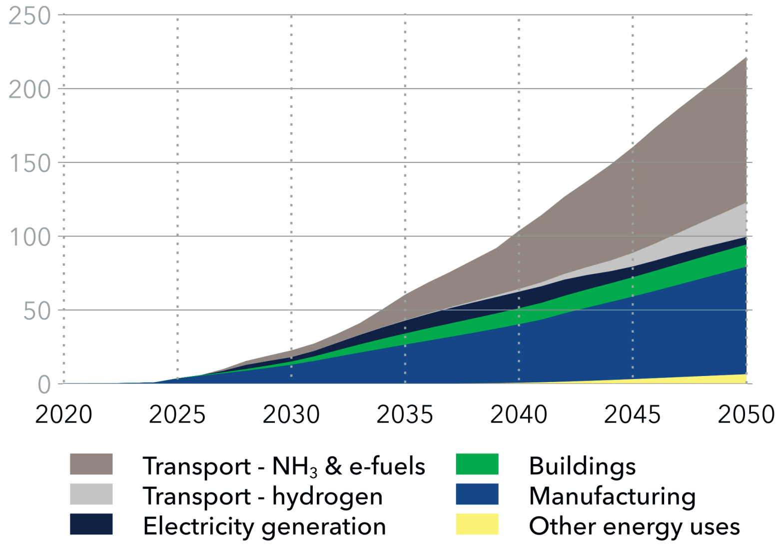

Figure 5. Global demand for hydrogen and its derivatives as an energy carrier, by sector (million tpy hydrogen).

The future of hydrogen: take an energy systems perspective

Hydrogen is essential to a clean energy future, but a big lift is needed if the world is to the reach the Paris Agreement goals. There is no other energy carrier that can decarbonise the hard-to-abate energy sectors at scale. While there are many challenges to overcome across production, transport and end use, the overarching challenge is to take a systems approach to hydrogen: building successful, competitive, low-carbon hydrogen value chains.

DNV's 'Hydrogen Forecast to 2050' takes an energy systems perspective. It provides the most likely future for hydrogen in the world's energy system, and deep dives into hydrogen production, transport and end use. It considers key enablers in safety, investment and policy, and provides pioneering examples of future hydrogen value chains.

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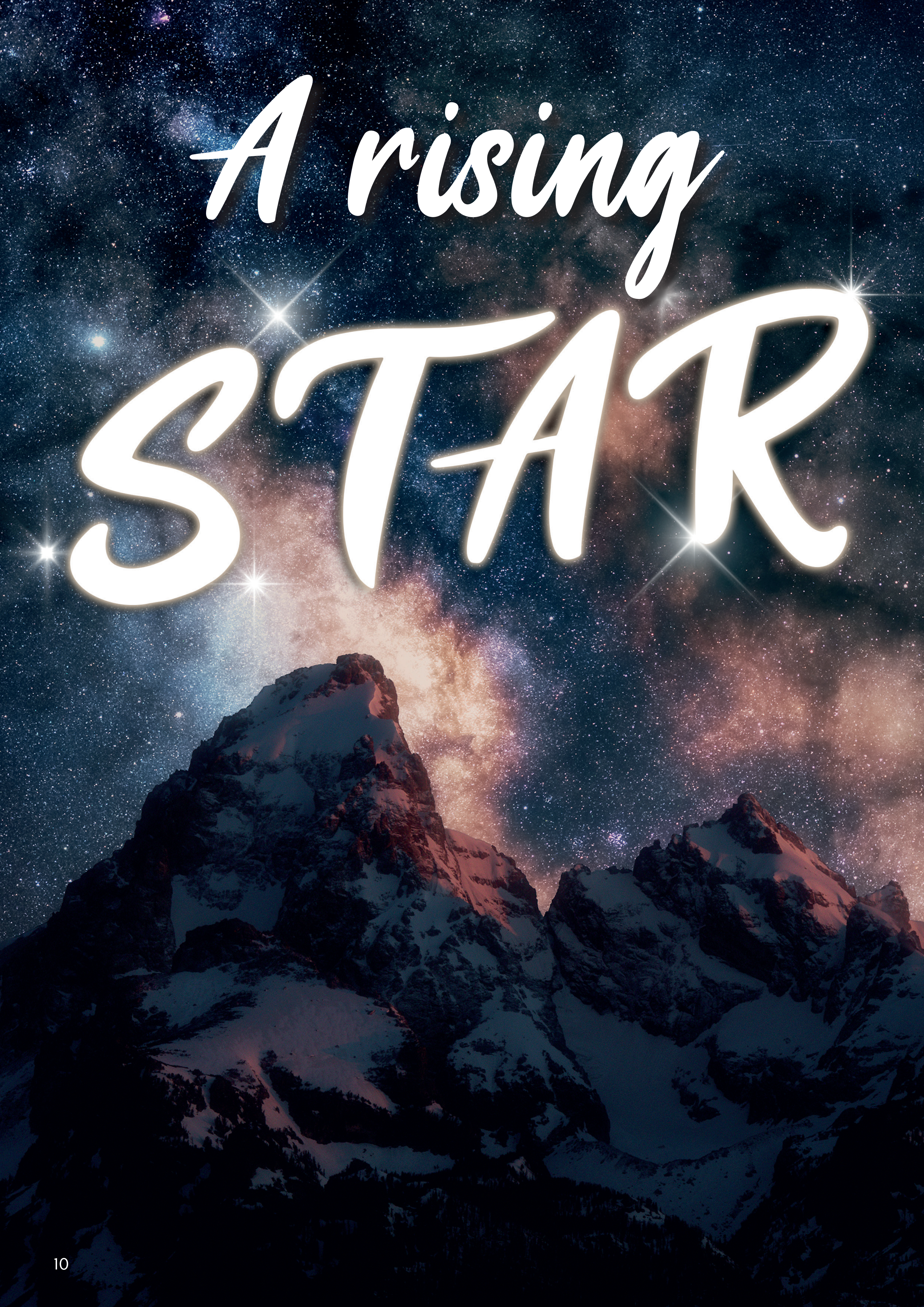

Dr Hans Dieter Hermes, Worley, discusses the challenge of scaling up clean hydrogen to meet the growing demand for this fuel of the future.

The global hydrogen market is forecast to grow 1000 fold by 2040, with demand for clean hydrogen projected to reach 500 million tpy between now and 2050.[1, 2] This is underlined by the EU pinpointing hydrogen as central to decarbonising European industry, transport, power and buildings.[3]

Why such demand for one product?

Clean hydrogen has the potential to decarbonise chemical, cement, iron and steel production, and provide combined heat and power from a single source. It will enable surplus energy from other sources to be stored and circulated across sectors and regions, creating a circular economy of renewable energy where wasted energy is continually recycled into power. This is why hydrogen is critical to the EU strategy of energy system integration, as it can produce heat and power from multiple sources.[4]

It is also a prime electrofuel – a renewably-sourced drop-in replacement fuel to rapidly decarbonise sectors such as shipping and aviation.[5] And crucially, hydrogen can provide renewable fuel for sectors including freight transport and shipping, which are unsuitable for direct electrification.

Recent international climate agreements have accelerated the demand for clean hydrogen. Yet there is a growing gap of a factor of 10 between global supply and demand for green and blue hydrogen over the next two decades. For example, in a microcosm of the global shortage, the current hydrogen capacity would need to be scaled up by a factor of 100 to power the commercial truck fleet in a country such as Germany alone. This is driving increasing industry demand for a more competitive levelised cost of hydrogen to encourage the necessary investment in extra capacity.

So, how can we establish sustainably lower-cost hydrogen derivatives compared to fossil fuels to keep them competitive and fade out government support in the future?

Cross-sector and international collaboration

Ramping up clean hydrogen production will require a mix of energy sources, underpinned by cross-sector cooperation and integration. This is because clean hydrogen calls for a blend of power sources, such as solar and wind-based energy, and a parallel convergence of previously-separate sectors and specialisms – from electrolysers and petroleum, to offshore wind and gas. A fragmented, siloed hydrogen value chain could act as a significant drag on development speed at a time when it is crucial to scale up production.

Hydrogen-based energy convergence is already taking shape in combined heat and power plants, offshore wind-to-hydrogen projects, hydrogen-fuelled transport, as well as household heating. Similarly, there are cross-sector consortiums of chemicals, heating, electricity, and green energy producers making green ammonia and e-methanol, and pioneering partnerships between fossil fuel and renewable energy firms to produce green hydrogen.[6, 7] With 'REPowerEU', the European Commission has presented an accelerated hydrogen strategy, targeting the production of 10 million t of clean hydrogen in the EU by 2030, and imports of another 10 million t from other countries.[8] So far, oil and gas exporting nations such as Oman, and new entrants such as Namibia, are well on their way to developing their position as future suppliers in the emerging clean hydrogen market.[9]

Breaking down sector siloes

However, this involves the challenge of breaking down national and sector siloes and uniting industries that have never worked together, as identified in 'From Ambition to Reality' – a paper written by Worley in collaboration with Princeton University, US.[10] The widely-varying standards, cultures, tools and technologies across relevant industries, from electrolysers to petrochemicals, could create disjointed development. For example, there could be conflicting business models, design approaches, and engineering methods across industrial clusters or partnerships. This means that incompatible tools and technologies could hamper cross-sector collaboration and data sharing. Similarly, there could be a culture clash between project partners with contrasting corporate cultures, such as chemicals or wind.

Figure 1. Mock-up onshore solar and wind farm.

Figure 2. The green hydrogen and ammonia process.

Hydrogen standards

There is a growing demand for global standards to ensure that there are consistencies with technologies, processes, safety, and sustainability across the hydrogen value chain. Cross-sector energy system integration requires cross-sector oversight and harmonised standards or regulations. If EU hydrogen legislation was streamlined and aligned with hydrogen industry representatives and voluntary initiatives under the umbrella of the Hydrogen Act, this would ensure that there is consistent, safe and sustainable production across sectors and countries.[11, 12] This would provide a benchmark for best practices across all industries involved in clean hydrogen, and help to harmonise diverse efforts around common objectives.

Connecting a diverse ecosystem

Integration also requires project management specialists spanning every relevant sector to act as an ecosystem hub connecting all hydrogen tools, technologies, sectors and suppliers. Neutral conveners would help to ensure that there is a seamless integration of diverse project partners, policies, people and processes. This would enable the industry to avail of 'optioneering', drawing on the full array of tools to find the optimal mix of best-in-class solutions for everything from cost to carbon efficiency.

As an example of this, Worley provides asset integration services, including selecting the best blend of technologies to develop Shell's pioneering Holland Hydrogen I green hydrogen facility. This project will draw on the company's experience across multiple relevant sectors, from offshore wind to electrolysis, coordinating collaboration between Shell and an offshore wind farm to produce 50 000 – 60 000 kg/d of hydrogen.

This demonstrates how neutral conveners straddling multiple sectors can drive the holistic, 'whole system' asset integration and cohesive collaboration that is necessary for hydrogen. It offers a microcosm of how the wider energy sector could be managed as an interconnected 'system of systems' feeding clean hydrogen.

Importantly, this project shows how independent third-party organisations can provide neutral consultancy to help industrial clusters or consortiums to select the optimal mix of products and processes from all sectors, for any hydrogen application. Vendor-neutral 'open' design standards for hydrogen could similarly create a shared ecosystem of hydrogen technologies, so that all projects are able to draw on a best-in-class blend of solutions.

The hydrogen revolution

The clean hydrogen revolution will require an unprecedented effort to unite industry, academia and government to develop a massive value chain spanning multiple industries and sectors. This energy system integration has the capacity to simultaneously decarbonise various industries – from transport to heating – and store and spread clean power and heat across our economy. However, a fragmented and siloed hydrogen value chain will mean that new generating capacity cannot keep pace with demand for decarbonisation.

Speeding up development will require us to harmonise diverse practices and technologies through common standards, regulations, project management models, and cross-sector specialists bridging multiple industries. There is a need for the creation of industrial clusters, consortiums, and public-private partnerships uniting industry, investors, governments and regulators to drive collaborative research and development.

Finally, there is also a demand for overarching frameworks for the standardisation and coordination of hydrogen production, storage and distribution. Ultimately, the aim is to manage the energy sector as a single interoperable ecosystem where energy sources, expertise and assets can circulate freely across sectors.

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ALL ROADS LEAD TO GREEN

Chris Jackson, Protium, UK, outlines the issues with 'bridging fuels', and explains why a change of mindset is essential in order to focus on cleaner alternatives, including green hydrogen.

In the last 30 years of climate discussions, it has become common for businesses, governments and investors to describe the energy transition as a series of bridges that need to be crossed, as new technologies are developed and deployed at scale. The problem is that these bridges often reinforce the very problem we are trying to resolve – namely a move away from fossil fuels and towards green alternatives.

This article will outline the challenges and limitations surrounding the energy transition, including issues with the current rhetoric on the topic. It will then discuss how this can be overcome by shifting focus to investing in, developing and deploying truly net zero solutions such as green hydrogen – the true bridge to sustained reductions globally, and a net zero future.

The challenge of our time is to find a series of strategies that are inclusive, economical, technically-feasible and deliverable by 2050, so that the world experiences global temperature increases of below 1.5°C. This is no easy task. Within the energy sector alone, we have just 28 years to deliver the largest energy sector transition known in economic history. The scale of that concept is challenging for almost everyone to comprehend and therefore requires some context. In the 120 years since the first commercially-recorded usage of electricity, in Thomas Edison's lighting micro-grids in New York, US, electricity's share of energy has grown from 0% of global consumption to approximately 20%.[1] Even after the industrial revolution, globalisation, and the material increase in global wealth witnessed over the last 40 years, around 20% of global primary energy usage still comes from traditional biomass i.e. wood, waste and other forms of energy for generating residential, commercial and industrial heat.[2] In short, energy transitions take enormous amounts of time and investment to deliver, yet we do not have much of the former, and we are not being fast enough on the latter.

Given the scale of the net zero challenge and the corresponding societal challenges that it presents, it has become fashionable to use the idea of bridging fuels/technologies/strategies in the energy sector to help the public, policymakers and investors to envisage a path from the present day towards a cleaner and (hopefully) more affordable future.

The first bridge solution, proposed in the early 2000s, was the idea that natural gas could play an intermediary role as a transition fuel from coal, and in some countries even away from petrol/diesel in the transportation sector. Natural gas has, in recent history, been low cost, produced considerably lower carbon dioxide (CO_2) emissions than almost all fossil alternatives, and is relatively efficient to store, transport and consume. As such, it was argued that a shift to natural gas would be more affordable, reduce CO_2 emissions, be technically deliverable, and require fewer changes to existing global infrastructure and supply chains.

Another common bridge solution has been the idea of hybrid cars instead of pure electric or fuel cell electric. These vehicles allow consumers to enjoy the benefits of internal combustion engines, namely fast refills, lower prices (than full electric vehicles [EVs]), and reduced range anxiety. They have also allowed vehicle original equipment manufacturers (OEMs) to broadly continue with business as usual, and existing fossil fuel producers to slowly taper down their production/distribution of fuel, without experiencing a sudden, rapid drop off in demand.

As the examples above demonstrate, the idea of bridge solutions can be very compelling intellectually. Systemic inertia has always been a major challenge for any policymaker to overcome. We are creatures of habit and even where there are cost advantages in transitioning to clean alternatives, consumers typically have a higher perception of risk when changing technologies than their perceived risk of changes to the status quo. This is notably the case in the context of energy, where changing consumer behaviour has always been challenging. Examples of this are the public resistance to turning down thermostats, the poor rollout of smart meters, and the challenges of convincing people to install loft insulation.

Similar challenges exist among business users where, despite consumer, investor and cost pressures, businesses have continued to use coal and fuel oil for heat generation in lieu of even well-established lower-emission options such as natural gas, let alone green gases, biomass and/or electrification-based technical solutions. Even after billions of investment globally in battery electric vehicles (BEVs), EV charging networks, public subsidies, and overnight time of use tariffs for almost 15 years, the International Energy Agency (IEA) estimates there are just over 10 million BEVs on roads globally, from a fleet of over 1.3 billion.[3]

Rapid change in energy systems is also challenging for investors, regulators, utilities and energy supply chains. Infrastructure is by its nature a long-term game. To build a new offshore wind farm in the UK takes roughly 12 years, while even onshore solar photovoltaic (PV) can take two to four years to permit at utility-scale.[4] Even these timescales seem like lightspeed when contrasted with nuclear power plants such as Hinkley Point C in England, and major public transport projects such as Crossrail (one of Europe's largest rail projects).[5] Thus, when facing these challenges, the temptation to say we should make a series of small, incremental changes to our system, with a series of bridge solutions that gradually move towards the desired end outcome, is enormous – but it is also flawed.

Something that sounds deceptively obvious but is often misunderstood is that our aim is to deliver a net zero carbon energy system; not to deliver a 60%, 80% or 90% reduction. To do this means that for every kg of CO_2 that we put into our climate from our primary energy sources, we require new technologies and/or nature to find a way to remove that additional kg from the climate balance sheet. The analogy given is often of a full bathtub, where the taps cannot produce more water than the drain can take away, otherwise the bath floods. In the global context this means that we must all recognise that either every country in the world must be carbon neutral by 2050, or (and indeed inevitably) some countries will have to be carbon negative by 2050, i.e. on balance the country must sequester more CO_2 than it produces in order to offset those which will not be carbon neutral.

Given the current state of global economic development, it appears improbable that India, Brazil, Nigeria, Indonesia and other leading developing markets will be able to achieve net zero by 2050. China has already stated that its target date is 2060. That means that for the developed world, i.e. the UK, the EU, North America and other Organisation for Economic Co-operation and Development (OECD) markets, emissions will not only have to be reduced to zero, but there will also be a need to help finance other means to offset the additional CO_2 that is being produced in the developing world.

What does all of this mean in practice?

