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Unlocking the Green Hydrogen and Power-to-X Market: A Holistic Approach to Safety and Sustainability

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Abstract

Renewable energy creates challenges for a world that needs a constant, reliable supply to meet demand. Green hydrogen and power-to-x play a key role in bridging the supply-and-demand gap to accelerate clean energy transition. However, scaling up green hydrogen production to industrial size (100MW+) poses unfamiliar technical, economic, and environmental challenges, especially in terms of safety and sustainability.

This paper presents a holistic approach answering to the challenges in Green Hydrogen industrial installations, including safety, environmental, and water scarcity risks. It mentions how these risks could be mitigated through innovative integrated and mutualized design, breaking barriers with electrolyser supplier. This synergy between safety and optimization leads to cost reductions and paves the way for unmanned platform possibilities.

As a joint venture of Technip Energies and John Cockerill, Rely brings together the expertise of two industry leaders: Combining know-how in large-scale engineering projects and technology innovations.

Our parent companies have safely delivered over 1,000 hydrogen electrolysers and successfully built over 30% of installed hydrogen capacity worldwide, making Rely a strong partner for companies looking to develop and implement large-scale hydrogen projects that are cost-competitive, sustainable, and reliable.

Introduction

The role of low-carbon hydrogen and its derivative molecules, or Power-to-X, are clear: They play an important part in the Global Net Zero emissions roadmap, especially in decarbonising the hard-to-abate emissions sectors such as industry and transport. Although industrial solutions exist to-date, there remains a gap between market expectations and the reality of projects realized. The levelized cost of hydrogen (LCOH) for green hydrogen remains far from competitive. Lack of technology robustness, clarity on risks, and firmness on policies and regulations make it a challenge for projects to financially take-off.

Although hydrogen (H2) has been industrially used in human activities since the early 20^{th} century, and safety protocols exist, industrial-scale green hydrogen (GH2) production facilities of 100 MW capacity and above are not yet common to-date.

This paper highlights the challenges posed by safety and environmental risks associated with large scale green hydrogen plant listed below, and how these risks are managed throughout design, engineering, procurement, construction, commissioning, and operation.

- Safety
  - Risks associated with exposure at scale to hydrogen reactivity, wide flammability range and low ignition energy, and likelihood to leak.
- Environmental
  - Risks of competition for fresh water in areas where renewable power is abundant and thus large-scale green hydrogen production installations are most competitive.
  - Risks of potential indirect climate impact of hydrogen releases in atmosphere, believed to contribute to increasing methane's atmospheric lifetime.

It discusses how Clear100+, Rely's productized yet configurable 100MW green hydrogen plant solution, addresses these challenges. Key features include the seamless integration of pressurized alkaline technology in the balance of plant, safety-driven optimal layout design, water consumption and hydrogen fugitive and vented emissions management solutions. Alongside these design features, the plant integrated control system with multi-electrolyser controller ensures an optimized distribution of renewable energy and extends the lifetime of the electrolyser, whilst keeping plant load factor at optimum.

Future generations of our product will embark the technology innovations in core electrolysis and balance of plant, integrating and mutualizing the systems to further drive down the LCOH. Our integrated energy management system (iEMS) digital solution is being developed alongside to provide optimum setpoint recommendations to plant operators and certify the use of green electrons in the production facility, preparing for plant remote operation in the future.

Today, the odds are high for large scale green hydrogen market to take-off and Rely is in a unique position to be part of the solution. With our mother companies' proven expertise and industrial experiences in manufacturing Electrolysers, and safely designing, and delivering industrial scale Hydrogen facilities worldwide, our integrated product and the future innovations that it will embark, and strong collaborations with key technology players and supply chain partners, our holistic approach will thus be key to successfully unlock this market.

Green Hydrogen & Power-to-X Market Challenges

The role of Hydrogen and its derivatives in Net Zero Roadmap

The International Energy Agency (IEA) roadmap to achieve net zero emissions by 2050 requires a radical transformation of the global energy system. The roadmap highlights seven key solutions to achieving the Net Zero, amongst which the need to massively electrify our energy consumption. It also states that hydrogen and its derivatives, such as ammonia, synthetic fuels and methanol, are essential to decarbonize sectors that are hard to electrify, such as heavy industry, long-distance transport and aviation. The IEA estimates that hydrogen and hydrogen-based fuels could provide around 20% of the total energy demand by 2050, compared to less than 1% today. This would require a massive scale-up in the production of low-carbon hydrogen, mainly from renewable electricity and electrolysis, commonly known as green hydrogen, as well as the development of infrastructure and markets for hydrogen and its derivatives.

