Industrial Decarbonisation Frontiers Report

Hydrogen Generation

Since its launch in 2021, the Industrial Decarbonisation Research and Innovation Centre (IDRIC) has funded 100 projects, investigating and addressing the key dimensions of the whole system of industrial decarbonisation. This work has generated a vast body of knowledge, offering critical insights into the challenges we face in decarbonising and into the solutions – technical, economic and social – that are emerging. The *Frontiers Reports* series brings together all these insights to share with our industry and policy stakeholders.

Each report synthesises key findings from multiple projects conducted on a closely related theme, providing a comprehensive perspective on a specific aspect of industrial decarbonisation. Far more than simply research summaries, these reports translate academic insights into practical, evidence-based recommendations for our stakeholders. These recommendations are shaped by the expertise and evidence gathered by our research teams and are designed to support decision-makers in advancing their net zero goals.

The *Frontiers Reports* are anticipated to serve as catalysts for meaningful discussions between academia, industry, and policymakers on the most viable paths forward. We welcome constructive debate and are eager to support the implementation of recommendations that best align with our stakeholders' priorities and goals towards net zero.

This report brings together all IDRIC's research on Hydrogen Generation.

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Executive summary

Hydrogen is a critical component of the United Kingdom's strategy to achieve net zero emissions by 2050, particularly for industrial decarbonisation in hard-to-electrify applications and for large-scale energy storage. The UK Government's ambition to produce 10GW of clean hydrogen by 2030 and scale this to between 250–460 TWh by 2050 underlines the importance of developing efficient, scalable and cost-effective hydrogen generation. IDRIC's research addresses major challenges in clean hydrogen generation, including improvements in low- and high-temperature electrolysis, use of co-products, hydrogen production and recovery from industrial streams, hydrogen carriers and point-of-use generation.

Key findings

Green and blue hydrogen trade-offs
Green hydrogen produced via wind-powered electrolysis offers significant emissions reductions, with up to 95% compared to natural gas use. Blue hydrogen is more energy efficient than green hydrogen but results in up to four times greater emissions impact.

Environmental impacts
Life cycle assessment (LCA) methods across the hydrogen value chain are inconsistent which makes comparisons difficult. This highlights the need for a harmonised approach to LCA and specifically more comprehensive data on energy use, water consumption, land use and waste generation – especially beyond the hydrogen production stage.

Hydrogen safety and regulation
Hydrogen's unique characteristics – including rapid dispersal, wide flammability range and risk of material embrittlement – require robust safety management. The UK possesses a robust foundational safety regime, but further refinement is necessary to address hydrogen-specific hazards across the supply chain, including offshore production. Improved alignment with global best practices is recommended.

Electrolysis and co-product valorisation
Electrolysis remains central to green hydrogen deployment. Whilst PEM electrolysers are achieving full commercial viability, emerging Anion Exchange Membrane electrolysers are showing promise. Co-production of oxygen could potentially lower costs and energy use in sectors like wastewater treatment and steelmaking. However, there is also potentially significant underexplored value from other electrolysis co-products. High-value oxidants (e.g., hydrogen peroxide, ozone) could significantly improve system economics.

High-temperature electrolysers
High-temperature electrolysers improve efficiency by using waste heat, replacing up to 20% of electrical energy with thermal energy. Industrial processes, such as methanol and ammonia production, generate heat that could offset electrolysis energy costs. These electrolysers are also well-suited to producing carbon-based molecules, making them ideal for syngas applications in the UK chemical sector.

Hydrogen recovery
Technologies such as Sorption-Enhanced Water Gas Shift (SEWGS) show promise in recovering hydrogen and separating CO_2 from industrial syngas streams. IDRIC work has also demonstrated the use of Solid Oxide Electrolysis Cells (SOECs) to produce low-emission hydrogen production from ammonia more efficiently than established ammonia cracking.

Recommendations to industry

Optimise hydrogen production efficiency and emissions
Selecting natural gas feedstocks with lower emissions intensity for blue hydrogen and pursuing improved heat integration strategies. For green hydrogen, co-location of electrolysers with renewable generation is crucial for high efficiency.

Improve sustainability and environmental performance
Life Cycle Assessment (LCA) practices need to be enhanced. It is critical that fugitive hydrogen emissions are addressed and brine waste from saline electrolysis is managed.

Invest in safety and risk management
Greater emphasis is required on stringent risk management of hydrogen projects, particularly for newer market entrants. Knowledge sharing through industry consortia will help establish best practices and ensure efficient, compliant hydrogen deployment.

Utilise electrolytic co-products
Project developers should assess opportunities to exploit the value of co-produced oxygen in various industrial sectors. Other oxidants (e.g., hydrogen peroxide, persulphates) require support for further development but potentially offer greater co-produced value.

Accelerate adoption of high temperature electrolysers (HTE)
Explore the potential for co-production of green chemicals alongside green hydrogen using HTEs, particularly targeting building block chemicals like ethylene or methanol, or ammonia.

Support Innovation in hydrogen recovery
Advance SEWGS and similar technologies through investment in catalysts, process modelling and pilot-scale validation. Explore modular systems to support flexible industrial deployment.

Explore ammonia-based hydrogen systems
Develop modular ammonia cracking units and improve SOEC-based hydrogen production from ammonia. Support research and development (R&D) into catalyst durability and efficiency for ammonia decomposition.