There is no pathway to achieving net zero and preventing catastrophic climate change unless every developed country is able to either stop or capture at least 100% of its carbon emissions – and that does not include investments to sequester carbon. This means that every technology that we use that reduces emissions by 60%, 80% or even 95% cannot continue to operate after 2050, as they must all be zero carbon. Herein is the fundamental issue with bridge solutions, whether they be natural gas, its sister solution blue hydrogen, hybrid vehicles, or diesel for back-up power and off-road rail machinery. If they have to switch off in less than 30 years, why even invest today instead of committing to zero-carbon solutions now?

The average life cycle of most capital assets is at least 10 years, and for industrial and power generation assets it is frequently 20+ years. The average locomotive is 25 years[6], and the average truck is 14 years.[7] Thus, if we continue to invest in assets that are positioned as a bridge, in reality we are either investing in an already-stranded future asset, or a solution that will lock in fossil fuel usage at a level above the 1.5˚C trajectory.

Recognising that we must now focus only on investments that can ensure the delivery of a net zero energy system, and that we must avoid creating a new category of stranded assets, it is crucial to take a holistic system approach. In this context, green hydrogen is important. The process of splitting water using renewable power and water provides us with an energy vector that can deliver truly net zero solutions for a wide array of energy applications today. Commercially-available hydrogen boilers, burners, combined heat and power (CHP) systems and fuel cell vehicles are on the market and are being utilised across sectors such as food and drink, steel, data centres, warehouses, buses and trucking. There are also multi-billion-pound, hydrogen-derived green fuel projects under development that can produce green ammonia and green methanol, thus decarbonising existing industrial emissions for these products, and producing a drop-in fuel for retrofits to existing assets.

As a result of the flexibility that green hydrogen offers the energy transition – through its ability to create green molecules – we are now in a position where we can bypass misleading bridge technologies that require sustained fossil fuel usage, with the help of sustained investment. The defining features of the modern energy system are flexibility and storage, which allow us to access energy when and where we

need it. While solar PV, wind and various other renewable electricity technologies are competent at creating low-cost energy, these sources are intermittent and non-dispatchable. In short, we must either shift when we consume energy, or shift the renewable power we produce into a storable form, so that we can use it when there is demand. As such, green hydrogen's role in supporting the integration of renewables into modern power grids, while also enabling sector coupling where renewable power can become a renewable fuel for transport and industrial heat, will help to finally to break the last argument holding back a full-scale transition away from fossil fuels.

Conclusion

This article started by talking about the scale of the energy transition challenge. As of May 2022, the UN estimates that the world needs to spend US$4 trillion/yr until 2030 to ensure a net zero world by 2050.[8] This requires a 12x increase from present renewable spending, and an end to the continued public sector funding of fossil fuels, where the International Monetary Fund (IMF) estimates that US$5.9 trillion was spent on subsidising the fossil fuel industry in 2020 alone. This can only happen when we stop believing that fossil fuels are a bridge.

We have the tools to achieve net zero, but what we lack is the focus and commitment. Green hydrogen, working alongside other net zero technologies such as batteries, heat pumps, energy efficiency, digital tools, offshore wind, nuclear power and carbon capture (not for blue hydrogen), provides the world with the final key technology to enable a technically-viable transition to a net zero energy sector by 2050. Now is the time to prove it.

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CERTIFIED SUSTAINABILITY

Michael Landspersky, TÜV SÜD Industrie Service, Germany, discusses how hydrogen producers and distributors are preparing for future mandatory certification.

To unfold hydrogen's full potential as a climate-friendly energy carrier, standardised criteria for assessing its sustainability needs to be established. This assessment must include all emissions along the entire supply chain.

Around 600 billion m³/yr of hydrogen is produced worldwide, and demand continues to grow – from the production of nitrogen fertilizer in the chemicals industry, to fuel cell drives in the transport sector, and energy storage solutions for utility companies. Whilst the hydrogen that has been produced using renewable energy sources is classified as 'green', this does not prove that it is also sustainable.

Stages along the supply chain – such as emissions caused by plant operation or transport – are sometimes left out of the calculations. In addition to this, the level of emission reductions required is not always clearly defined. Yet emissions caused by transport may significantly impact the carbon footprint of hydrogen, particularly if the production and consumption locations are geographically distant from each other.

While third-party certification of sustainability is the sole means of ensuring a chain of custody – in other words, transparency across the entire value chain – the only schemes and standards available to date for this type of certification have been on a voluntary basis.

The EU: a pioneer on the hydrogen market

In an emerging market, guarantees of origin (GOs) and proofs of sustainability (PoS) can be critical for the competitiveness of hydrogen. By working with existing certification schemes, producers and distributors can gain guidance and knowledge of the requirements of the sales markets, and thereby get off to a headstart. As part of the process, they also familiarise themselves with the complex issue of carbon emission accounting.

Seeking to reduce emissions and reach carbon neutrality, the EU published its hydrogen strategy in 2020, which outlines specific steps for establishing a clean hydrogen economy.[1] In the long run, the strategy aims at using predominantly green hydrogen, to be produced by electrolysis with electricity from renewable sources. According to the EU, green hydrogen offers the greatest decarbonisation potential. However, since blue or turquoise hydrogen can also contribute to the reduction of greenhouse gas (GHG) emissions, these forms might be acceptable throughout the transition period, but cover the risk of lock-in effects that could delay the full performance of green hydrogen supply.

To date, no binding legal definition of green or sustainable hydrogen has been drawn up. The European Commission is currently developing a regulatory framework for the use and funding of green hydrogen. In the transport sector, the use of green hydrogen is governed by the Renewable Energy Directive (RED-II, 2018/2001/EU). Its scope is likely to be expanded in the future to include heat and electricity generation, as well as use in the steel and chemical industries.

With RED II, the EU is developing a promising market for green hydrogen in the transportation sector. Renewable fuels of non-biological origin (RFNBO) can count towards the fuel quota that is required for meeting minimum renewable fuel targets. For the transport sector – the only sector that has failed to reduce its GHG emissions over the past few decades – this marks an important first step towards climate protection.

The large volume of enquiries received by TÜV SÜD – mostly from South America and the near East – asking about the definitions of and certification requirements for green hydrogen prove this emerging market to be a highly promising one. These regions offer many opportunities for using energy from renewable sources. Given this, Germany is not the only country preparing to produce green hydrogen; many other countries worldwide are following suit.

As RFNBO schemes are still in development, stakeholders can currently choose to be certified according to voluntary standards. They can choose between two different basic approaches – book and claim, and the mass balance method.

Book and claim

CertifHy, a consortium of experts from the worlds of technology, politics and law, led by HINICIO, was initiated in 2014. TÜV SÜD is also a member of this consortium. Its GOs are aimed at increasing transparency for consumers and creating incentives for the production of sustainable hydrogen. The GOs are distributed in accordance with the book and claim principle (i.e. they are traded separately from the delivery of the hydrogen itself), and consider only the emissions caused by production. By purchasing and cancelling a GO, consumers prove that they have supported the production of green hydrogen.

CertifHy differentiates between green and low-carbon hydrogen: the CertifHy Green Hydrogen certification applies to hydrogen produced with the help of biomass, wind, solar or hydropower, while CertifHy Low-Carbon Hydrogen also permits the use of conventional but low-emission energy and carbon capture and storage (CCS). The emission ceiling for sustainable hydrogen is 36.4 gCO_2eq/MJ of hydrogen.

Plans for the further development of CertifHy envisage the establishment of a voluntary certification scheme for RFNBO, in accordance with the EU Directive.

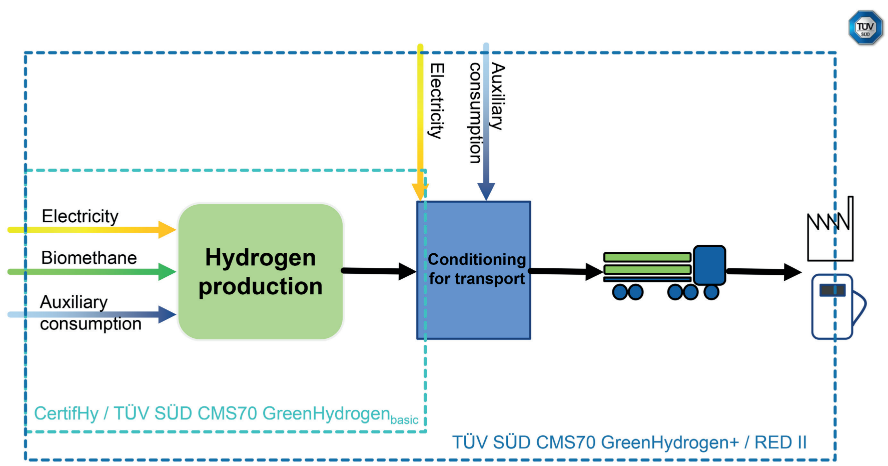

Figure 1. TÜV SÜD's green hydrogen scope.

The GreenHydrogen plus mass balance approach

Hydrogen producers and traders can also guarantee the sustainable origin of their products by opting for GreenHydrogen certification in accordance with the TÜV SÜD standard CMS 70 GreenHydrogen plus. However, for the GreenHydrogen certification, the GHG reduction potential of sustainable hydrogen must be at least 70% compared

to that of conventional hydrogen. In addition to the GHG reduction potential, the standard defines requirements for feed materials and energy input regarding temporal and local correlation between electricity production and consumption. This certification is limited to hydrogen that is produced by one of the following methods:

- Electrolysis of water by means of electricity from renewable sources.
- Steam reforming of biomethane.
- Catalytic conversion of waste.
- Electrolysis of salt solutions by means of electricity from renewable sources.

The emission ceiling for the GreenHydrogen certification is 28.2 gCO_2eq/MJ of hydrogen. The crucial difference from the CertifHy GOs is that the GreenHydrogen plus certification also considers the emissions caused by transport and distribution. Using mass balance, hydrogen is recorded throughout the entire supply chain right up to the consumer, and can thus be transported together with conventional hydrogen.

GHG reduction potential of over 80%

Using the GreenHydrogen certification, TÜV SÜD was able to prove that a hydrogen facility offered an 80% GHG reduction potential. The plant owner produces the green hydrogen using a proton exchange membrane (PEM) electrolyser – a method that offers reliable and robust control even under load fluctuations, and produces high-purity hydrogen that can be used in fuel cells. The hydrogen made by this producer is subsequently fed into the natural gas grid as a substitute for natural gas, or supplied to hydrogen filling stations via truck trailers.

The PEM stacks are supplied with electricity produced from hydro and wind power, and achieve a total capacity of up to 6 MW. After electrolysis, the hydrogen is placed in interim storage at two different pressure levels: 8 MPa at level 1, for the gas to be subsequently fed into the natural gas grid; and 22.5 MPa at level 2, for the hydrogen to be filled into the truck trailers.

An assessment by TÜV SÜD covered electricity supply, service pressures, hydrogen purity and emissions – from production and processing, to transport and the end consumers. At 15 gCO_2eq/MJ of hydrogen, emissions were almost 50% under the required ceiling of 28.2 gCO_2eq/MJ of hydrogen. In the end, the certificate enabled the owner to prove a reduction in GHG emissions of over 80%.

Thinking of tomorrow, today

The chain of custody, as the transparency of sustainability along the entire supply chain is known, is turning into an increasingly important differentiator. Until the EU has completed uniform regulatory acts for defining green hydrogen, manufacturers and traders will benefit from voluntary certification standards. Companies opting for the GreenHydrogen certification by TÜV SÜD are getting ready for tomorrow's requirements today.

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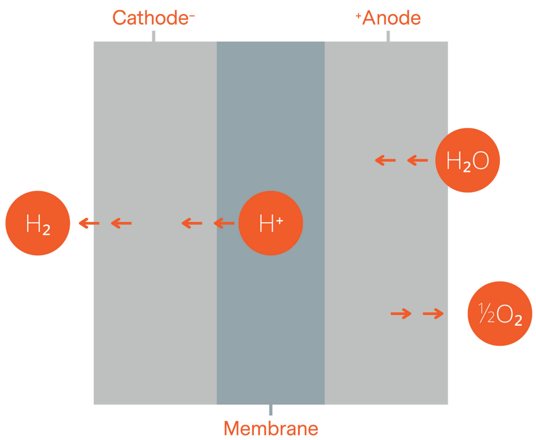
POWER UP YOUR POWER CHOICES

Andreas Breitkopf, Advanced Energy Industries Inc., USA, introduces new power control technologies that could improve electrolyser efficiencies and reduce lifetime operating costs.

At present, around 5% of hydrogen gas used worldwide is created by electrolysis, but according to market research firm, Industry Research, the global hydrogen electrolyser market is set for rapid growth of around 25% from 2022 to 2028.[1] This is driven by a variety of factors ranging from companies seeking more environmentally-friendly ways to produce this increasingly-important gas, and global commitments to increase electrolyser capacity in line with environmental commitments. As a result, it is estimated that global electrolyser capacities will reach an unprecedented 213.5 GW by 2040.

One of the key challenges for companies building and maintaining electrolysers is keeping operating costs as low as possible over the anticipated lifetime. Reducing the energy requirements of the high-power systems that provide the electrolyser's energy is therefore a key objective. These applications require high current approaches. This can be achieved by insulated bipolar gate transistor (IGBT)-based high power switching and silicon-controlled rectifiers (SCRs). These are also known as thyristors, and are commonly used for high-power, high-current applications because of their proven reliability, availability of suitable ratings of semi-conductor switches, robustness, long life, and simplicity.



$H_2O \rightarrow 2H^+ + \frac{1}{2}O_2 + 2e^-$ *Anode*

$2H + 2e^- \rightarrow H_2$ *Cathode*

$H_2O \rightarrow H_2 + \frac{1}{2}O_2$ *Total Reaction*

Figure 1. Overview of the PEM electrolyser.

This article will look at the power requirements of electrolyser systems, discuss the lifetime energy savings that even a few percentage points efficiency gains can bring, and explore how deploying SCRs for power control can help deliver these gains when compared to IGBT technologies.

Electrolysers: an overview

An electrolyser uses electricity to break water into its constituent parts, hydrogen and oxygen, through the process of electrolysis. They form an essential part of the green energy chain as the hydrogen they produce can be used in a multitude of applications – as can the oxygen that is a valuable byproduct of the process. There are several types of electrolyser available, depending on the size and function required.

Alkaline electrolysers are a well-proven and commercially-used method. They have been used on a large-scale since the 1920s, and use a liquid electrolyte (potassium hydroxide or sodium hydroxide) and water. The hydrogen is produced in a cell, appearing at the cathode when a current is applied, while oxygen is created at the anode.

High-temperature solid oxide electrolyser cells (SOEC) have great potential for the efficient and economical production of hydrogen by replacing the liquid electrolyte with a solid. They can operate at temperatures above 500°C.

The final electrolyser type, and the one that will be the focus of this article, is the proton exchange membrane (PEM) electrolyser that uses a solid polymer (usually formed from a special plastic) as the electrolyte. When a current is applied to the cell stack, the water is split into hydrogen

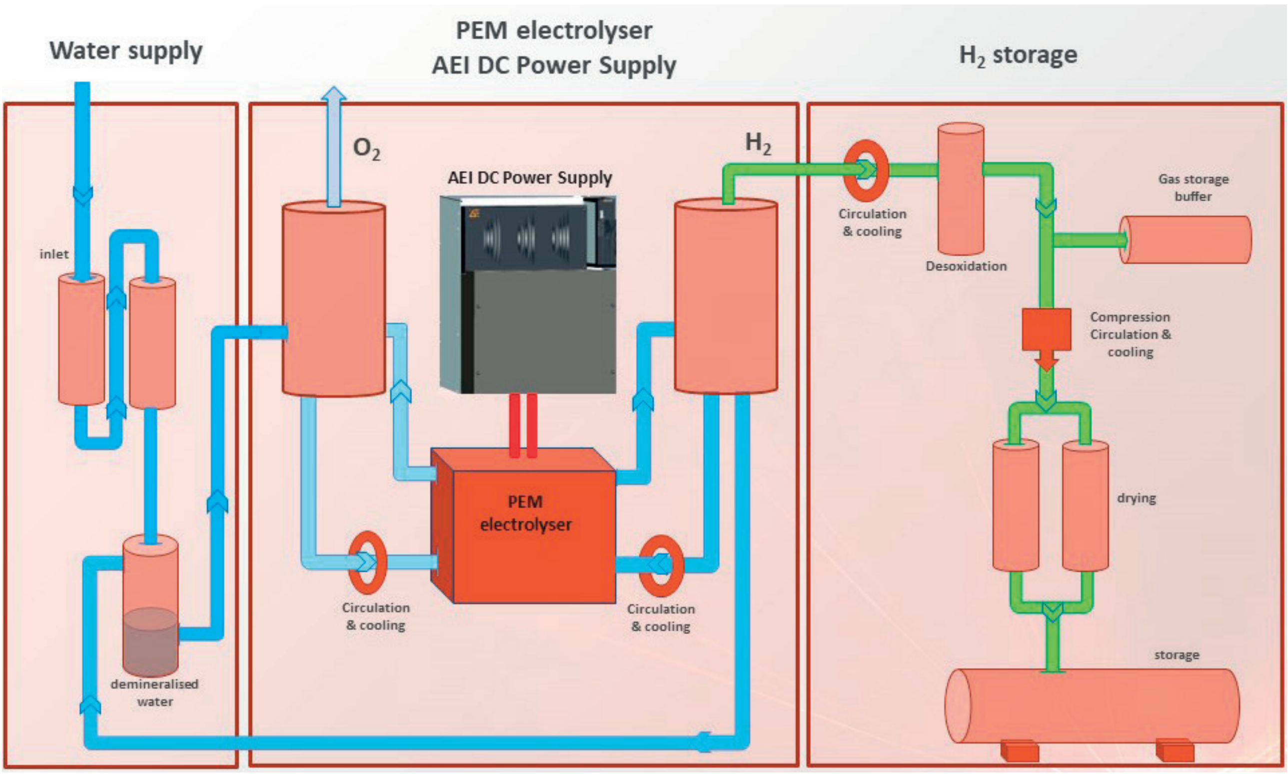


Figure 2. Block diagram of a typical electrolyser.

and oxygen. As the positively-charged hydrogen ions (protons) pass through the membrane, they form hydrogen gas around the cathode.