The gap between market expectations and reality

With the geopolitical and climate change-driven energy transition comes the energy trilemma – the challenge to provide energy that is secure, affordable and sustainable. For hydrogen and its derivatives, this means ensuring that they can be produced, stored and transported safely and reliably, whilst remaining cost-competitive, without compromising on environmental impact. However, the current technologies and markets are not yet ready to meet this challenge, as there is a price gap between low-carbon and fossil-based alternatives, a lack of proven solutions at scale, and policies & regulations clarity and firmness. Market needs confidence that investments will see financial returns, technologies will be reliable, and risks are safeguarded.

Bridging the gap

In order to achieve market competitiveness for green hydrogen and its derivatives, it is essential to reduce the LCOH of green hydrogen. This is achieved by reducing the risks, improving the efficiency and performance of electrolysis technologies, increasing the availability and affordability of renewable electricity, and increasing the facilities load factor.

Safety in Large Scale Green Hydrogen Installations

Introduction

Hydrogen specific characteristics compared to other fuels or flammable materials shall be taken into consideration when dealing with safety of hydrogen installations. Hydrogen is the smallest molecule in the world which makes hydrogen prone to leak thus increasing the likelihood of loss of containment. Its high reactivity (hydrogen burns eight times faster than natural gas) means that it can cause explosions with higher overpressure than conventional hydrocarbons. The wide flammability range and low ignition energy of hydrogen contribute to its elevated risk profile, making safety a paramount concern in its handling and use. The fact that there is limited reference data of industrial hydrogen safety incidents and green hydrogen plants of 100MW and above are yet rare, expertise and rigour are required to understand and manage the risks.

Pressurized Alkaline Technology

For large scale production of 100MW and above, there exist mature electrolysis technologies such as Alkaline Water Electrolysis (AWE) and Proton Exchange Membrane (PEM). This paper focuses on AWE, the technology that has the most proven track record for large scale green H2 production.

In terms of safety, 15-30barg pressurized AWE have many benefits over its atmospheric equivalent. One of it being no vacuum risk in case of system shutdown, as no Nitrogen purging or H2 buffering is required to prevent air ingress, making it more robust to intermittency. H2 flare system operation and leak monitoring in equipment like exchangers are simpler. Overall, pressurised AWE has a higher response rate, is more space-efficient, and has reduced compression and water consumption needs.

Overview of Main Safety Risks

The safety considerations for pressurized alkaline green hydrogen projects are detailed below:

- **Leakages**: Pressurized systems at 15-30 barg can produce a higher release rate than atmospheric alkaline systems, which necessitates robust leakage monitoring and prevention strategies. There exist also risks for KOH electrolyte solution with H2 or with O2, leaking at higher pressure.

- **Risk of Mixing Gases**: There is a higher probability of hydrogen (H2) and oxygen (O2) mixing in the separation/stack, which can create a potentially explosive environment.
- **Diaphragm Damage**: Unbalanced pressure can lead to a higher risk of damaging the diaphragm that separates the 2 half-cells, affecting the integrity and safety of the system.
- **Electrical Risks:** Presence of high voltage electricity in the plant, electrochemical reaction risks.
- **Vents Releases**: H2 releases during depressurisation & continuous O2 releases, when it is not valorised as by-product (in most cases).

The major risks with potential for hazardous consequences escalating to a potential fatality, are highlighted below:

Table 1 – Major risks in a GH2 plant system

Plant System Localization	Major Risk
Electrolyser Stack	Pressurized Leakage (KOH + H2) H2/O2 mixture inside stack cells (HTO crossover) Electrical shock
H2 / O2 Lye Separators	H2/O2 mixture formation inside one separator (HTO crossover) Pressurized H2 leak with potential for fire and explosion in case of ignition Pressurized O2 leak with potential for fire and explosion in case of ignition H2 transfer in O2 separator, and vice versa
Purification & Drying Unit	Pressurized H2 leak
Compression System	Pressurized H2 leak

Leakage inside the Stack causing H2 to O2 (HTO) crossover is less critical than the leakage inside the separators, due to inventory volume differences. Additionally, within the stack, gases are diluted in a relatively cool lye solution, providing inertia and the ability to absorb minor explosions. Other main H2-associated risks to consider globally at plant level are H2 leakages inside the electrolyser stack building, and H2 metal embrittlement, a known phenomenon in the industry. References to past H2 installations incidents exist but not as well documented as the Oil & Gas industry. This remains a challenge in understanding the risks and standardizing the mitigation approach.