Beyond the electrolyser cell, the wider system consists of a water supply inlet with filtering and a storage tank for demineralised water that will be passed through the electrolyser. The power supply for the PEM electrolyser is a key element in determining the cost and performance of the system. A paper published by MIT estimates that the power solution makes up around 30% of total system costs – making it the most expensive single item.[2] Furthermore, with rising energy costs, the efficiency of the ACDC conversion process is critical to controlling operating expenses. With a 10 MW power supply, every percentage point of efficiency equates to 100 kW of losses, incurring the cost of the wasted power, as well as any cost associated with removing the waste heat from the system.

In some systems, the oxygen is simply released to the atmosphere as a harmless byproduct of the process, while in others it may be stored and used (or sold) as a valuable commodity. In all systems, the hydrogen gas is processed and stored. Initially, there is a deoxidation process, followed by compression and cooling before the gas enters a storage tank, ready for transport or use.

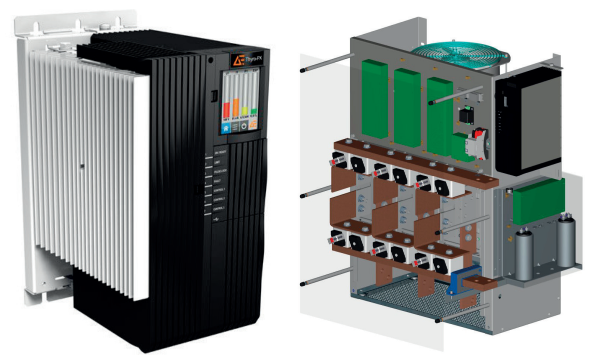


Figure 3. Modern SCR power controllers are sophisticated and highly efficient.

Table 1. Expected savings in a US installation

Price per kWh (US$)	0.10/kWh	T_{op}
Estimated operating hr/yr	7000 hr	T_{op}
Lifetime	15 yr	T_{op}
Efficiency of IGBT solution*	98.50%	η_{IGBT}
Highly-efficient AE B12 thyristor rectifier*	99.84%	η_{B12Rec}
Delta efficiency thyristor to IGBT solution	1.34%	Δ_{η}
Power losses savings	134.5 kW	P_{VS}
Annual energy savings	941 383 kWh	-
Annual cost savings	US$94.138	-
Cost savings across whole lifetime (15 years)	US$1 412 075	-

* Without fuses, transformer and chokes

The uses and market for electrolysers

Electrolysers are used to produce hydrogen for four main applications:

- Industrial: crucial industrial processes such as the manufacture of flat glass, steel and semiconductors all rely on hydrogen as an essential part of the process.
- Transportation: hydrogen can be used to power fuel cell-based electric vehicles (EVs) including buses, commercial vehicles, trains and boats. It is an environmentally-friendly solution that overcomes the long recharge times associated with batteries.
- Fuel processing: hydrogen is used in fossil fuel refineries for sulfur removal.
- Chemical production: hydrogen is also used in the production of environmentally-friendly chemicals such as fertilizers (ammonia), methanol and Jet-A1 fuel.

As there is growth in the applications that use hydrogen, the demand for the gas and electrolysers is also growing.

Hydrogen is a clean energy source, especially when the electricity used to produce it is also from a sustainable source. While power sector decarbonisation is currently centred around wind and solar power, these technologies rely upon nature and can be intermittent. However, hydrogen can play a role here, bridging the gaps when there is not enough wind or solar energy to meet the needs of the grid. Additionally, when solar or wind levels exceed the grid's needs, the excess electricity that is generated can be used to produce more hydrogen to be stored for future load levelling.

Another driver behind the growth in electrolysers is the move toward domestic energy production as nations seek to reduce the risks of being overly dependent on foreign energy sources. Hydrogen production is seen as an environmentally-friendly way of increasing sovereignty over energy supplies, while accelerating the journey towards sustainability.

DC power for electrolysers

Despite delivering power levels in the megawatt region, the requirements for ACDC power supplies for electrolysers are similar to smaller units: high efficiency, small in size, and reduced cost. In many applications, the power supply is integrated into a container along with the electrolyser, so the space can be limited.

Efficiency is crucial in designing these supplies. Significant power losses generate heat, especially for power levels that are often beyond 1 MW. As every percentage point of reduced efficiency represents 10 kW of loss at 1 MW (and 100 kW at 10 MW), inefficient power solutions require significant cooling, which increases size and cost. However, the use of water cooling can only improve the situation to a certain extent.

In applications such as steel plants that require constant (24 hr/d) hydrogen supply, the electrolyser runs constantly.

As a result, if losses are significant, operating expenses can rise dramatically.

The SCRs that are used in electrolysis must be highly reliable. This is especially important for applications that rely on a constant supply of hydrogen. Less obvious, but equally important, is the ability to control and monitor the power supply as part of an overall system.

There are various types of solution and technologies available to deliver the required power. At low power levels, MOSFET-based switch mode power supplies (SMPS) may be used, either by itself or in a parallel configuration. This will typically suit requirements of up to around 10 – 20 kW. As power needs increase, IGBT technology comes to the fore. While this does not offer the ultimate efficiency, it is a robust and established technology that generally produces fewer harmonics. The benefit of this is reduced filtering requirements. IGBT power is suitable for power levels of up to around 500 kW.

At the very highest power levels, where efficiency becomes critical – certainly above 1 MW – SCR technology is the preferred solution. While this may require more noise filtering than IGBT, it offers better efficiency and reliability.

SCRs: an introduction

Since their introduction in the 1960s, SCR power controllers have progressed from handling several hundred watts, to the megawatt region. Built around thyristors, these systems can switch electrical loads quickly for billions of operations. Compared to other solutions, they are more reliable and cost-effective, offer a finer degree of control, and require less maintenance.

SCR power controllers offer infinite resolution, allowing for the precise, accurate and stepless control of any load. Their solid-state nature (no moving parts) results in excellent longevity and an extremely fast response – typically within milliseconds. Perhaps the greatest benefit is their ability to deliver up to 99.8% efficiency, which exceeds all other technologies, including IGBTs.

Modern SCR power controllers (such as the Thyro family from Advanced Energy) include a wide range of features that simplify the design of electrolysers, including the ability to switch current, voltage or power, and control ohmic or reactive loads. A semiconductor fuse provides safe operation with the ability to auto-reset. Basic models include LED indication on the front panel, while more sophisticated versions may include a touchscreen to allow operators to monitor and control the unit.

Depending upon the sophistication required by the application, standard units may also include a communications interface (Ethernet/IP, Profibus, Modbus, TCP/IP, Profinet or EtherCAT), as well as multi-zone capability for several disparate loads. Most manufacturers also provide software to speed up the process of configuring the controller.

Potential energy and cost savings over the electrolyser lifetime

Using an SCR-based rectifier in different topologies could provide efficiency gains of between 1 – 2%. Table 1 is an example of the expected savings in a US installation.

Table 2. Expected savings in a German installation

Price per kWh for Germany (€)	0.17/kWh	T_{op}
Estimated operating hr/yr	7000 yr	T_{op}
Lifetime	15 yr	T_{op}
Efficiency of IGBT solution*	98.50%	η_{IGBT}
Highly-efficient AE B12 thyristor rectifier*	99.84%	η_{B12Rec}
Delta efficiency thyristor to IGBT solution	1.34%	Δ_{η}
Power losses savings	134.5 kW	P_{VS}
Annual energy savings	941 383 kWh	-
Annual cost savings	€160.035	-
Cost savings across whole lifetime (15 years)	€2 400 527	-

* Without fuses, transformer and chokes

Expected savings are calculated by increasing the efficiency of a 10 MW electrolyser system by 1.34%, from 98.5% to 99.84%.

Due to higher energy costs in most European countries, expected savings are even higher. Table 2 is an example of the expected savings in a German installation. Expected savings are calculated by increasing the efficiency of a 10 MW electrolyser system by 1.34%, from 98.5% to 99.84%.

Conclusion

As we transition to a green future, hydrogen is becoming more important within industrial processes, and as a fuel for vehicles. With the current energy crisis, countries are moving rapidly to increase control of their energy supply chain, and hydrogen generation is proving popular as it is relatively quick to establish – and environmentally-friendly.

The electrolysers that split water into its constituent parts (hydrogen and oxygen) are significant consumers of electrical power. As a result, to achieve the cost reduction targets for hydrogen, it is essential that these systems operate efficiently, and are compact and reliable.

While other options such as SMPS and IGBT controllers are available, these struggle to produce the power needed and/or achieve the very high efficiencies that are required. However, modern SCR power controllers are able to operate at efficiencies of as high as 99.84%, while providing a range of safety and operating features.

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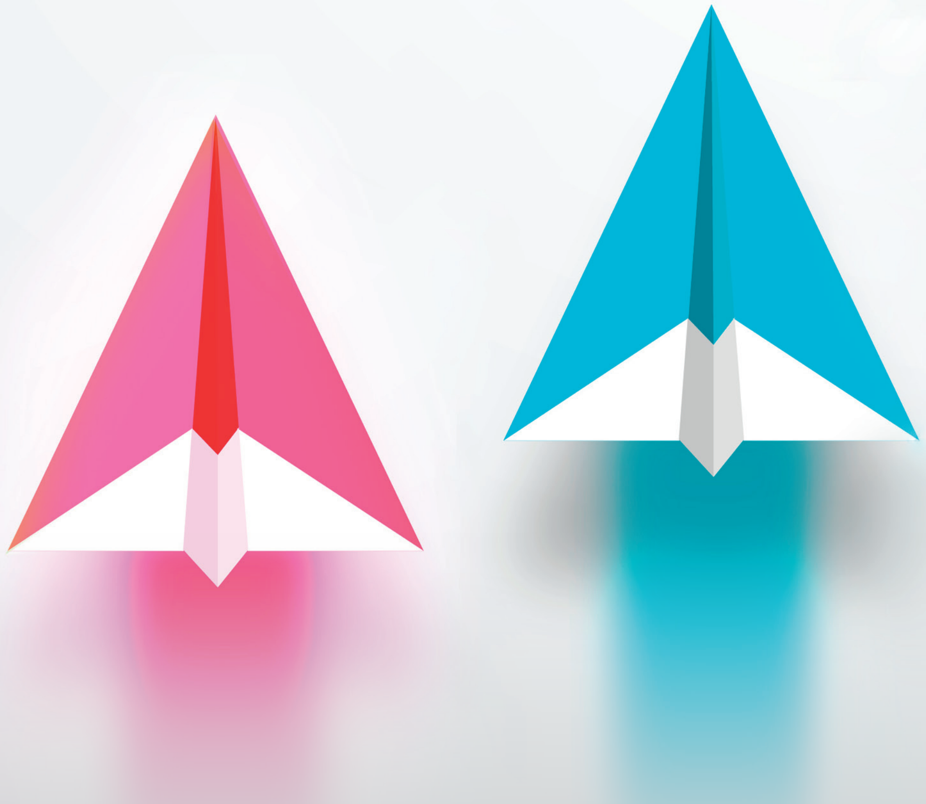
TURBO PRODUCTION TO MEET DEMAND



The upsurge in interest in hydrogen over the past decade comes on the back of its exciting potential as a carbon-free energy carrier in mobility and power applications. Historically, hydrogen has been used in refining, chemical processing, steel industries, and ammonia production. Today, the growing momentum for, and commitment to, clean fuel and energy has led to enormous opportunities for the turbomachinery industry within the hydrogen supply chain.

Hydrogen is typically produced by steam methane reforming (SMR), where syngas (hydrogen and carbon monoxide [CO]) is generated by the reaction of hydrocarbons with water. Hydrogen produced by SMR is considered grey when carbon dioxide (CO_2) is released to the atmosphere in the process. Blue hydrogen is produced in a similar fashion, only much of the waste CO_2 is captured to reduce its environmental impact. The future of hydrogen, however, is green – where hydrogen produced by electrolysis uses zero-carbon electricity sourced from renewables.

With renewable energy costs shrinking overall, green hydrogen production is becoming an increasingly viable solution, and scalable methods of storage and transport are being addressed. Hydrogen liquefaction is one of the few preferred methods to store and transport pure hydrogen. As countries across the world step up efforts to cut greenhouse gas emissions and achieve commitments to net zero by 2050, the demand for green hydrogen liquefiers

Louis Mann, Atlas Copco Gas and Process Division*; Jacob Thomas, JTurbo Engineering & Technology; and Trevor Mayne, Qenos Altona Olefins refinery, explore how turboexpanders in the petrochemical industry can advance the technology required for green hydrogen liquefaction.

is rising. As a result, the demand for turbomachines to carry out cryogenic hydrogen services is growing.

Turboexpander performance is critical

To produce liquid at standard pressure, hydrogen must be cooled to near 20 K. Radial inflow turbines, or turboexpanders, are commonly used to facilitate this required cooling through near isentropic expansion of a low boiling point refrigerant (hydrogen, helium, neon, or mixtures thereof). The turboexpander performance is critical to providing enough sub-cooling to the process. Changes in the specific heat near the critical point, and energy release during the ortho-para conversion in heat exchangers, require careful selection of system operating temperatures. Minor performance improvements in the turboexpander can greatly impact the specific power of the plant, and thus the economic viability of the operation.

Turboexpander design for hydrogen is challenging due to high isentropic enthalpy drop across the stage, low discharge volume, and the required high operating speeds. Hydrogen turboexpanders have unique aerodynamic and mechanical designs, including low-flow coefficient turboexpander wheels, high-peripheral speeds, heat soak and thermal management, special materials, and non-contaminating sealing systems. Practical challenges arise from hydrogen's flammability, resistance to being contained by joint seals, and its tendency to cause embrittlement in common materials. Moreover, when a turboexpander load is balanced by a high-flow coefficient booster compressor for energy recovery, unique rotordynamic challenges arise.

Hydrogen's physical and thermodynamic properties

Hydrogen is the lightest element in the universe and exists as a gas in standard conditions. With a molecular weight of 2.02, hydrogen has a low density, high specific heat, and high speed of sound.

Due to its low mole weight, hydrogen has high enthalpy difference (head) for a given pressure ratio. While head is comparatively high for hydrogen, density is exceptionally low, resulting in high volumetric flow rates and generally low energy per unit volume for turbomachinery. Conversely, low density of hydrogen also results in a high speed of sound, making Mach number limitations less of a concern.

Finally, hydrogen's inversion temperature of approximately 200 K or less (depending on the pressure) makes refrigeration via the Joule-Thomson (JT) effect unfavourable – if not impossible – above deep cryogenic temperatures. Refrigeration above or near the inversion temperature requires either external refrigeration or isentropic expansion, where additional energy in the form of work is removed from the gas. For decades, turboexpanders have excelled at performing this near-isentropic expansion.

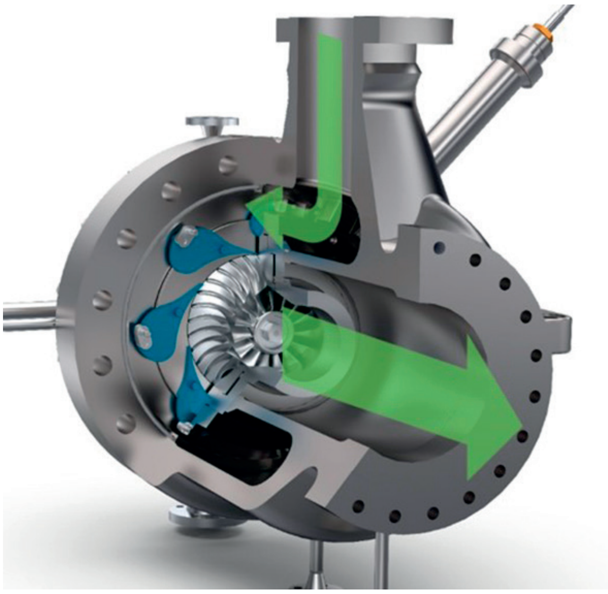


Figure 1. Radial inflow turbine, turboexpander.

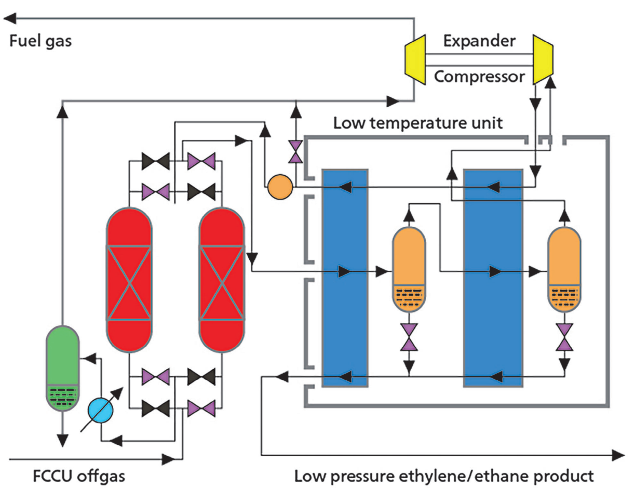


Figure 2. Ethylene treatment, distillation and recovery (source: Tomlinson 2002).

Turboexpanders

In a turboexpander (see Figure 1), high-pressure fluid passes through variable inlet guide vanes (vIGV), where potential energy is converted to high tangential velocities before entering an expander wheel in the radial direction. An ideal 90˚ turboexpander is a 50% reaction turbine, whereby approximately half of the enthalpy drop across the expander stage is used by the vIGVs to accelerate the fluid. The remaining expansion occurs in the turboexpander wheel, where the gas turns and exits at a lower pressure.