Inherent Safety in Design

For effective risk mitigation, there exist the Inherently Safer Design (ISD) principles categorized by the Centre for Chemical Process Safety (CCPS). These principles include:

- Minimise or eliminate the hazard source wherever possible,
- Substitute a material with a less hazardous one,
- Moderate, or reduce the strength of a hazardous effect, and
- Simplify, or design the facility to reduce complexity, increasing resilience to possible human errors.

Implementing this ISD philosophy is crucial to preventing or mitigating hazards in the process design of hydrogen handling facilities. Hence implementing ISD as far as practicable has been a key driver for Rely in developing its Clear100+ product.

Risk Assessment through Safety Studies

To effectively manage the risks involved in a large-scale green hydrogen production facility, and implement safety-by-design (ISD) philosophy to safeguard the installation, a series of safety and environmental risk analysis are carried out:

- Safety Concept
- Flammable Gas & Fire Detection Philosophy
- Hazardous Area Classification (ATEX)
- Emergency Shutdown and Depressurization philosophy
- HSE Reviews including:
  - HAZID => Hazard Identification Study
  - ENVID => Environmental Identification Study
  - HAZOP => Process Safety Hazard & Operability Scenarios Identifications & safeguarding
  - SIL/LOPA => Safety-instrumented functions (SIF) requirement and design

Furthermore, to effectively assess and manage the risk associated with a large-scale green hydrogen facility, detailed HSE studies are performed:

- Noise study
- Consequence Analysis -> based on worst credible scenarios

- Quantitative Risk Analysis (QRA) – rigorous analysis of all identified scenarios, including CFD Dispersion and Explosion assessment

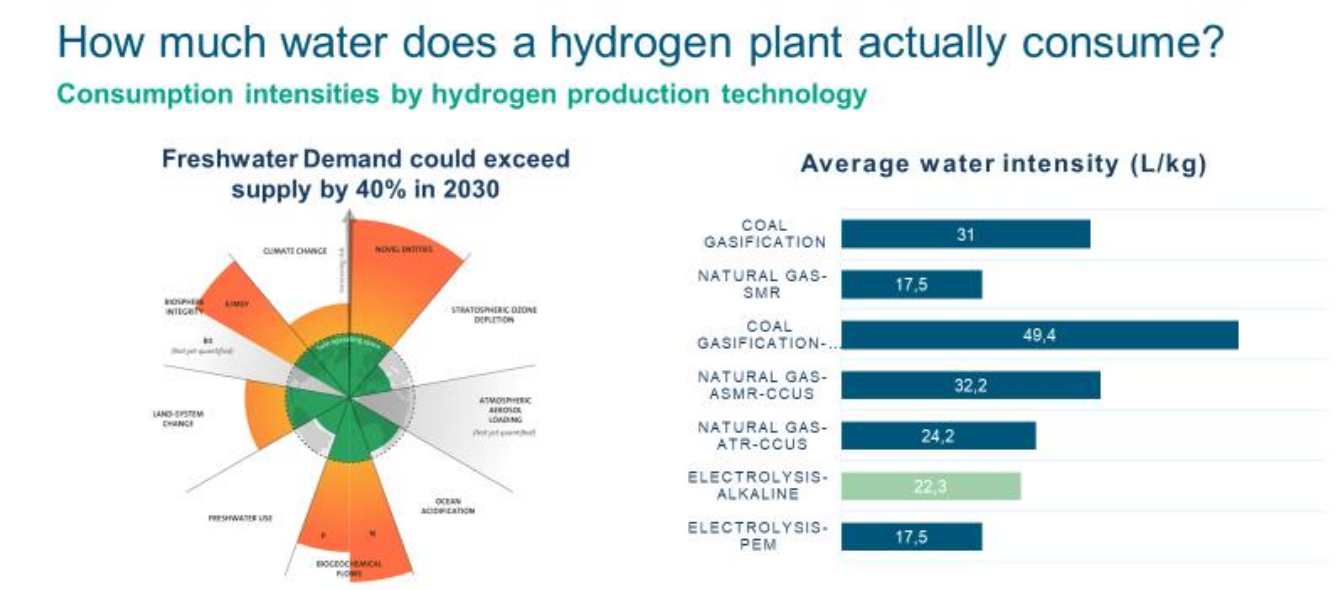
Doing the above suite of HSE-in-Design activities from the preliminary reviews (HAZID & ENVID) to the detailed risk assessments such as QRA is key to rigorously identify, understand, and manage the overall safety and environmental risks at plant scale.

Environmental & Sustainability Considerations

Water Consumption

Amongst various industrial H2 production routes today, green hydrogen is the most water-efficient, while coal gasification is the most water-intensive. Freshwater withdrawals for global hydrogen production could more than triple by 2040 and increase six-fold by 2050, driven by the expansion of global demand for hydrogen. Notably in Northern China, GCC countries, and EU the risk of water stress is significant.

Figure 1 – Freshwater demand projections 2030 & average water intensity for various hydrogen production pathways (source: Adopted from Richardson et al., "Earth beyond six of nine boundaries," 2023. IRENA and Bluerisk (2023), Water for hydrogen production, International Renewable Energy Agency, Bluerisk, Abu Dhabi, United Arab Emirates.

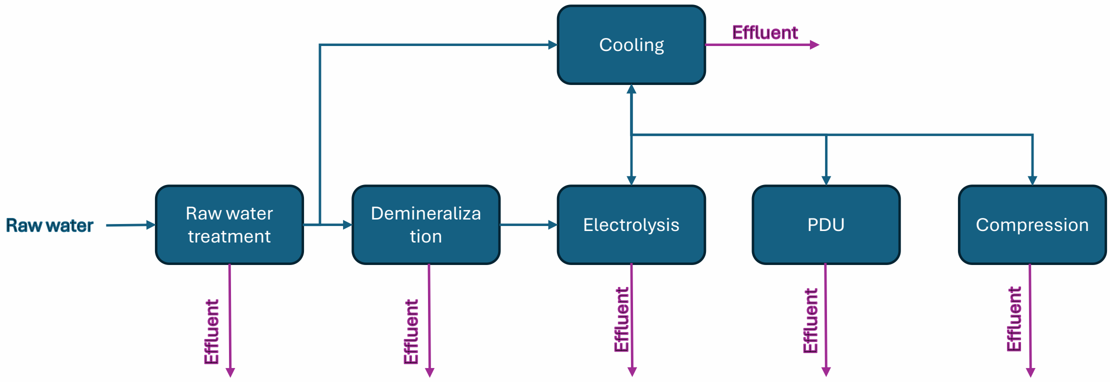


Green hydrogen production is most optimal where green electricity generation is most abundant and accessible. Several regions around the world have been identified as optimal locations, including Egypt, Australia, Namibia, Oman and Chile. However, these same areas have high risk of water stress. Sobriety in water consumption and utilization of unconventional water resources are thus key to the success of future GH2 projects.

Water & Effluents Management

Below schematic describes the overall water balance in a typical GH2 production plant:

Figure 2 – Block Flow Schematics of Water Balance in a Typical green hydrogen production plant (source: Rely)



Water Consumption

Three major water consumers in a GH2 production unit include:

1. **Electrolyzer feed water:** Demineralized water needed for the electrochemical reaction producing hydrogen. Losses during pretreatment and demineralization of raw water source range from 10-30% for soft to hard fresh water whilst using saline water could lead up to 70% losses. Two main demineralization technologies are ion exchange and membrane-based (e.g. reverse osmosis and electro-deionization), which is preferred although has more water losses as it does not need to deal with brine regeneration discharge and high chemical use.
2. **Make-up water for cooling systems**: Cooling is needed for the electrolyte circulating thru the stack. Optimizing the cooling system is crucial to reducing the GH2 unit's water demand, which can account for over 70% of the plant's overall water consumption. Combinations of different

cooling systems technologies (air coolers, open-loop, semi-open loop) should be explored to optimize water usage.

3. **Lye change-out and maintenance** needs demineralized water for batch dilution and cleaning. The frequency of these operations and the lye concentration are related to the electrolysis stack technology.