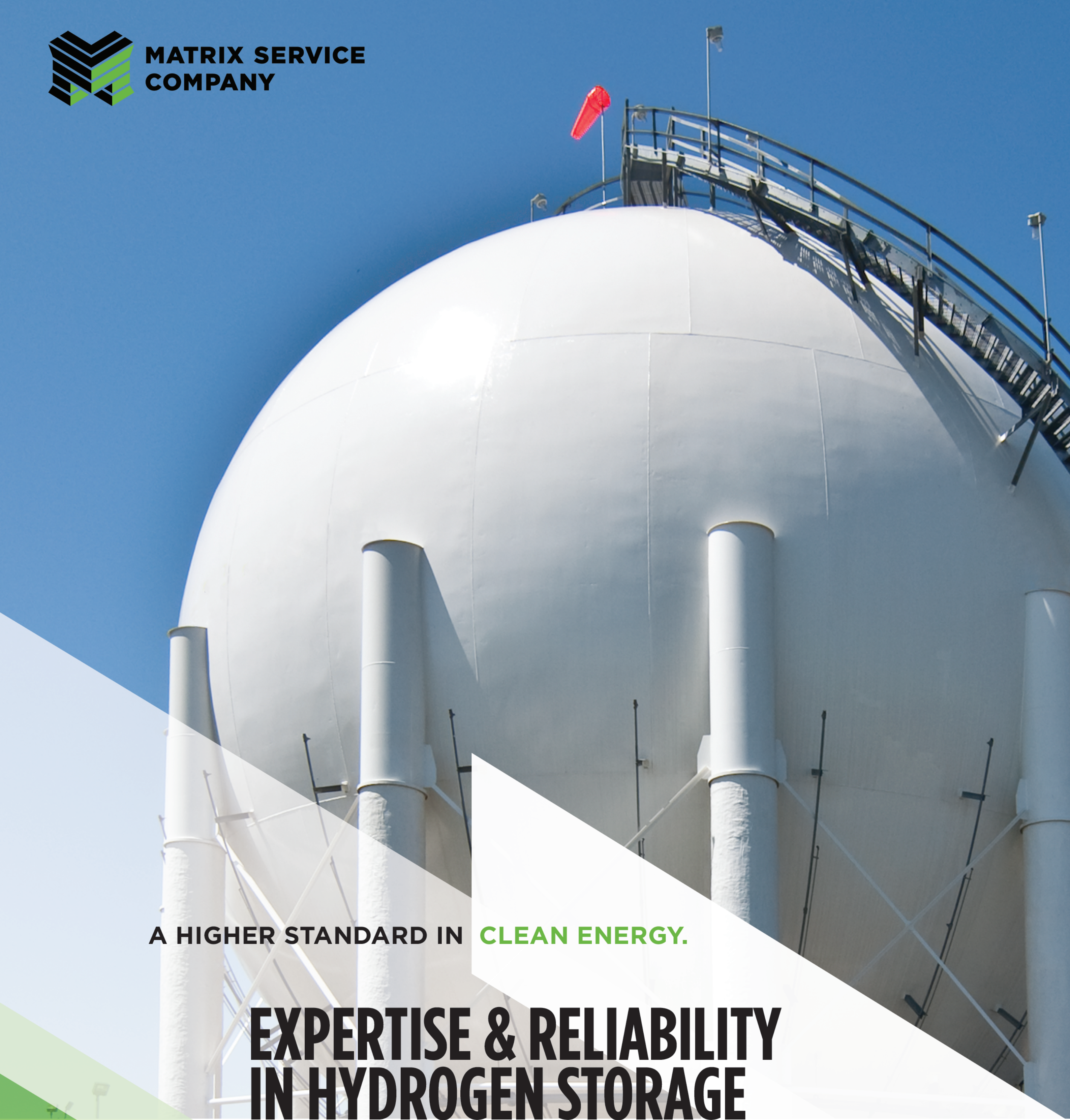
Expansion through a turboexpander is a near-isentropic process in which energy extracted from a working fluid is converted to mechanical work. This mechanical work is absorbed by a variety of devices, which are classified into two major categories: energy dissipating and energy recovery. Energy dissipating turboexpanders reject the produced work, typically in the form of heat. In contrast, energy recovery expanders convert the work to useful and free energy, often via a directly coupled booster compressor or generator. While turboexpander utility typically focuses on the energy extraction from the fluid (refrigeration), the free energy recovered by a loading mechanism can directly improve the specific power of a given process.

Turboexpanders and ethylene production

In ethylene, propylene or isobutylene production, turboexpanders are found in the cryogenic section of the plant, where they expand hydrogen-rich overhead vapour (off gas) to produce deep refrigeration for product recovery. These petrochemical processes require cryogenic temperatures of as low as 100 K to separate gas mixtures containing up to 96% hydrogen.

Amongst petrochemical processing, ethylene is the world's most produced organic compound, and over the last 60 years turboexpander technology has evolved to support improved ethylene production. The manufacture of ethylene is primarily to produce polyethylene, the plastic polymer, and the introduction of turboexpanders into the distillation/recovery chill train (shown in Figure 2) of ethylene production has played a vital role in maximising plant yields.

The chill train of an ethylene plant takes advantage of byproduct propylene and the ethylene product itself as a suitable refrigerant to produce the



low-temperature cryogenic process conditions required for the ethylene product recovery. At a pressure approaching atmospheric, propylene and ethylene have boiling temperatures of -50°C and -100°C, respectively. At these temperatures, the original ethylene plant chill trains were configured to recover the bulk share of the ethylene production, with a considerable amount of ethylene carrying through with the tail gas. To improve on this, the final tail gas streams leaving the chill train units were further cooled using simple JT expansion valves.

The introduction of turboexpanders into the ethylene process over JT let-down, or the more costly methane refrigeration process, was an elegant and practical inevitability. A turboexpander is a free energy approach. The final pressure let-down from the chill train unit is provided and paid for by necessary upstream compression. A turboexpander loaded by a compressor relieves some of this upstream compression duty by recovering free work in the near isentropic expansion process. Temperature reductions in the order of 40°C across the turboexpander are common for these process let-down conditions, adding to the chill train's final cryogenic refrigeration loop and creating ethylene separation at temperatures of -135 to -145°C.

The big challenge for turboexpanders in ethylene plants comes from the chill train's service factor and its absolute intolerance to any contamination that can freeze and foul out the process equipment. In fact, when using a turboexpander for high-purity hydrogen duty in an ethylene chill train, machine vendors must ensure a number of things. These include zero process contamination, robust process control by inlet guide vanes, minimal shaft seal leakage, and the ability to handle thermal cycling of start-ups and plant upsets.

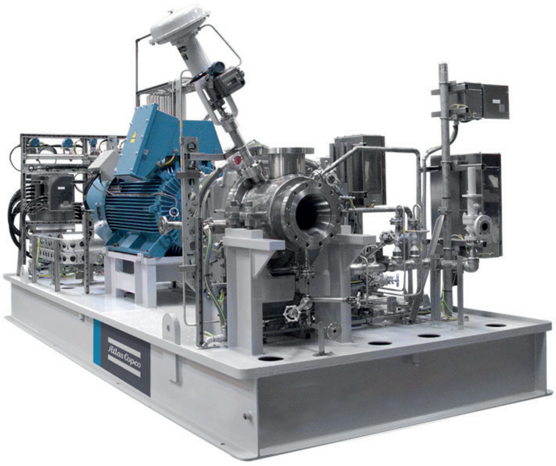


Figure 3. An expander-generator package.

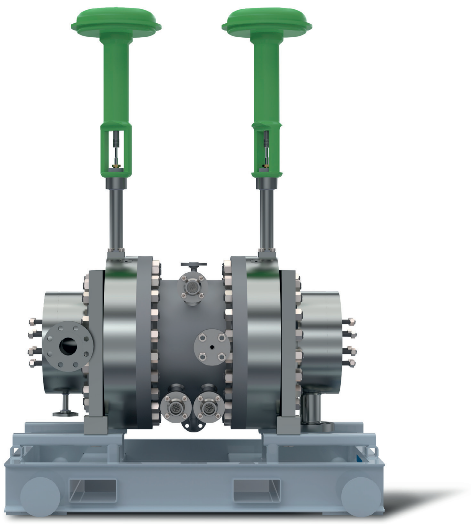


Figure 4. An expander-generator (permanent magnet) with AMB.

Turboexpander configurations for ethylene

Turboexpanders have evolved over the years to meet the increased demand of ethylene production. As the size of ethylene plants has grown, energy recovery turboexpanders that are configured with compressors have become the preferred option. Turboexpanders paired with booster compressors offer a hermetically-sealed system with no external shaft seals. Due to sealing loss and the potential for oil carryover to the process, expander compressors equipped with active magnetic bearings (AMB) became the preference for hydrogen-rich processes when introduced in the early 1990s. AMB systems are hermetically-sealed with oil-free sealing gas fully contained in the process. Sealing gas sourced from the hydrogen-rich process cools and protects the AMB components from cold, unfiltered process gas. With no permanent magnets, AMB materials are fully compatible with hydrogen service.

Expander-compressors in hydrogen-rich applications have a unique challenge, as the process tends to demand high-head, low-flow expanders paired with high-head, high-flow compressors. This imbalance in turbomachinery geometry creates challenges with both the tip speed and rotordynamics. Turboexpander designs over the last several decades have pushed these limits, increasing customer acceptance of higher tip speed machines and optimising compressor geometry to maximise energy recovery.

Another energy recovery option used in hydrogen-rich service is the integrally-geared expander-generator. These configurations offer low-seal leakage with dry gas seals (DGS), and energy recovery via generated electricity. Typical expander-generators are not hermetically-sealed because they rely on an oil-fed gear box to reduce shaft speeds. Expander-generator packages (Figure 3) are commonly deployed in hydrogen-rich service where recompression is not required. Propane dehydrogenation (PDH), a process specific to propylene recovery, typically utilises expander-generators in a two-stage configuration.

Furthermore, innovative high-speed generators have been deployed for lighter duty applications, where gearbox cost or performance may be prohibitive for the application. In a similar arrangement to expander-compressors with AMB, permanent-magnet, high-speed generators have been arranged with two turboexpander stages rotating on a common shaft (Figure 4).[1]

The lessons learned from the evolution of turboexpanders in ethylene plants places the current machine configurations and vendors at an ideal point to take the next step in deeper cryogenic applications that the hydrogen industry requires.

Turboexpander design for hydrogen liquefaction

The hydrogen liquefaction process involves compression of hydrogen feed gas to the liquefier, pre-cooling normally down to 90 K, then further primary cooling down to 30 K or lower. The cooled hydrogen then expands, further reducing the temperature to near 20 K. Primary refrigeration for hydrogen liquefaction is carried out either in a Claude cycle or closed-loop Brayton cycle, often with turboexpanders operating in a refrigerant of pure hydrogen. Today's liquefiers range from 10, 15, 30 to 40 tpd for local production, with plans for industrial scale up to 500 tpd.

Hydrogen refrigeration cycles pose several design challenges for turbomachines and material selection, high tip speed and aerodynamic considerations require evaluation when converting a traditional hydrogen-rich turboexpander to pure hydrogen liquefaction service.

The main factors determining material selections are suitability for hydrogen embrittlement, strength, and heat transfer. Some examples of suitable materials for hydrogen turbomachines are austenitic stainless steels and aluminium, depending on the effect of cryogenic temperature on their properties. Copper and other materials used in active magnetic bearings operate at relatively low temperatures, and are proven to be immune from hydrogen attack. With limitations in material selection, minimising stress from high-speed rotating components becomes an important design factor.

Most liquefier turboexpanders require high speeds in order to achieve higher performance, due to low volume and high head. With constant mass flows in the refrigeration cycle, the high enthalpy drop on the turboexpander translates to high enthalpy rise and tip speed on the booster compressor. Aluminium alloys such as 7075-T6 have outstanding strength-to-weight ratios and enable high tip speeds for both turboexpander and booster compressors.

Design consideration for high tip speed include stress and deflection in the impeller disk/blade, and wheel fixation to the shaft. With proper design and feature selection, high tip speeds required for optimum aerodynamics can be achieved. The aerodynamic design must optimise blade geometries for minimising the aerodynamic losses while maintaining lower stress levels and avoiding hub and blade resonances. Because compressor boost is less important than turboexpander refrigeration, the compressor impeller design may focus more on mechanical limits rather than aerodynamic optimisation. The high specific speed compressor impeller must be custom engineered for mechanical integrity, with minimal overhung mass to improve the rotordynamics for maximum speed. Furthermore, higher head coefficient compressor designs enable smaller diameter impellers and lower tip speeds.

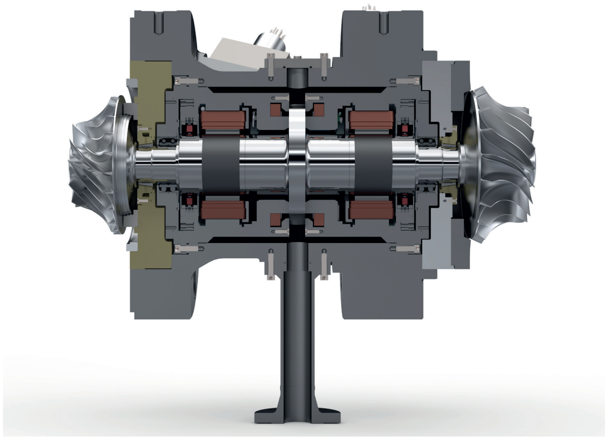


Figure 5. Magnetic bearing rotor-bearing system.

Rotor-bearing system

Depending on the turboexpander load, cryogenic turboexpanders typically use active-magnetic, oil-lubricated, or gas bearings. Liquefier expander-compressors have a very low-pressure ratio across the compressor, making automatic thrust load control per conventional design less effective. Thrust load compensation on the expander side is not recommended since it adds to leakage and thermal losses. AMB technology (Figure 5) offers an oil-free design with improved thrust capability when compared to gas bearings, and it can typically handle the process loads without the need for additional thrust compensation. The rotor design aims to maximise the speed with the required double overhung impeller weights, and maximise thrust load capacity to cover different process conditions.

Conclusion

Turboexpanders have been used extensively in hydrogen-rich applications in the petrochemical industry for the last half century. Developments in the petrochemical industry over decades are now being adapted to the demands of green hydrogen liquefaction. Turboexpander design for hydrogen liquefaction requires challenging aerodynamics, high tip speeds, innovative sealing systems, minimal clearance losses, suitable material selections, and robust thermal management. Numerous hydrogen-rich turboexpanders designed and operating in the field have validated the design process. With careful evaluation, these machines can be adapted and qualified for hydrogen liquefaction at all scales.

Note

- This article was originally presented at the Asia Turbomachinery and Pump Symposium 2022, Kuala Lumpur, Malaysia.
- * Behrooz Ershaghi (retired from Atlas Copco Gas and Process) contributed to the original article as a co-author.

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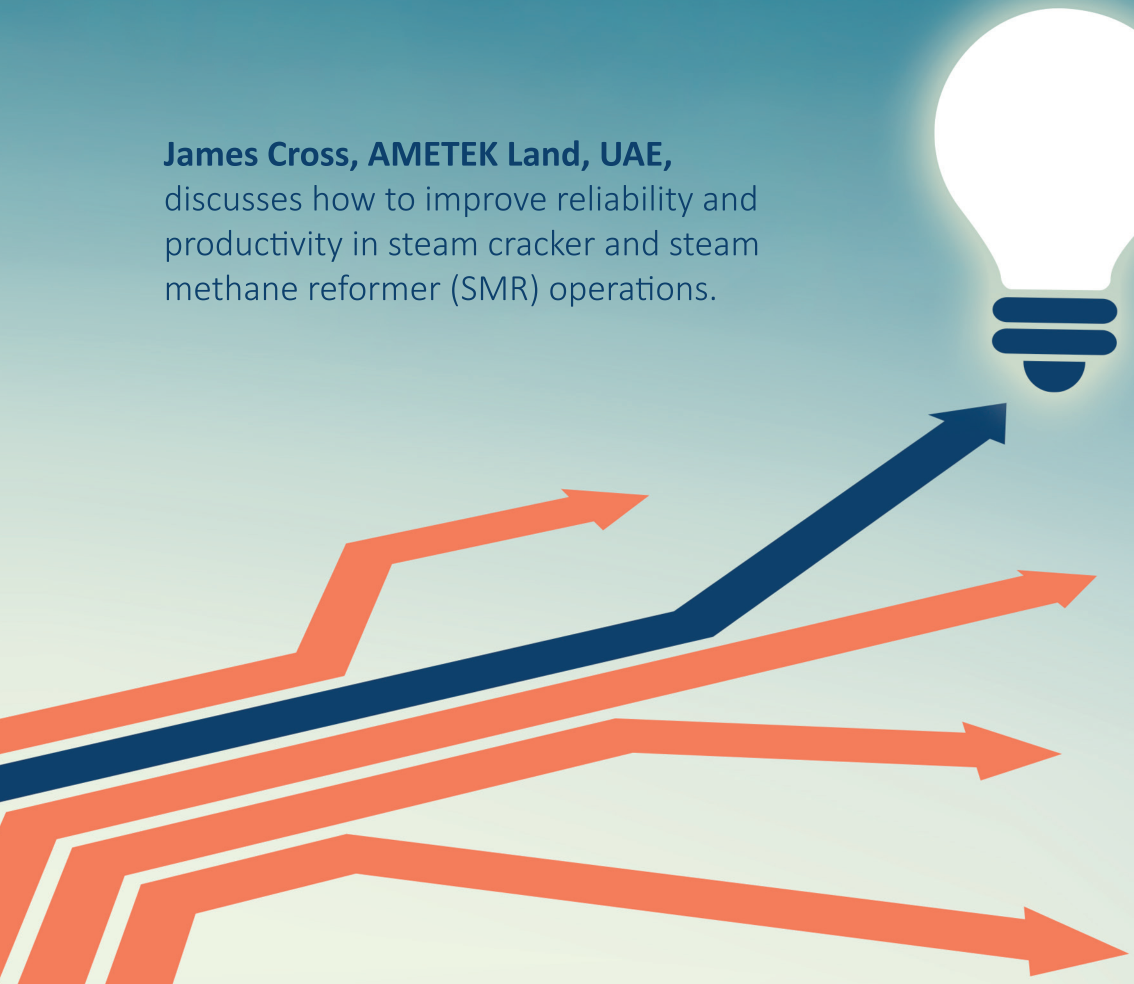
BLUE H_2

THE RIGHT WAY

James Cross, AMETEK Land, UAE, discusses how to improve reliability and productivity in steam cracker and steam methane reformer (SMR) operations.