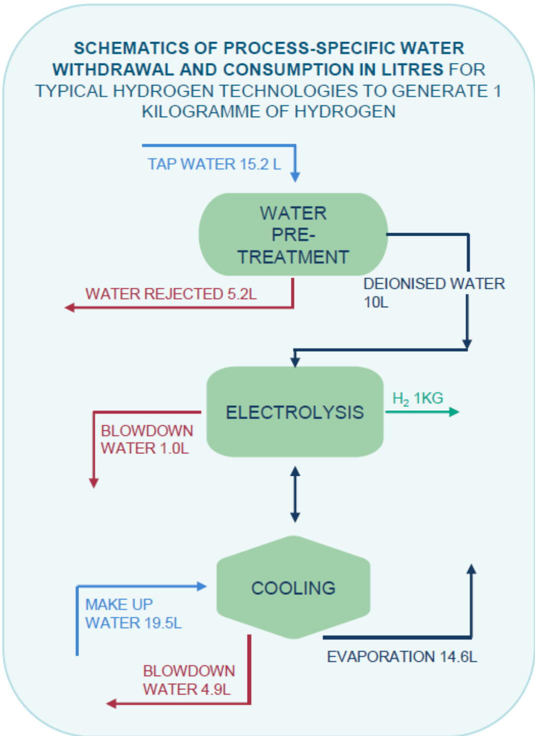
Water Effluents

Four main effluents are produced by a GH2 plant:

1. **Reject from the demineralization unit:** Volume and composition depend on the feed water source. It can be concentrated from an ultrafiltration unit, brine from a reverse osmosis unit. These effluents contain suspended solids, conditioning chemicals, and 2-5 times higher minerality than the feed water. In case of usage of ion exchange technology, the produced brine has a salinity close to sea water.
2. **Condensates from PDU Unit:** This effluent contains traces of lye from electrolyser liquid carryover and may also contain traces of metals such as iron and nickel from lye pollution over time.
3. **Cooling systems blowdowns:** Depending on the cooling technology, it may be large continuous (open-loop, or evaporative cooling) to small intermittent (closed-loop). Traces of chemicals such as biocide and corrosion inhibitors may be present.
4. **Effluents from maintenance operations:** These effluents contain about 1 g/l of lye and pollutants that may have built up during the electrolyzer operation, such as iron and nickel.

Figure 3 below further shows an example of typical order of magnitudes for water consumptions and rejects with tap water quality feed.

Figure 3 – Example of Water Balance in a Typical green hydrogen production plant (source: IRENA and Bluerisk (2023), Water for hydrogen production, International Renewable Energy Agency, Bluerisk, Abu Dhabi, United Arab Emirates)



Water Consumption Philosophy

To reduce water demand from conventional sources (i.e. fresh water sourced from surface waters or ground waters), the 3R (Reduce, Reuse, Recycle) philosophy shall be applied:

- **Reduce**: Selecting low water consumption technologies whenever possible, without impacting the overall efficiency of the production unit. This includes implementing air cooling systems or open loop cooling to minimize water use;
- **Reuse**: Identifying opportunities where a water stream exiting one unit may be of suitable quality to be used as a water source by another unit. This can be determined through a water pinch analysis. Additionally, the reuse of low concentration effluents from one unit as feed to another, or using rainwater collected on the plant is also considered;

- **Recycle**: After minimizing effluent quantities through the Reduce and Reuse strategies, the remaining wastewater is treated to remove contaminants, achieving a water quality grade suitable for the plant's usage.

Potential Climate Impacts

Several reputable scientific sources[i] have associated H2 emissions with risks of indirect global warming effect. Research suggests that hydrogen interacts with tropospheric hydroxy radicals, inhibiting their ability to break down methane, a greenhouse gas with significant warming effects. Consequently, this increases methane's atmospheric lifetime. Universally, climate experts agree on the necessity to reduce all types of hydrogen emissions, both vented and fugitive, to accomplish the full benefits of GH2 in GHG emissions abatement.

With unclear regulatory standards, measuring and monitoring the releases, as well as interpreting the gravity of the impact remain a challenge today. It is thus essential to stay in the loop of regulatory developments while scouting technological advances in measurement, reporting, and verification (MRV) solutions. Means to mitigate at-source venting emissions such as thermal oxidation are to be considered.

Rely's "Clear100+" Productized Plant Solution

Clear100+ productized yet configurable large scale green H2 plant solution has been conceived putting safety and sustainability in the heart of its performance.