Refineries and petrochemical industry operators find themselves in an ever-changing regulatory environment, where new global strategies for carbon emissions reduction are released frequently, often setting challenging targets and recommendations.

The US government has proposed a reduction in the country's greenhouse gas emissions by 52% of 2005 levels by 2030 – a much shorter timeframe than its previous pledges. In summer 2021, the UK government issued its low-carbon hydrogen strategy built around blue and green hydrogen, committing to net zero emissions.

To meet these new economic and technical challenges, plant operators must make significant short-term improvements in efficiency, and radical changes in the longer term. The optimisation of the most carbon-intensive fired heater processes is the logical place to begin.

Fired heater processes and CO_2

Steam methane reformers (SMRs), mostly used to supply hydrogen to refineries for ammonia/methanol production, and steam crackers for ethylene production, are two of the largest and most carbon-intensive refinery and petrochemical fired heaters.

It is estimated that SMRs emit around 800 million tpy of carbon dioxide (CO_2), while steam crackers produce approximately 260 million tpy of CO_2 emissions.

There is much focus on reducing CO_2 emissions from these fired heaters by upgrading burners, changing tube/coil/refractory materials, and improving combustion efficiency. However, temperature monitoring and control can play an important role in improving process efficiency.

Steam reforming

SMR is used to produce more than 95% of the world's hydrogen, typically using desulfurised natural gas, refinery off-gas, LPG, or naphtha as the feedstock.

This process works by preheating the feedstock, then mixing it with steam before it enters the primary reformer. At this point, the mixtures pass over a catalyst, reacting to produce hydrogen, carbon monoxide (CO) and CO_2. The CO is shifted with steam to create additional hydrogen and CO_2, and then pressure swing adsorption (PSA) is used to separate hydrogen.

The hydrogen generated is known as grey hydrogen when there is no carbon capture, usage and storage (CCUS) involved; however, when CCUS is used, blue hydrogen is produced.

SMRs emit CO_2 in two main ways: producing it alongside hydrogen in the reforming reaction in the primary reaction furnace, and through combustion of the fuel. For the reformed gas, capturing CO_2 is a relatively simple and low-cost process. However, post-combustion CO_2 capture is more expensive because it needs to be separated from nitrogen.

Grey hydrogen production typically captures CO_2 from only one of these sources, but blue hydrogen production captures CO_2 from both. Using this method, SMRs can achieve a conversion efficiency of 74% and a CO_2 capture rate of up to 90%.

Autothermal reformers (ATRs) can also be used together with CCUS to produce blue hydrogen. Technology licensors claim conversion efficiencies of 84%, with CO_2 capture rates of 95% from this method. Heat for the reforming reaction is supplied by combustion of the natural gas feed, so no separate fuel source is needed, as with SMRs.

Since there is only a single CO_2 stream, using this process means that ATRs can achieve higher conversion efficiencies and CO_2 capture rates than SMRs.

To remain competitive in the modern industrial environment, it is imperative that SMR operators improve their efficiency and CO_2 capture in order to maximise plant profitability.

Primary syngas reformers

Primary syngas reformers are complex and important pieces of major equipment in refineries and petrochemical complexes, and they present unique and often frustrating challenges from the perspective of temperature measurement, reliability and optimisation.

It is also important to consider that refinery hydrogen producers have different objectives to other hydrogen producers – although demand for hydrogen as a fuel stock is certainly increasing at refineries around the world.

When optimising fired heaters, the primary goal is to run the tube outlet temperatures close to their design limits, while considering safety and minimising energy costs and emissions. By using industry-leading temperature and imaging technology, it is possible to operate with both higher yields and reliability.

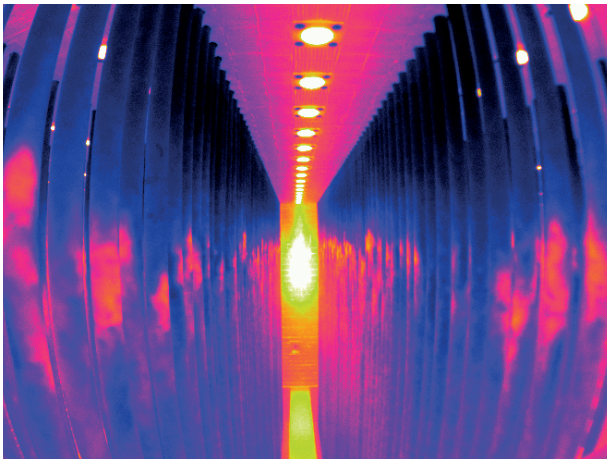


Figure 1. Thermal imaging of a top-fired SMR.

Figure 2. Portable system being used onsite to assess an SMR.

Many refineries use the AMETEK Land Cyclops C100L and C390L for tube metal temperatures on high-temperature fired heaters, including primary syngas reformers used for hydrogen production, and for steam crackers used to produce ethylene. The Gold Cup reference pyrometer is utilised frequently to provide reference measurements for those devices, which are occasionally (but rarely) deployed on lower-temperature equipment.

AMETEK Land has also recently seen increasing demand from refineries for non-contact temperature measurement on lower-temperature fired heaters as efficiency improvements are sought. For example, crude oil preheaters heat products to between 330°C – 385°C, which is significantly lower than the typical temperatures inside an SMR. They also pose unique temperature measurement challenges depending on heater design. For instance, viewing ports generally expose nearby tubes to cold ambient air, meaning that those tubes are not good candidates for Gold Cup measurements, whereas better candidates are out of reach of the Gold Cup.

Temperature measurements in these ranges are usually performed by fixed thermocouples which measure surface temperatures less reliably than infrared measurements. Customers have tasked AMETEK Land with devising better methods for these lower temperature ranges.

The newly-developed Portable Thermal Imaging System can be used with either a mid-wave or short-wave (near) infrared camera, so that it can measure temperatures of as low as 300°C and as high as 1800°C.

Both portable and fixed thermal imagers provide accurate, repeatable temperature coil readings, independent of operator expertise. Thermal imaging delivers a high-resolution image which identifies, in real time, the temperature measurements of the tube skin and refractory surface. The air-cooled system means that the operator/inspector can fully and safely insert the camera lens into the hot flue gases without risking the camera or themselves.

When selecting a portable thermal imaging system, considerations include the borescope length and the camera's Field of View (FoV). The borescope length should be long enough to comfortably extend through the peep door, and the FoV must be wide enough to see all tubes in the furnace, or narrow enough to focus on an area that may be some distance from the viewing point. Multiple options are available.

Captured images allow for easy identification of hot and cold spots in a fired heater with a high degree of accuracy, so that mitigation or process control decisions can be made and monitored. In addition to this, advanced software enables sophisticated processing of the temperature profile data, allowing emissivity and background temperature adjustments to be made on each tube, or for each zone.

Customers have already reported using the system to measure areas of the furnace, through previously unused ports, that they did not think it was possible to get a measurement from. An example of this is the corners of top-fired primary syngas reformers (where risks of tube rupture may be high) or headers/collectors. AMETEK Land has seen images showing issues relating to coking, poor temperature balance, damaged burner tiles, poor tube sealing, flame impingement, hot spots/band, and catalyst damage.

Furnace monitoring

Reducing oxygen setpoints and increasing the hydrogen content in fuel stocks to achieve the necessary

reduction in CO_2 emissions has led to an increased need for improved visual and temperature monitoring inside both steam crackers and SMRs.

These trends create new uncertainty, an increased risk of material failures, and potentially unsafe conditions, as flue gas and surface temperatures may be higher, new flame behaviours may be observed, and burner nozzles, tiles and insulation may deteriorate faster. Potential increases in NOx emissions and other changes to the characteristics of the fired heater must also be watched for closely.

Depending on the furnace design, if the pyrometer measurements determine that temperatures on an SMR have approached or exceeded the design limits of the tube, firing can be reduced, burners can be gagged or, in extreme cases, the burners may be shut off. This is a labour-intensive and reactive response, so usually any conditions of potential concern are only acted upon if observed and recorded by the inspection team. When it comes to optimising temperature homogeneity, the reactive, single-point, manual data collected by a pyrometer will not match the volume of information from thermal imaging systems that automatically and continuously monitor a measurement array.

Although fixed monitoring systems provide this comprehensive data continuously in real time, portable systems are also highly-valuable tools for inspection and thermal survey.

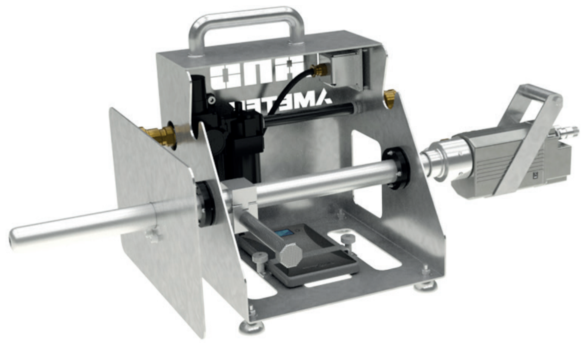


Figure 3. A portable furnace thermal imaging system.

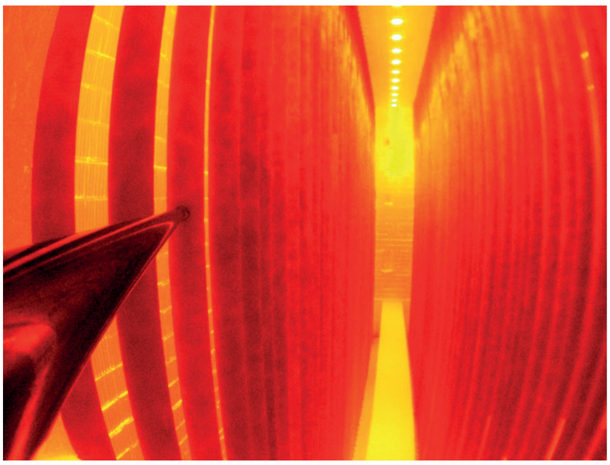


Figure 4. A thermal image taken whilst AMETEK Land's specialist engineer took a Gold Cup measurement.

Optimisation using thermal imaging

High-resolution images and videos, along with extensive temperature data, can be provided by both portable and fixed thermal imaging systems. Fixed systems can also deliver automated image analysis, continuously monitor and alarm on tube metal temperatures (TMTs), and watch out for potential coking on steam crackers. Employed on an SMR, they can identify insulation, burner tip/tile condition, and potential hot bands or catalyst issues. Real-time, continuous surface temperature data allows the remaining tube lifetime to be calculated.

Portable borescope systems, on the other hand, are ideal for furnace inspections and can see parts of the steam cracker or SMR that operators may not be able to see with the naked eye through peep doors. They allow for regular, easy, quick inspections while also providing thorough temperature data that can be analysed and archived. These systems should use a wavelength suitable for the gas atmosphere, while the borescope length should be sufficient to extend through the peep door comfortably, and the fields of view should suit the peep door design and tube layout.

Verification of accuracy

Although handheld pyrometers and thermal imaging systems provide repeatable data, it is essential to verify the accuracy of the temperature data produced using reference measurements. This can be achieved using the AMETEK Land Gold Cup, a water-cooled 3 m long probe that creates near black-body conditions at the measurement point to deliver repeatable, reliable reference temperatures.

When using non-contact infrared measurements, it is necessary to compensate for surface emissivity and incident radiation if the environment has a hotter background – which is usually the case in a steam cracker or SMR.

By using a hemispherical reflector (the 'gold cup' which gives the instrument its name), a measurement is produced that is independent of emissivity and incident radiation. A narrow protective edge, suitable for contact with the tube, blocks incident radiation from entering the cavity formed between the tube and the cup. This energy escapes through a tiny aperture in the back of the cup, where it is measured by the pyrometer module's detector. A handheld display continuously records the temperature data.

Designed only for periodic reference measurement readings that can increase the accuracy of non-contact devices, the Gold Cup has been successfully used across the industry to improve the temperature accuracy of steam cracker and SMR measurements.

Conclusion

The way our industry works is already changing due to the impact of global decarbonisation trends. End users, technology licensors, and instrument manufacturers are continuously looking for both incremental and radical improvements to process efficiency.

Supported by the necessary technical knowledge, the implementation of digital solutions and infrared technologies can help SMR operators to improve temperature homogeneity and fuel efficiency, delivering improvements for reliability and product yield in an increasingly-competitive environment.

THE HYDROGEN ROADMAP TO RELEVANCE

COVER STORY

Andy McIntire and Praveen Sam, Honeywell Connected Industrial, USA, detail the use of industrial-grade software to support the digital transformation of the hydrogen sector.

From industry to transport, many sectors are adopting hydrogen as a key pillar of their national and international energy system strategies that are aimed at tackling climate change by reducing greenhouse gas (GHG) emissions. By the beginning of 2021, over 30 countries had released hydrogen roadmaps, and announced more than 200 hydrogen projects and ambitious investment plans. Governments worldwide have committed more than US$70 billion in public funding. This momentum exists along the entire value chain and is accelerating cost reductions for hydrogen production, transmission, distribution, retail, and end applications.

Hydrogen is already a commodity that is being used as feedstock in different industrial applications, ranging from refineries to ammonia and methanol production. The global demand for pure hydrogen has tripled since 1975. Current hydrogen demand is mostly supplied by fossil fuels, including natural gas, oil and coal, because they represent the cheapest pathway. However, hydrogen has also been proposed as a potential energy carrier to support the wider deployment of low-carbon energy, mainly produced from renewable energy sources.

The reason for hydrogen

The universe's most abundant element has long been considered a potential alternative to traditional forms of fuel. However, until now, the cost barriers associated with hydrogen production were too high to make it a viable zero-carbon fuel source.

Three factors are behind the rise in a renewed interest in hydrogen:

- The introduction of favourable government policies.
- Technological improvements and scale driving down costs.
- Increased demand driven by sectors seeking to decarbonise.

Varying waves of enthusiasm have supported the narrative of low-cost, clean hydrogen as an alternative to fossil fuels, mainly exploiting fuel cell applications in the transport sector, and heating as a lower-cost alternative to electricity. Scientific and industrial interest in the potential of hydrogen technologies first occurred during the oil crises of the 1970s, as the world was looking for alternative solutions to tackle potential oil shortages and addressing environmental problems such as local pollution and acid rains. Research programmes on hydrogen were implemented, but they did not have significant effects since, due to new oil discoveries, the oil prices eventually decreased, and the fear of shortages disappeared.

Rising concerns over climate change and peak oil scenarios renewed interest in hydrogen in the 1990s and 2000s. Again, low oil prices limited the diffusion of hydrogen technologies, and so did the economic and financial crisis at the end of the 2000s.

Today, a growing consensus is once again building up on the potential of hydrogen, mostly due to a stronger climate agenda with more challenging targets. Clean hydrogen is part of a group of technologies that need to be deployed across final uses to ensure a transition towards climate-friendly energy sources.

Blocks to overcome

Sustainability is good for business, and has become a source of future competitive advantages. However, turning initiatives such as hydrogen into reality is a challenge. With green hydrogen costing six times that of traditional energy production, and blue hydrogen costing two to three times as much, the transition to cleaner production through carbon capture and renewable energy must be strategic. To win in the future, operators must begin laying the foundation with OT data management and software solutions.

The infrastructure necessary to support a low/zero-hydrogen economy consists of transport, storage and distribution stations. This can be extremely costly compared to other decarbonisation efforts, such as electrification. Cheaper and more abundant renewable energy sources are integral to scaling low and zero-carbon hydrogen use. There are a lack of proven applications at scale to date, though large-scale efforts are in their planning phases.

Hydrogen's low density presents unique and costly distribution challenges that have yet to be solved. With over 1 million t of clean hydrogen projected for transport in the next five years, those who invest in advancing storage and transportation infrastructure today will steer the development of the sector, influence and standardise policy, and reduce administrative costs associated with import and export.

Industries and governments are focusing on three key areas to scale the hydrogen economy:

- Infrastructure development: hydrogen behaves differently to natural gas, and will require new or adapted infrastructure.
- Hydrogen production: hydrogen can be produced in several ways, but if it is to help in the battle with climate change, the process will have to be decarbonised.
- Safety research: the scale of the future hydrogen society will be determined by success in demonstrating safety.
- Digital solutions for hydrogen reduce both CAPEX and OPEX, driving innovation across all project phases – from design and build, to operate and optimise.

Faster and leaner start-up: design and build

A strong foundation of digital intelligence builds the critical infrastructure that enables reliable, autonomous operation. Digital twin simulations enable engineers to create steady-state/dynamic models for plant design, performance monitoring, troubleshooting and operational improvements. It is important to optimise equipment design before users make large capital investments and begin operations. The following should be observed:

- Simulate the entire hydrogen production from electricity supply to hydrogen storage with easy-to-use and comprehensive flow sheeting.
- Achieve economic benefits via lowest total cost of ownership.
- Create a digital representation of a physical asset either in design or operation – a 'process digital twin'.

Comprehensive digital twin process models provide engineers with a complete view of heat and material balances for evaluating limiting design cases and other operating conditions. Additionally, simulation is used to perform feasibility studies, assess alternative process configurations, and identify risks. Engineers leverage this information to ensure that designs are safe, meet environmental regulations, and maximise the operational and business performance of the asset.

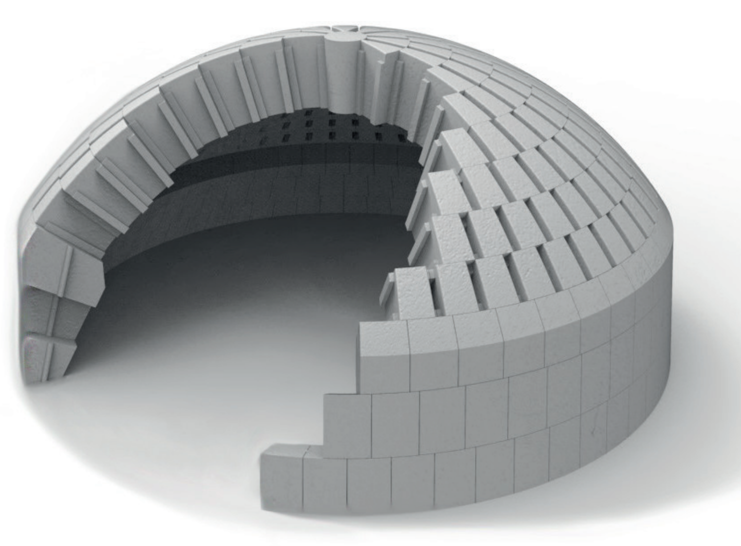
A steady-state digital twin can only provide a snapshot of the starting and end conditions, while a dynamic model can accurately predict intermediate process conditions during the transition. With the capability to replicate start-up, shutdown, the impact of equipment failures, and other abnormal conditions, a dynamic digital twin can better serve engineering design analysis, decisions and outcomes that otherwise may not be known, or will be discovered far too late in the project life cycle.

The early conceptual phase of a green hydrogen project will include sorting through numerous options with the following key process variables:

- Electrolyser technology: alkaline, proton exchange membrane (PEM), or solid oxide.
- Variability of electrical supply if coming directly from a renewable source such as solar or wind.
- Water quality, both at the source and entering the electrolyser stack.

CALDERYS REFRACTORIES

FOR THE HYDROGEN SECTOR



A WIDE RANGE OF CUTTING-EDGE PRODUCTS THAT REDUCE YOUR CARBON FOOTPRINT VIA EFFECTIVE INSTALLATION, FASTER DRYING TIME AND OPTIMAL THERMAL INSULATION

- Spraycast products & insulating products: fast spraycasting installation for high-quality castables without moulds, castables range for safe and efficient installation and Strong insulating properties
- Bricks & tiles selection
- Project engineering: management and installation for your turnkey projects

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- Discharge water quality: in the case of alkaline electrolyser, potential need for purge or discharge of water/KOH electrolyte.
- Main electrolyser stack: technology-specific parameters such as electrical voltage, current density, conversion efficiency, heat balance, etc.
- Battery limit conditions of product streams such as hydrogen and oxygen.

Digital twin process simulation is central to analysis of the various options that will determine the economic and operable feasibility of the selected design. Much near-term attention will be focused on modelling the electrolyser stack. The process simulation tool needs to represent the overall performance of this stack, and the overall balance of the plant.

The process simulation needs to be validated for use in representation of the main electrolyser stack, as well as the balance of the plant. In addition to this, production management software orchestrates hydrogen production efficiency throughout the value chain and provides insightful production analytics and accurate production accounting.

The software maximises throughput and improves capacity-asset utilisation to meet stringent quality standards, thereby streamlining analysis, execution and reporting of single-plant and enterprise-wide operations. Operators are then clear to schedule and dispatch, track, store and ship, and statistically reconcile accounts.

Optimised reliable operations

Asset performance management (APM) systems provide a real-time analytics solution that continuously monitors asset and process performance across the enterprise, detects impending health issues, and predicts time to failure. APM provides a flexible platform to implement asset-model driven, templated calculations, logic rules, diagnostic events, and fault models. Capturing performance characteristics and templating enables the possible definition of all the asset relationships in the hydrogen production plant – from cells, related to a stack, to multiple stacks, related to a rectifier, and onwards through the plant. A full engineering library can be used as a starting point from which engineers may design and configure new templated asset models that are suitable for a green hydrogen plant, and capture key performance indicators (KPIs) into one overarching view. The successful engineering surveillance of green hydrogen production units can lead to higher overall efficiencies, for longer periods of time, and therefore generate more hydrogen efficiently.

Advanced process control (APC) delivers maximised operating profitability by optimising hydrogen production trade-offs, managing product specifications, and pushing operating envelopes to constraints. APC technologies optimise operations across the entire production facility through advanced multi-variable control. It also sustains performance and optimisation benefits through adaptive control and real-time monitoring.

Operations management software enables standardised work process across clusters of hydrogen production units, and drives informed decisions and operational compliance. End-to-end alarm life cycle management helps hydrogen production units to reduce a console operator's alarm load, improve situational awareness, and significantly limit process upsets and shutdowns, turning control room noise into operational knowledge, and rationalising alarms to drive operator effectiveness.

Workforce competency solutions also promote the safety and effectiveness of operations personnel, enabling end-to-end management across departments. Immersive simulations instill staff with veteran-level understanding of green hydrogen processes and operations, guiding them to realise their full potential faster. The value from using dynamic simulation models for training is well established and contributes to a suite of safety, reliability and operator effectiveness, productivity, and performance benefits. Some of the best run facilities have integrated OTS training interventions into their competency management system. Training investments can be optimised, targeted and deployed to address specific competency gaps.

Extending digital twins from design to operations

Digital twin modelling offers what-if analysis and visualisation of opportunities for improvement. Process engineers can confidently use the dynamic model to evaluate the impact and benefits of various process changes or upgrades in hydrogen production units, such as debottlenecking studies, fine-tuning operating procedures, resolving equipment constraints, etc. Whether during design or on an operating plant, hazard and operability studies (HAZOP) can identify potential hazards that may arise from deviations from the intended design conditions. While subject matter experts (SMEs) typically hypothesise over various scenarios and outcomes, dynamic digital twins for green hydrogen can enhance a HAZOP by spotting high-risk probabilities, narrowing safe ranges of operation, and testing risk mitigation strategies. Dynamic simulation results improve the HAZOP process and operational safety by supplementing the SME discussion with a rigorous and credible engineering evaluation of the dynamic process response.

The role of industrial-grade software

While less than 1% of global dedicated hydrogen production is considered green hydrogen, this will change – but there is no easy way forward. The roadmap to relevance and sustainability calls for operational efficiency. Digital intelligence connects awareness and understanding of assets, people and processes across the plant, affording transparency and empowering operators with predictions to make data-driven decisions and optimise.

Successful digital transformation requires proven, industrial-grade software, delivered by operational domain experts who understand process industries. Building sound, reliable data infrastructure and avoiding 'proof-of-concept purgatory' is critical to supporting operators who are committed to putting hydrogen on a low-carbon path to a net zero future.

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THE FUTURE IS WHAT WE MAKE IT

MAINTAINING THE PIPELINES OF THE FUTURE

Decarbonisation and net zero are buzz words that are being used in the energy arena, but what do they mean for pipelines? **Dr Mike Kirkwood, T.D. Williamson, UK,** explains.

Every future projection for energy includes fossil fuels. For example, the US Energy Information Administration (EIA) projects that in 2050, natural gas and oil will supply nearly 50% of the world's energy, compared to 54% in 2020.[1] So, fossil fuels will be key to energy needs well into the future. However, with the drive for cleaner energy as well as the added imperative of security of supply, one key fuel that will likely move us closer to this goal is hydrogen and the use of pipelines as a cost-effective means of transportation.[2] This article will look at some of the issues related to the conversion, construction and operation of these new breeds of pipelines.

Transmission pipelines: new challenges

There are over 4500 km (2800 miles) of hydrogen pipelines in operation worldwide. One of the first hydrogen systems was built in 1938 and now runs 875 km of pipeline between 25 chemical and petrochemical plants in the Rhine-Ruhr area, Germany. Using hydrogen in pipelines is not new, but current systems mainly operate in industrial areas, are relatively short in distance, and run at low pressures equivalent to a stress level of ≤ 0.5 x the specified yield strength (SMYS) of the pipe material.

The next phase of development will have major implications for new and existing infrastructure, including designing new pipelines and converting existing ones to receive gases in different volumes, pressures, cycles and constituents. To prepare for this, the industry needs to look now at pigging, in-line inspection (ILI), and intervention.

Pipeline pigging

Before operation/conversion, cleaning of pipeline systems is normally accomplished by running conventional cleaning pigs, and this will be no different for hydrogen. As normal post-construction/post-decommissioning cleaning would follow, standard procedures using water, air or nitrogen could be maintained, and no special consideration would be required.

When in hydrogen service, it will be necessary to select the right components to endure the aggressive environment:

- Bolts and fasteners need to be low strength to prevent failure, and need to be sized correctly for the same stress.
- Brush material should be austenitic steels, aluminium or plastic based, which are less susceptible to embrittlement and sparking.
- If there are canisters (e.g. data logger, transmitter, etc), elastomers that are resistant to explosive decompression will be required.
- Careful selection of urethane hardness, flexibility and wear resistance for cups is needed.
- Cleaning in a dry atmosphere may create static electricity, hence the requirement to have non-sparking components or including some form of earthing.

Although 100% hydrogen pipelines will be relatively free of impurities, blended hydrogen and natural gas will still contain corrosive products that call for careful management by way of utilising pigging processes.

The transition to hydrogen will require a deep review of current field working practices and the roll out of enhanced procedures to protect employees, the public and infrastructure. The most critical areas requiring focus are launching, receiving and retrieving in-line tools and pigs. These impacts include:

- The elimination or mitigation of worksite sources of ignition, and appropriate zoning.
- Awareness of potential operational sources of ignition such as pyrophoric black powder from cleaning legacy methane pipelines.
- Assessment of the surrounding facilities to identify potential ingress routes, equipment that may create sparking, and inert objects that may also be ignition sources e.g. loose, hard surfaces such as flint stone, dropped objects, and even large compost or manure heaps with elevated temperatures.
- Availability of inerting mediums such as nitrogen with venting procedures in place.
- Planning appropriate venting pathways to safely remove the hydrogen or hydrogen mix, preferably to flare.

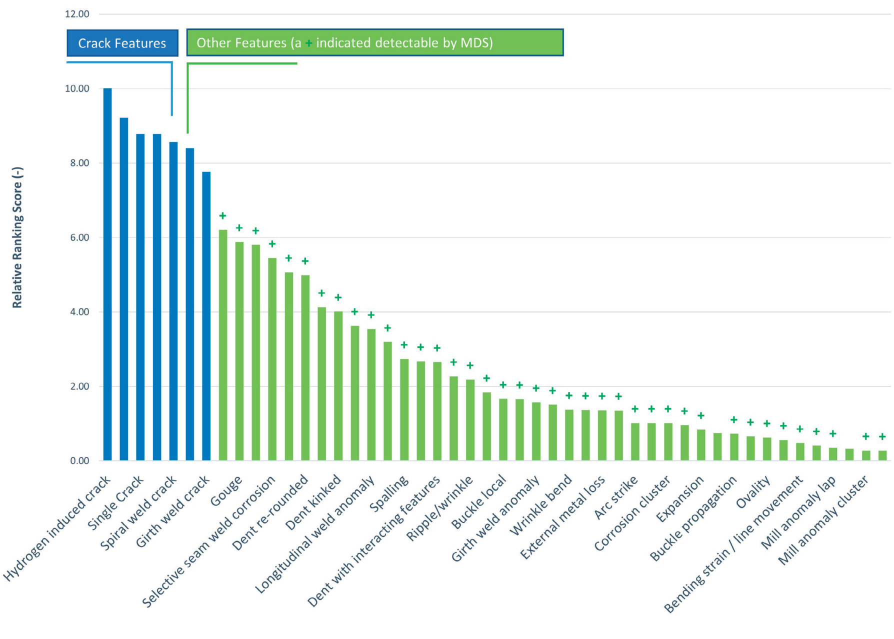


Figure 1. Critical anomalies for hydrogen – SME pairwise ranking.[3]

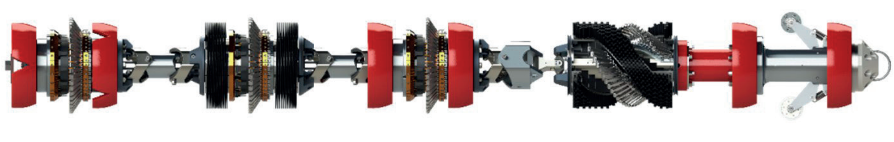


Figure 2. Multiple dataset (MDS) combination tool.

Figure 3. Electromagnetic Acoustic Transducer (EMAT) tool.

- Active monitoring of the effectiveness of the inerting process prior to breaking containment by actuating the closure door.
- Rehearsed contingency plans with resources onsite to respond to any incident.

Pigging solutions including closures, pigs and pig signallers can all be made hydrogen-ready. Soon, the focus will need to turn towards procedure development and the associated management of change.

Pipeline ILI

The current European Hydrogen Backbone report predicts that 53 000 km (33 000 miles) of pipeline infrastructure will be developed in 28 European countries by 2040.[3] The backbone is expected to be made up of 60% repurposed natural gas pipelines in 2040. This requirement for conversion will demand an assessment of all defects that are susceptible to hydrogen attack or degradation.

As part of the investigation into the tool technology that is required by an operator to detect high-threat defects for hydrogen service, a pairwise assessment was conducted utilising internal subject matter experts (SMEs) to rank the importance of each anomaly against its pair. This meant asking each SME to score 1128 individual entries to allow a pairwise matrix of importance to be developed.[4] The resulting ranking is shown in Figure 1. This highlighted that crack features ranked as extremely important to find, but there are still a significant group of non-crack defects that will be susceptible to hydrogen attack.

There are many technologies that can be used to measure these defects, as listed below:

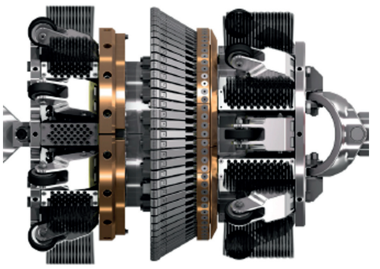
- Geometric features such as ovalities, dents, etc.
- Metal loss features such as corrosion, gouges, etc.
- Crack features such as weld cracks, fatigue cracks, environmental-induced cracking, etc.
- Pipeline movement such as strain from geohazards, wash out, storm damage, etc.

Multiple dataset (MDS) tools combine these technologies to detect complex interacting defects such as dents with gouges, which represent significant defects for any pipeline. One such platform for pre-hydrogen service is the MDS tool in Figure 2. This uses five sensing technologies that can find most defect types that are not cracks, as identified in Figure 1. For crack detection in a gas environment, the Electromagnetic Acoustic Transducer (EMAT) tool can be utilised (see Figure 3).

To highlight the benefits of running the MDS tool, a green '+' has been used in Figure 1 to highlight those defects that can be detected. The defects highlighted in the blue bars would be detected by the EMAT tool. In combination, a two-tool run pre-assessment would capture all those defects that are susceptible to hydrogen.

One dataset that is unique to the MDS tool is low field magnetic flux leakage (LFM). LFM identifies magnetic permeability changes in the steel microstructure due to mechanical working and/or heating/cooling. In normal magnetic ILI tools, strong permanent magnets impart a magnetic circuit into the steel, saturating the pipe wall with magnetic flux shown in the far right of the B-H curve in Figure 4. At the location of a volumetric change, the flux leaks from the pipe and is detected by sensors placed in the field. LFM is good at finding areas where the material has been strained, such as where dents have re-rounded. Additionally, LFM can be used to determine differences in the pipeline material, such as identifying changes in the steel from pipe joint to joint and hard spots.

As an example, Figure 5 shows how the MDS detects hard spots. The MFL dataset indicates that metal loss exists, though this is not always the case. LFM sees material change and then another dataset, spiral MFL (SMFL), pinpoints an axial-planar defect within the hard spot. This example highlights the need to use multiple technologies to identify this threat, especially as the hardened material may be susceptible to hydrogen induced cracking (HIC). Hard spots are a good example of what, in natural



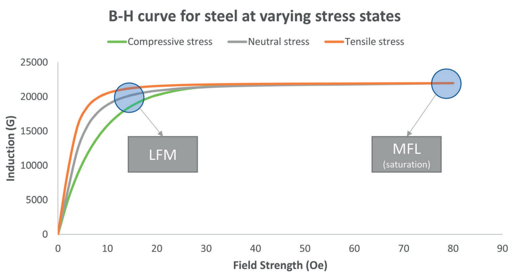


Figure 4. LFM dataset. LFM sensor array (left); B-H curve for steel (right).

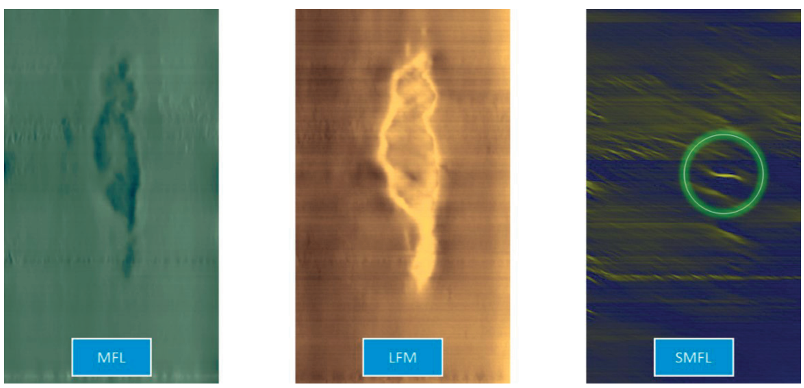


Figure 5. Hard spot as seen by the MDS tool.

gas systems, are seen as relatively benign, but become an anomaly of concern in the move to hydrogen.