Safe-by-design

- The core electrolysis technology embedded is a proven 15barg pressurised alkaline, no continuous safety purging system required.
- **Comprehensive Safety Measures**: Clear100+ includes results of extensive safety reviews such as HAZID, ENVID, HAZOP/SIL/LOPA, and risk analysis such Consequence Analysis, QRA, as well as detection philosophy for flammable gas, oxygen, and fire, hazardous area classification, and emergency shutdown philosophy to ensure safety in all plant operating modes. QRA includes CFD

studies for dispersion and explosion modelling, and dynamic simulations were completed to model the effectiveness of the Safety-Instrumented Functions in place.

- **Inherent Safety Design**: Clear100+ promotes inherently safer design by minimizing potential major scenarios, installing most equipment outside the electrolyser building, reducing H2 inventory accumulation in confined space. Process and electrical equipment are segregated to separate flammable from ignition sources. Layout carefully considered for easy handling, no lifting for electrolyser stack replacement. Balance of plant is mutualized to minimize flanges and connection points, i.e. source of leaks. Layout design ensures no worst credible scenario occuring outside the fence, and no hazardous escalations between adjacent Clear100+ plots.
- **Project Customization**: Although Clear100+ is pre-designed as product, it can be configured to specific project requirements and local norms with minimal impact, thanks to all the safety studies carried out and risks analysis quantified.

Sustainable-by-design

- **Water Consumption:** The core technology of the electrolysis integrates a performant stack that reduces the need for cooling. Clear100+ configurable design easily adapts to specific site conditions and regulations. As a basis, air cooling is integrated in the design, most adapted to high water stress areas.
- **Energy Efficiency:** With the performant John Cockerill Hydrogen "P-Series" 15barg pressurized alkaline electrolyser stack seamlessly integrated in the balance-of-plant of Clear100+, less energy is required for H2 production and compression. The Plant integrated control system comprises an electrolyser system controller that orchestrates multiple electrolyzers operation, enhancing overall performance and delaying wear during intermittent usage.
- **Minimising Climate Impacts:** A hydrogen flaring system is in place to prevent cold venting, and efforts are made to minimize venting to only leaks and small quantities from analysers. The balance of plant systems is insulated to withstand fluctuations in renewable power sources.

Combining a standardized approach with a single, whole-plant Energy Management System, Clear100+ optimizes both CAPEX and OPEX to deliver the lowest cost of hydrogen. LCOH is calculated by dividing the total cost of producing hydrogen over the lifetime of the plant by the total amount of hydrogen produced. By focusing on risk reduction and management, Clear100+ increases confidence in overall performance guarantees. This is further enhanced when coupled with comprehensive Operations and Maintenance (O&M) strategies, creating a holistic approach to Levelized Cost of Hydrogen (LCOH) reduction. Leveraging digital technology, we support the plant's life cycle, offering solutions and operational optimizations, including predictive maintenance.

Innovating for Future Generations

Thanks to our unique positioning, the strong foundations built by our mother companies, our technology DNA and our partnership collaborations, the evolution of green hydrogen and power-to-x technologies will continue to feed the next generations of our products and solutions.

Our innovations span from scaling up next generation electrolysers with our technology partners, integrating them in the balance of plant design, pushing boundaries with new materials and mutualization of equipment to drive down the LCOH of 100MW and above production. Process integrations with downstream e-molecule synthesis technologies to increase flexibility and load factor optimization are key focuses on our roadmap, with the Energy Management System development which aims to optimize the distribution of each renewable electron to the final molecule. Life Cycle Analysis (LCA) is in our agenda; as we integrate LCA in our design and technology selection criteria for the future operations to the end-of-life of the installations.

Conclusion & Key Takeaways

GH2 market challenges remain its affordability, security, and sustainability. A **holistic approach** is therefore needed to build and deliver robust solutions. Having safety and environmental sustainability **inherently designed** at the heart of our solutions will drive down LCOH and achieve long-term competitivity.

Clear100+, our productized-yet-configurable solution comes with overall performance guarantee, pre-derisked safety, giving peace of mind for long-term operability and durability.

Our innovation and R&D teams continue to work on next-gen technologies integration and O&M digital solutions, and together with our partners we accelerate the adoption of future technologies at large scale in our products & solutions.

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[i] Clean Hydrogen Joint Undertaking; U.S. Department of Energy; European Commission; Hydrogen Europe; Hydrogen Europe Research; the Hydrogen Council; International Partnership for Hydrogen and Fuel Cells in the Economy
All contributors to the JRC report