Once hydrogen pipelines are operational, they will still need to be inspected. While internal corrosion is less of a concern, external corrosion and mechanical damage remain threats. It is well known that metal components can be susceptible to hydrogen. T.D. Williamson (TDW) found that some components on ILI tools would be impacted when exposed to very small amounts of hydrogen, even as low as 50 ppm (0.005%), which is well below some early adoption percentages for blended hydrogen and natural gas. TDW has been working with hydrogen operators using hydrogen, and has developed a tool that is capable of running in 100% hydrogen.[5]

The hydrogen tool required has the following specifications:

- Encapsulation of magnets.
- New sealing approach to protect the sensitive electronics and batteries within the pressure vessels.
- New brushes to support the magnetiser and couple the magnetic flux to the pipe wall.
- Re-engineering of all high-strength steel components, including the tool's body-to-body coupling system.
- New wiring harness materials.
- New composition of the urethane cups and discs.

The development of inspection tools that are capable of operating with pure hydrogen is possible, and the industry knows what is needed from tool design and operation conditions to acquire high-quality inspection data. The next-generation fleet of ILI tools will be built to include 100% hydrogen compatibility as a standard requirement.

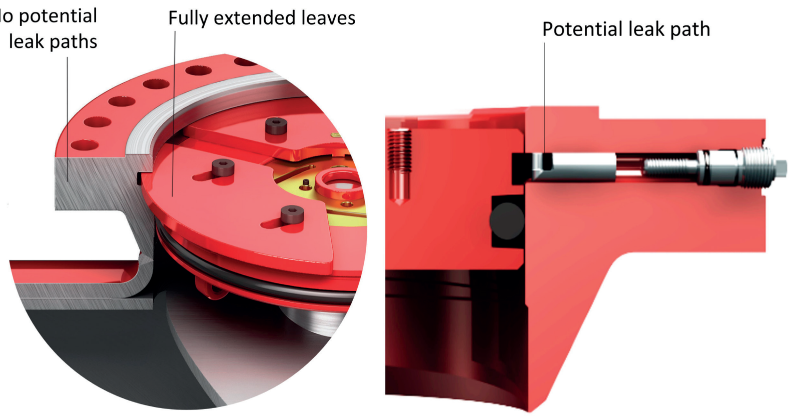


Figure 6. The new design of HT&P completion plugs. New completion plug set in place with extended leaves that fit in the flange groove; no leak paths (left). The old design of plug is held in place with segments that are extended with a screw mechanism drilled through the flange (right).

Isolation and connection

A common way to gain access to the pipeline is to make a hot tap and connection, or to stop flow to isolate the live pipeline. For decades, intervention and isolation operations have been performed successfully on all types of pipelines. However, the characteristics of hydrogen may increase some of the associated risks. For example, hydrogen molecules are smaller than those of natural gas, meaning that they can escape more easily where there is a connection or potential leak path, which can occur when using a hot tap and plugging (HT&P) approach.

Additionally, hot welding and the permanent connections, e.g. split tee fittings, which are left on the pipeline, all become a consideration. In fact, there is such concern that the recent supplement to IGEM/TD/1, which is specific to high-pressure hydrogen pipelines, states: "Under-pressure (i.e. 'hot tap') operations shall not be carried out on pipelines operating in hydrogen service unless proven to be suitable."[6] This highlights the need to work together, as TDW has proven technology and has experience of hydrogen pipelines, and the company has developed processes and procedures to ensure that hot tapping can be carried out confidently.

TDW leads the development of HT&P technology to meet the future demand for hydrogen. For example, to satisfy the pipeline industry's need, it has created a new completion plug that locks into place rather than screwing into the flange, as in the previous design. The design eliminates penetrations in the flange that would allow gas to seep through Figure 6.

The company is also using extensive knowledge in other applications, including sour services hydrogen sulfide (H_2S), carbon dioxide (CO_2) and ammonia (NH_3), to manufacture fittings for hydrogen pipelines and revise processes and procedures so that existing technology can continue to be used.

Conclusion

Fossil fuels will remain with us for some time, but as the hydrogen market is developed, the energy map will change – especially for transmission pipelines. A lot of people are asking: are we going to be ready? The simple answer is: we must be ready. The impetus is on the industry to solve some of the major obstacles, and many projects are already underway. Collaboration is the way forward, and TDW is one company preparing a full range of products and services to be ready for this shift.

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STAINLESS STEEL STORAGE

The growing hydrogen industry will require high-performance materials in many applications – from gas storage and water management, to electrolysis and carbon capture. **Marie Louise Falkland, Outokumpu, Sweden,** discusses how stainless steel fits the bill for different applications.

Hydrogen holds a lot of promise as a low-carbon source and carrier of energy for transport and heavy industry. Ensuring its safe and effective production and storage will require stainless steel at many stages along the hydrogen value chain: for hydrogen storage tanks, in fuel cells and electrolysers, as tanks onboard ferries or at fuelling stations, and for hydrogen pipelines.

Cryogenic performance

One of the most important applications is storage and transportation. This will require tanks that are practical, safe and reliable. Stainless steel is ideal for this as it has the beneficial combination of ductility at extremely low temperatures, and the ability to withstand hydrogen embrittlement.

The challenge with storing and transporting hydrogen as a liquid is that its boiling point at atmospheric pressure is -253°C, so operators will need materials that can cope. Cryogenic operation requires ductility at low temperatures to avoid brittle fractures that could impact the structural integrity of a storage vessel.

Multiple grades of stainless steel are already well proven for this type of environment, and are listed in technical standards such as the ASME Boiler and Pressure Vessel Code, and EN 13445-2. What these have in common is that they have an austenitic microstructure that enables them to operate at temperatures of as low as -273°C.

Figure 1. The growing hydrogen industry will require high-performance materials in many applications, such as pipelines.

Figure 2. Many grades in the stainless steel family offer the ideal combination of strength and corrosion resistance for the wide range of applications in hydrogen production, storage and consumption.

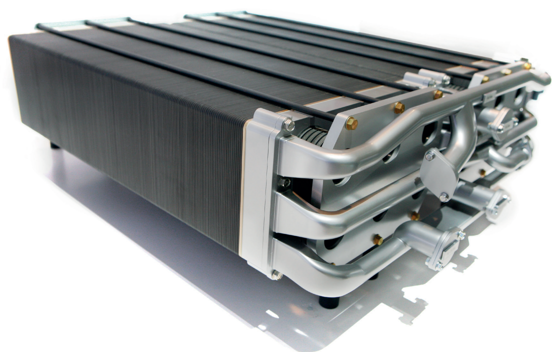

Figure 3. Stainless steel is important for fuel cells as the material for stacking plates that guide the flow of air and fuel.

Resisting hydrogen embrittlement

The other big issue is the potential for hydrogen embrittlement of steels and metals in general. Sensitivity to hydrogen embrittlement varies, depending on the material. High-strength steel, titanium and aluminium alloys are all vulnerable to hydrogen embrittlement. Sensitivity also varies between different types of stainless steel.

Austenitic stainless steels have higher resistance to hydrogen embrittlement than ferritic and martensitic alloys, as hydrogen's rate of diffusion through the material is low. Therefore, along with the low-temperature ductility, this makes austenitic stainless steel a good option for hydrogen storage.

The risk of hydrogen embrittlement increases with the pressure. There is little risk of hydrogen embrittlement at low pressures. As such, most stainless steels are suitable for storing or transporting hydrogen when pressure is not excessive.

However, as the pressure rises, so does the force that pushes atoms into the internal surface of a tank. As a result, it becomes more likely that hydrogen atoms will diffuse into the steel matrix of tank walls or the body of pipework. As austenitic stainless steel has a lower diffusivity of hydrogen than other stainless steel types, it is the preferred material – especially in many storage applications that operate in the range of 200 bar, with some sites working at up to 800 bar.

Alloying elements in the stainless steel also play a role in reducing susceptibility to hydrogen embrittlement. The industry has a rule of thumb that the most suitable materials are low-carbon austenitic stainless steels with around 12 – 13% nickel, and 2 – 3% molybdenum. This combination of nickel and molybdenum has been found to resist the diffusion of hydrogen, making it particularly attractive for hydrogen storage and transport tanks as the industry develops.

This is a current area of research for Outokumpu's metallurgists who are working on a long-term project that has the goal to fully understand how the alloying elements influence how hydrogen diffuses into the material, and eventually find the optimum alloy to avoid hydrogen embrittlement.

Storage and transport tanks

The storage of compressed hydrogen will require robust tanks. The basic construction of these will be based on a tank or cylinder with an inner and outer shell, with the inner shell containing the hydrogen and the outer having the purpose of resisting the internal pressure.

Four design options are available:

- Type I with walls made from metal alloys that have the capability to contain up to 200 bar.
- Type II tanks with a metal inner skin and an outer that is cylindrically covered with resin-soaked glass or carbon fibres to provide capability of withstanding up to 1000 bar.
- Type III uses a metal liner fully covered by a carbon fibre outer, which has the capability of withstanding up to 350 or 700 bar, which is the standard for vehicles.

- Type IV features walls constructed from composites, e.g. a carbon-reinforced tank with a polymer liner.

The metal inner tank material varies between steel, aluminium and stainless steel. Meanwhile, tanks for liquid hydrogen storage will call for materials that can withstand cryogenic conditions. Tanks will have inner and outer shells, with a vacuum or a layer of insulation between them. In terms of construction, the inner tanks will need to be able to manage the low temperatures, whereas the outer shells need to resist the outer environment.

A further option for storage is underground tanks. In these tanks, the walls will be built from a gas-tight material such as stainless steel, and the mechanical support will come from the rock walls of the underground chamber. This might be a pit made solely for this purpose, or an old mine.

Hydrogen production and use

Green hydrogen is usually produced by an electrolyser – in which electricity is used to split clean water into hydrogen and oxygen – whereas in the fuel cell, the hydrogen is converted to energy and water.

Multiple technologies are available and under development for electrolysers and fuel cells, all with different requirements for the materials being used. The material requirements are similar for a technology no matter whether it is used in an electrolyser or in a fuel cell. Material selection is determined by the type of technology, i.e. in terms of electrolyte, operating temperature, fabrication demand and physical properties, and further by the type of usage, e.g. the mobility if it is stationary use or a mobile application.

Fuel cells and electrolysers

Typically, the fuel cell technologies that operate at higher temperatures of 200 – 1000 °C, such as solid oxide fuel cells (SOFC), molten carbonate fuel cells (MCFC), and phosphoric acid fuel cells (PAFC), have a long lifetime. However, they have a long start-up time to reach the required operating temperature, making them less suitable for many vehicle applications where intermittent operation is required.

Conversely, alkaline fuel cells (AFCs) and polymer electrolyte fuel cells (PEFCs) operate at around 100°C and 80°C, respectively. Compared with high-temperature fuel cells, they have a higher power density and have more flexible operation. The fact that they require less protective packaging and insulation makes them more compact and lightweight for mobile applications such as trucks.

Stainless steel as the material for stacking plates that guide the flow of air and fuel over each side of the electrolyte is important for fuel cells. It is used as the material to make three types of plate component. The first is the thicker end plates that hold the stack together.

Figure 4. Stainless steel is ideal for applications across the hydrogen production chain, such as the ball valves shown here.

Figure 5. Stainless steel is produced under tightly-controlled conditions to ensure high quality and performance.

Secondly, the thinner interconnecting plates provide strength and apertures for fuel and air to flow into the stack, and for water to escape. The third and final stainless steel plate in a fuel cell stack is the cathode contact, which has flow channels machined into its surface to guide air and fuel across the electrolyte.

High-temperature technologies

Looking at the high-temperature end of the market, stainless steel has the right properties for SOFC technology, which operates in the region of 600 – 1000 °C, as it provides good strength and corrosion resistance in this range. In addition to this, it has a low thermal expansion coefficient and is electrically-conductive, and therefore performs both mechanical and electrical roles.

In 2020, around 150 MW of fuel cell capacity was deployed around the world and most of this was based on very high temperature technology that works at 850°C and above. It requires highly-specialist ferritic stainless steels that are complex to manufacture. These are typically produced in low volumes by specialist mills, and are therefore costly.

Meanwhile, steels based on grade EN 1.4509 (441) and 1.4622 are suitable for fuel cells that work in the range of 600 – 750°C. These make use of recently-developed ceramics that are able to work at the required temperatures. Because the temperature is significantly lower, fuel cells in this range are the less severe environments for all the materials, meaning that it is possible to save costs by using alloys that are more widely produced.

Low-temperature technologies

Similar properties are required for polymer electrolyte membrane (PEM) fuel cells and electrolysers that operate at up to 100°C, although thermal expansion is less of a concern. For example, a PEFC might have 200 – 400 plates in a stack, and so the plates must be amenable to straightforward manufacture and assembly.

This type of fuel cell for mobile use needs to have the flexibility to cope with fast load changes, as a vehicle moves in traffic. In addition to this, it needs to be suitable for cold start, and provide high power density in a compact package to fit inside vehicles. Stainless steel grade such as 316L is suitable for this. It is impermeable to gas, provides both thermal and electrical conductivity, and resists corrosion. In addition, it has the required level of formability for the shaping of channels, and has the strength to provide structural integrity in a lightweight sheet even thinner than 0.1 mm, which is used in mobile PEFC.

For stationary electrolysers using the PEM technology, weight is of less importance, and usually the plates are thicker than in the mobile versions. Stainless steel is used as an alternative to titanium for this type of application, and is significantly less costly. This makes it particularly attractive for mass production.

Additional applications in the hydrogen value chain

Tubes, fittings, compressors, heat exchangers, etc are used to connect equipment and adjust the temperature and pressure of hydrogen. For many of these applications, 316L type of stainless steel shows excellent performance when coping with the low temperatures and the hydrogen diffusion.

Meanwhile, to ensure a long life for the catalyst in the electrolysis of green hydrogen, producers need to treat water into its purest form before they can use it as feedstock. The corrosion resistance of stainless steel in water filters, reverse osmosis plants, distillation and water storage tanks will protect water quality.

Similarly, when producing hydrogen from methane, oil or coal as a feedstock, producers will need to adopt carbon capture and utilisation (CCU) or carbon capture and storage (CCS). Stainless steel is also useful in the processing equipment used for this.

Conclusion: choose the right grade

There are also many applications in hydrogen use that can benefit from stainless steel's corrosion resistance, gas impermeability and strength, i.e. as a structural material in fuel cells for heating systems, as well as for tanks on vehicles and vessels. When faced with a choice of grades, it is always important to find a material with the right set of properties. There are many grades in the stainless steel family that have suitable performance for the wide range of applications in hydrogen production, storage and consumption.

THE RACE TO IDENTIFY THE NEXT GENERATION OF MARITIME FUELS

Drue Smallwood, Burns & McDonnell, USA, details the solutions under consideration to support the decarbonisation of the maritime industry.

With the International Maritime Organization (IMO) pledging to slash the industry's greenhouse gas (GHG) emissions in half by 2050, compared with their level in 2008, the question of what will power the next generation of ocean-going vessels is a matter of debate. While fuel oil, diesel and LNG are currently the fuels of choice, pressure is building to transition away from these tried-and-true resources.

Given the growing demand for international shipping, shippers have a monumental challenge before them. A 2020 IMO study of industry GHG found that, despite efficiency gains, emissions are projected to increase by up to 50% until 2050. The sector currently consumes approximately 300 million tpy of fuel, generating 2 – 3% of global carbon dioxide (CO_2), 4 – 9% of sulfur dioxides (SO_X), and 10 – 15% of nitrogen oxide (NO_X) emissions.

Further complicating matters are the sheer number of ways that the maritime industry can approach GHG reduction. High transportation, handling and storage costs can be deal breakers for fuels with lower production costs. Fuels that

are carbon-free when burned may still leave a large carbon footprint, based on the method by which they were produced.

All of the alternative fuels under consideration are currently available, albeit in insufficient volumes to meet maritime needs. None tick all of the boxes.

Consider diesel and LNG, both of which can be made in renewable forms (renewable diesel and renewable LNG). The volume needed and the cost to produce renewable hydrocarbons, however, make them unlikely candidates for maritime applications, at least at scale. RNG can be used to lower carbon intensity, but feedstock variability and availability limits its impact. Likewise, onboard carbon capture and storage (CCS) systems can be designed to collect the carbon emitted post-combustion from existing fossil-based fuels, but these systems present both cost and logistical challenges.

Biofuels, such as biodiesel and biomethanol, are arguably the most available and sustainable fuels on the planet. Made from everything from agricultural waste to sewage to vegetable oils, these fuels can be integrated into existing fuel systems to lower carbon. However, scalability and feedstock variation remain a challenge.

Nuclear energy is testing for other reasons. Despite significant improvements in nuclear reactor design and its potential as a low-cost, GHG-free source of maritime fuel, considerable social and geopolitical hurdles must be overcome before it can win the required public support.

A far more likely scenario involves replacing the fossil fuels that now power the world's 70 000 ocean-going vessels with one or more of the existing no- or low-carbon synthetic fuels. Hydrogen looks to play a central role in almost every solution under consideration.

Major shipping companies and other industry players are now studying these alternative fuels and fuel system designs to accommodate them. Some are considering ways to convert the fuel systems in existing ships, and others are looking ahead to a new generation of ocean-going vessels. At present, all options remain on the table. Because the typical vessel has a 25-year life expectancy, new technologies need to be implemented today as ships are replaced to achieve 2050 emission reduction goals.

Next-generation maritime fuel options

Renewable synthetic fuels are central to most strategies for decarbonising the maritime industry. Because the production of these fuels requires substantial energy, however, the challenge is to find ways to manufacture it in a way that is sustainable and affordable using renewable resources such as wind or solar.

Given that the fuel volume needed by the maritime industry far exceeds current synthetic fuel supply, it is likely that several different alternatives will be harnessed to power the next generation of ocean-going vessels. These include the following:

Hydrogen

Hydrogen can be an effective energy source for marine applications. Engine manufacturers are testing hydrogen firing of medium- and low-speed reciprocating engines and gas turbines. Fuel cells are an alternative power source which convert hydrogen and air directly to electric power for integrated full electric propulsion (IFEP) ships. Hydrogen combustion in engines and turbines emits no point-source CO_2 (whilst still emitting NO_X), and fuel cells emit no pollutants at all.

Most global hydrogen for industrial applications is produced from natural gas or coal. A common method of hydrogen production is via steam methane reforming (SMR) – a process that produces CO_2 as a byproduct. While the resulting hydrogen fuel from this process reduces GHG at the point of use, the CO_2 emitted from the SMR process exceeds that which is emitted during the combustion of traditional fuels on a ship. As such, replacing traditional ship fuels with hydrogen that was created using natural gas or coal does not reduce the overall CO_2 emissions fuel value chain.

When replacing traditional ship fuels with hydrogen, the hydrogen must have been generated from a carbon-free source – such as renewable power or nuclear energy – in order to have a significant impact. Currently, only about 5% of global hydrogen is produced via electrolysis – a process that utilises electric power to split water molecules into their constituent elements: hydrogen and oxygen. Another low-carbon alternative is to produce hydrogen using an autothermal reformer (ATR) and capture and sequester > 95% of the CO_2 directly from the production process. Hydrogen can also be produced from biomass using a variety of technologies – from fermentation to gasification. Biomass production can be carbon neutral, or if combined with carbon capture, even carbon negative, and can be utilised in conventional processes. However, biomass hydrogen production is not widely deployed. Cost and scalability concerns limit its ability as a bulk source of hydrogen.

Table 1. The benefits and challenges of hydrogen

Hydrogen benefits	Hydrogen challenges
Emits no GHGs when combusted or used in fuel cells	To maintain the high density needed for merchant vessel applications, hydrogen must be stored at high pressures or at cryogenic temperatures below -253°C
No emissions are generated when produced from renewable sources	At high concentrations, hydrogen fuel is not compatible with many of today's marine engines
Currently less expensive to produce than ammonia and methanol alternatives	Hydrogen has a wide flammability range and requires additional safety precautions over most other fuels
As manufacturing capacity utilising electrolysis grows and renewable technologies mature, production costs are expected to drop further	Electrolysis is a high-energy process and renewable energy sources are a higher-cost option than traditional fossil fuels

Table 2. The benefits and challenges of ammonia

Ammonia benefits	Ammonia challenges
Emits no CO_2 when combusted	Ammonia fumes are toxic
Provides a convenient, lower-cost carrier for hydrogen	Ammonia combustion can create NO_X. If not abated, nitrous oxides are more toxic than CO_2
Requires less extreme storage conditions than hydrogen. While gaseous hydrogen may need to be stored at > 10 000 psi, liquid ammonia can have similar storage and handling properties as that of propane	Production costs for low- or no-carbon ammonia are two to four times that of conventional ammonia or traditional low-sulfur fuel oil
Extensive infrastructure and expertise already exist in handling and storing ammonia	Ammonia-burning engines are still in experimental stages and not yet approved for use
One and a half to three times higher energy density than hydrogen alone, and 13 x the energy density of lithium-ion batteries	Requires a specifically-designed pipeline and tank

Ammonia

Ammonia producers have traditionally built their businesses by marketing the value of the nitrogen in the ammonia molecule. The maritime industry opens a new opportunity to market the hydrogen molecule as well. Ammonia appears to have an edge over other transition fuels as it can serve as both a direct fuel in combustion engines or as an efficient carrier of hydrogen. Manufacturers are making multi-billion-dollar investments in facilities, anticipating that ammonia will be a major player in the decarbonisation of shipping and multiple other industries. A main benefit of ammonia is that it only requires hydrogen, nitrogen (easily separated from air), and energy. No other chemical feedstocks are needed.

While ammonia does not emit CO_2 when burned, the hydrogen typically used in ammonia production is often derived from carbon-emitting sources. To produce carbon-free ammonia, the hydrogen component must be produced either through the electrolysis process or from another carbon-free renewable feedstock. In addition to this, the nitrogen component must be produced with renewable energy. Carbon generated during ammonia production can also be limited by using carbon capture techniques if natural gas is used as a feedstock. There are many pathways offering great promise for ammonia as a low-carbon fuel for the mid- to long-term.

Table 3. The benefits and challenges of methanol

Methanol benefits	Methanol challenges
Renewable methanol reduces GHGs by up to 95%	When produced with traditional methods (i.e. using natural gas), GHG emissions are only about 15% lower than those produced by low-sulfur oil
Methanol requires fewer storage restrictions than hydrogen, ammonia and LNG, and can be used at room temperature	As with ammonia, methanol requires a dedicated pipeline and storage
It is water soluble and readily biodegradable with low environmental toxicity	Demand for methanol in other industries such as chemicals will continue to compete with the fuel market
Methanol-fuelled engines are already in use, enabling shippers to transition to this fuel with less engine R&D	While fossil-based methanol is cheaper than ammonia, long-term price forecasts for renewable ammonia are lower than renewable methanol

Methanol

Hydrogen is also integral to the production of methanol – a liquid chemical already used in thousands of everyday products, including plastics, paints, cosmetics and fuels. Since methanol can be marketed to many other industry sectors, scaling production can bring further benefits and may justify manufacturing in a wider range of strategic locations.

Traditionally produced using natural gas to synthesise CO_2 and hydrogen, methanol becomes an ultra-low-carbon, renewable fuel when made using renewable electricity sources or renewable feedstocks. GHGs can also be reduced dramatically by incorporating carbon capture systems into traditional production processes. A significant drawback to methanol in a decarbonised future is securing a cost-effective bulk source of non-fossil carbon or CO_2 to form the methyl group.

A business case decision for shippers

Ultimately, the fuels that shippers choose to propel the next generation of ocean-going vessels will be a business case decision, based both on fuel production costs and total life cycle costs, including storage, handling and transportation. Shippers will also need to consider their fleet age, the cost and time lost for potential fuel system upgrades, and their goals for the reduction of GHG, as well as SO_X, NO_X and other emissions. Ship design, fleet management, operations and incentives will also play significant roles in achieving the industry's ambitious goals. All are part of the bigger equation.

The calculations can be complex. Consider hydrogen, which is less expensive to produce than ammonia and methanol, but significantly more expensive to handle and store. Likewise, ammonia – even when produced from natural gas – is two to three times the price of natural gas, and 50% more expensive than methanol produced from fossil fuels. Other methods of renewable and sustainable ammonia production are also more expensive than synthetic hydrogen production.

Apart from in California, there is little state or federal government funding available to offset the production and use of these alternative fuels in the US. Even tax incentives available through Section 45Q of the US tax code that incentivise the construction and deployment of CCS projects have limited application. These credits support capturing carbon, rather than using carbon-free fuels, and the credits are not sufficient to cover the hundreds of millions of dollars needed to build and operate large-scale facilities. Despite this, other countries around the world are incentivising industry to implement these alternative fuels, and the US will likely follow the same path.

As alternative fuel use expands and supply grows, costs will continue to come down. However, the projects needed to kickstart the transition do not yet offer economies of scale. For the maritime industry to meet its ambitious decarbonisation goals, it will take shippers and manufacturers leading the way to reduce the carbon intensity of their fuels; governments incentivising industry players; and end users willing to pay the extra cost.

Looking ahead

If the maritime industry has learned one thing in its search for its next-generation fuel and vessel, it is that there will be no one silver bullet solution that will address the needs of all ocean-going vessels.

During the transition period, flexibility is essential. Only through studies and testing can shippers identify the environmental and financial options best suited to their needs. Additionally, it is likely that the transition will require shippers to have redundancy in their fuel supply until the technology and cost become more developed. Once decisions are made, it will take time to construct not only these next-generation ships, but also the fuel terminals and production facilities required to support this transition. The year 2050 is just 28 years away, and the clock is ticking.

NEWS

LG Chem selects Technip Energies' blue hydrogen technology

LG Chem has selected Technip Energies' proprietary blue hydrogen technology to supply its Daesan complex in South Korea.

The Blue H_2 by T.EN™ hydrogen plant will capture a significant amount of carbon dioxide (CO_2), and reduce carbon emissions from the petrochemical complex. LG Chem intends to utilise the captured CO_2.

The 56 000 Nm³/hr capacity hydrogen plant will utilise Technip Energies' proprietary steam reforming technology to convert methane-rich offgas from the naphtha cracking process into hydrogen. The hydrogen plant will include a selective catalytic reduction (SCR) unit for control of NO_x emissions.

The new hydrogen unit will be integrated with LG Chem's naphtha cracking complex (NCC) to allow LG Chem to convert the petrochemical pyrolysis complex to a more sustainable low-carbon process.

ABB and Hydrogen Optimized Inc. expand hydrogen partnership

ABB and Hydrogen Optimized Inc. (HOI) have signed an agreement to expand the companies' existing strategic relationship. This includes an investment by ABB into Key DH Technologies Inc. (KEY), as the companies seek to accelerate the green hydrogen production segment with unique large-scale architecture.

By accelerating this strategic collaboration, the two companies are advancing the deployment of economic large-scale green hydrogen production systems to decarbonise hard-to-abate industries.

The companies will leverage their respective capabilities and resources to rapidly commercialise HOI's patented RuggedCell high-power water electrolysis technology for the world's largest green hydrogen plants. This technology converts renewable electricity such as hydro, solar and wind power into green hydrogen for industry.

Worley awarded contract for Vertex Hydrogen's low-carbon hydrogen plant

Worley has been awarded a project management services contract by Vertex Hydrogen for a low-carbon hydrogen production plant at Stanlow Manufacturing Complex in Ellesmere Port, UK.

The 350 MW plant is the first in the UK to have completed front-end engineering, and is expected to be one of the first large-scale and low-carbon hydrogen plants in the world.

The plant will allow UK industrial businesses to transition away from fossil fuels, capturing around 600 000 tpy of carbon dioxide (CO_2). It is also an integral part of HyNet, one of two UK Government Track 1 clusters for industrial decarbonisation.

"Hydrogen has the potential to decarbonise hard-to-abate sectors, and this project is essential to the decarbonisation journey of the HyNet low-carbon cluster in the UK," said Chris Gill, Vice President Low-Carbon Hydrogen at Worley.

Worley's scope will cover the inside battery limit of the production plant, and all necessary outside battery limit works. It also includes support in creating the infrastructure needed to connect to feedstocks, products, and modifications within the refinery to accept low-carbon hydrogen as a means of powering production, instead of fossil fuels. The company's UK teams will deliver the work with support from its global experts.

"We are moving rapidly to deliver this vital plant and are delighted to have Worley onboard who share our vision to deliver real projects fundamental to the energy transition," said John Egan, Project Director at Vertex Hydrogen.

"We'll utilise our global expertise in low-carbon hydrogen with local teams in the UK to help Vertex Hydrogen achieve its vision and support our purpose of delivering a more sustainable world," added Gill.

Linde inaugurates hydrogen refuelling system for passenger trains

Linde has inaugurated the world's first hydrogen refuelling system for passenger trains in Bremervörde, Germany.

Linde's hydrogen refuelling system, which it built, owns and operates, will refuel 14 hydrogen-powered passenger trains, enabling each train to run for 1000 km emission-free on a single refuelling. It has a total capacity of around 1600 kg/d of hydrogen, making it one of the largest hydrogen refuelling systems ever built. Linde's future-ready hydrogen refuelling system has been designed and constructed with the ability to integrate future onsite green hydrogen generation. The new hydrogen trains will replace existing diesel-powered trains.

"Linde is committed to making a significant contribution towards decarbonising transport in Europe," said Veerle Slenders, President Region Europe West, Linde. "We are proud that Linde's innovative technology plays a key role in supporting this project and establishing a blueprint for cleaner public transport systems around the world."

Denmark to lead global hydrogen pipeline additions

For planned and announced hydrogen pipeline projects between 2022 – 2026, Denmark is expected to lead in terms of global length additions, contributing around 35% of the total global hydrogen pipeline additions in this period, reports GlobalData.

The company's latest report, 'Hydrogen Pipelines Length and Capital Expenditure (CapEx) Forecast by Region, Countries and Companies including details of New Build and Expansion (Planned and Announced) Projects, 2022- 2026', reveals that Denmark is set to have a total hydrogen pipeline length of 800 km by 2026, through announced projects.

Himani Pant Pandey, Oil and Gas Analyst at GlobalData, said: "Holstebro–Hamburg is the largest upcoming hydrogen pipeline project in Denmark with a length of 450 km. Expected to start operations in 2025, the pipeline aims to supply green hydrogen from offshore wind farms in Denmark to Germany to meet local industrial demand."

In brief

UK

Essar Oil UK has taken delivery of the first-ever hydrogen-powered furnace at a refinery anywhere in the UK, at its Stanlow site in Ellesmere Port. The furnace is capable of running on a 100% hydrogen source, and will replace three existing furnaces at Stanlow. Hydrogen used by the new furnace from 2026 will be produced by Vertex Hydrogen.

Namibia

Hyphen Hydrogen Energy is making positive progress on its discussions with the Namibian government as it moves towards the signature of the Implementation Agreement before the end of 2022 for its planned US$10 billion Namibian green hydrogen project. At full-scale development, the project is expected to produce approximately 350 000 tpy of green hydrogen before the end of the decade.

USA

BayoTech, an innovator in hydrogen solutions, has received an order for four HyFill™ hydrogen transport trailers from Chevron, one of the world's leading integrated energy companies. Chevron will use BayoTech's transport trailers to distribute high-pressure gaseous hydrogen for power generation, transportation, and industrial applications in the western US. Delivery is scheduled for 1Q23.

NEWS

Air Products and Associated British Ports partner on renewable hydrogen production

Air Products and Associated British Ports (ABP) have announced their intention to partner in bringing the first large-scale, green hydrogen production facility to the UK.

The facility would import green ammonia from production locations operated by Air Products and its partners around the world. This would be used to produce green hydrogen.

The UK government has plans for 10 GW of low-carbon hydrogen to be in production or construction by 2030. Currently, there is no significant domestic production of such hydrogen in the UK.

Air Products aims to help drive progress towards these targets, addressing the urgent task of decarbonising hard-to-abate sectors, and reducing the UK's dependency on fossil fuels.

The project will bring a wide range of benefits, eliminating up to 580 000 tpy of greenhouse gas emissions – the equivalent of taking 20 000 diesel HGVs off UK roads, as well as reducing nitrous oxide and particulate emissions.

Everfuel signs MoU with Karlstads Energi for hydrogen hub

Everfuel A/S has announced the signing of a Memorandum of Understanding (MoU) with Karlstads Energi in order to collaborate on the development of a hydrogen hub in Karlstad, Sweden.

The two parties plan to explore the commercial and technical feasibility of constructing a 20 MW electrolysis facility as a first phase of the hub development. The facility is intended to produce green hydrogen, supply excess heat to the local district heating owned and operated by Karlstads Energi, utilise the produced oxygen for industry purposes, and supply green fuel to both mobility and industry partners.

Everfuel and Karlstads Energi have a joint ambition to further develop the hub and expand the electrolyser capacity with an additional 100 MW in a second phase. The first phase is expected to be commissioned in 2025, depending on funding and permitting.

The project is intended to be a joint venture between Everfuel and Karlstads Energi, where Everfuel is the majority owner.

BP and thyssenkrupp Steel work together to advance the decarbonisation of steel production

BP and thyssenkrupp Steel have signed a Memorandum of Understanding (MoU) focused on the development of long-term supply of low-carbon hydrogen and renewable power in steel production. The move will help accelerate the steel industry's wider energy transition.

thyssenkrupp Steel accounts for 2.5% of carbon dioxide (CO_2) emissions in Germany, mainly at the Duisburg site where the main emitters, blast furnaces, operate. By replacing the coal-fired blast furnaces with direct reduction plants where iron ore is reduced with low-carbon hydrogen, thyssenkrupp Steel intends to make steel production climate-neutral in the long-term.

The companies will explore supply options for both blue and green hydrogen, as well as power from wind and solar generation through the use of power purchase agreements, and will jointly advocate for policies that will support the development of low-carbon hydrogen and the growth of green steel in Europe.

Woodside to drive the development of Australia's local hydrogen market

Woodside Energy, BGC and Centurion, with the support of the Western Australian government, are advancing plans for a proposed self-contained hydrogen production, storage and refuelling station, located in the Rockingham Industry Zone, Australia.

The project was successful in the Expressions of Interest stage of the Department of Jobs, Tourism, Science and Innovation's AUS$10 million Hydrogen Fuelled Transport Program. This programme aims to accelerate the uptake of hydrogen-fuelled transport, build local skills and capability, and stimulate local hydrogen production.

With matched funding from Woodside, the proposal targets the delivery of hydrogen fuel at a globally-competitive price of AUS$11/kg, and subsidises a number of large hydrogen fuel cell electric vehicles.

Named the Hydrogen Refueller @H2Perth, the project would be located adjacent to Woodside's proposed H2Perth project – a proposed domestic and export-scale hydrogen and ammonia production facility.

Ohmium and Shell India to investigate new hydrogen project opportunities

Ohmium International is collaborating with Shell India to evaluate hydrogen applications, markets and project opportunities in India and globally. As part of the collaboration, both parties intend to launch joint working groups to assess opportunities from the technical, commercial and safety perspectives.

Ohmium's interlocking modular PEM electrolysers provide an alternative to customised electrolysers. The collaboration is positioned at elevating Shell's ambition to help build a global hydrogen economy by developing competitive opportunities in the production, storage, transport and delivery of hydrogen to end customers.

"We have set an ambitious goal of becoming a net zero emissions business by 2050 with a target to reduce absolute emissions by 50% by 2030. Green hydrogen has a critical role in helping the world reach zero emissions" said Nitin Prasad, Chairman, Shell Group of Companies in India.

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