Recommendations to policymakers

Establish clear and long-term policy frameworks
Create stable support mechanisms for early adopters and introduce carbon pricing to incentivise low-carbon production. Cooperate internationally on hydrogen certification and trade to establish a global market and secure sustainable supply chains.

Standardise Life Cycle Assessment (LCA) methods
Mandate consistent LCA approaches across production, storage and transport to ensure full environmental impact evaluation. Cross-sector collaboration should be encouraged to improve data access.

Refine and strengthen regulation
Update Gas Safety (Management) Regulations to facilitate hydrogen blending, while streamlining EPR permits to accelerate project approvals. Offshore hydrogen production needs clearer regulatory pathways under SCR 2015.

Encourage use of electrolysis co-products
Policy mechanisms for hydrogen should consider the opportunities for co-products and should support the deployment of electrolysers near offshore renewable facilities to mitigate grid connection limitations and curtailment.

Advance hydrogen recovery technologies
Support hydrogen recovery processes, such as SEWGS as part of a broader clean hydrogen strategy by encouraging R&D in catalysts, sorbents and reactor design, along with offering incentives for pilot and commercial-scale projects.

Clarify policy on ammonia as a hydrogen carrier
Consider the role that green ammonia has as a hydrogen carrier across sectors and including for industrial use. The regulatory framework enabling ammonia as a transportable hydrogen vector needs to be explored.

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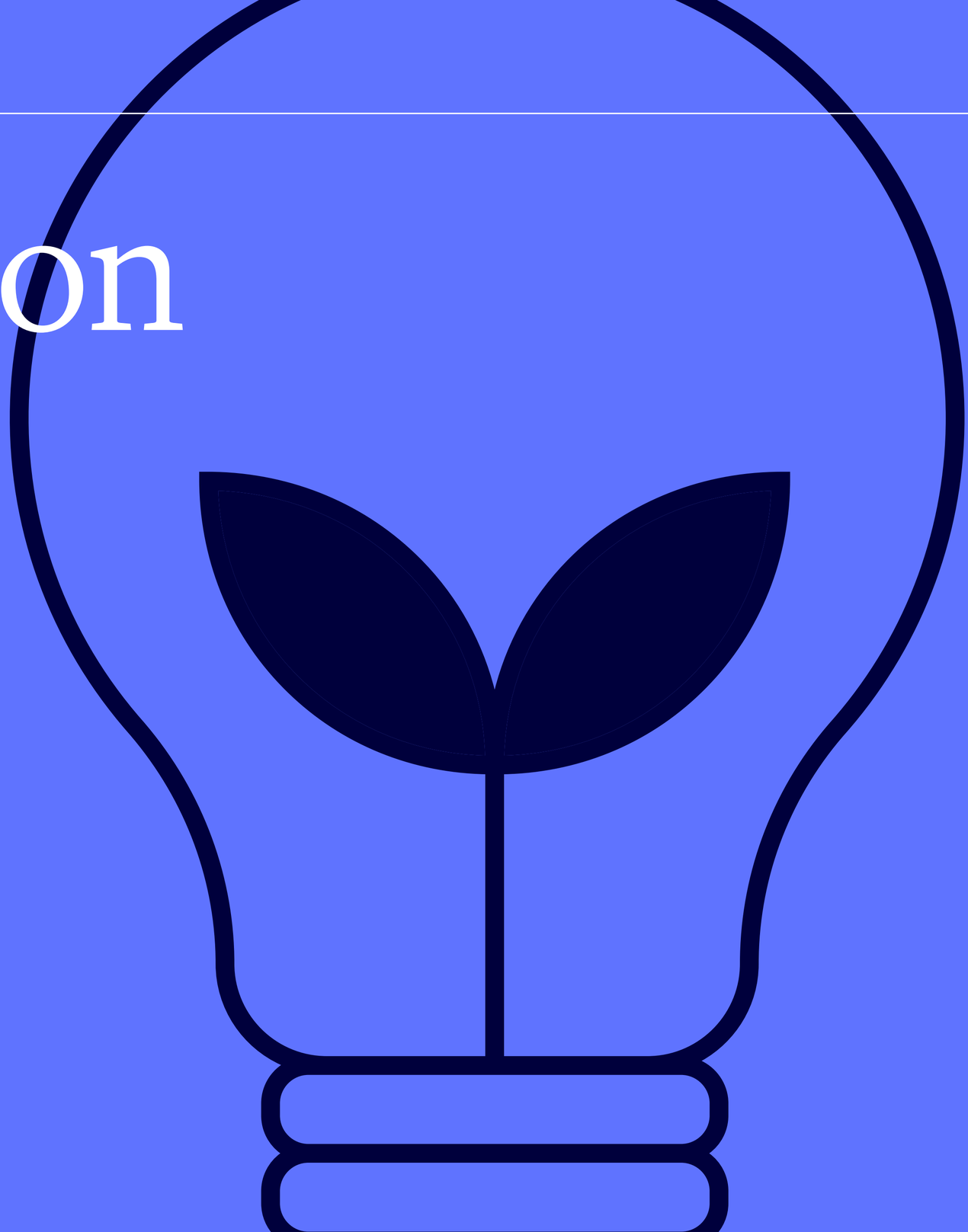
Introduction



Clean hydrogen generation

Hydrogen generation plays an essential part in United Kingdom's strategy to achieve net zero emissions by 2050, particularly within industrial sectors. Hydrogen is widely recognised as a key enabler of industrial decarbonisation due to its potential to replace fossil fuels in difficult to decarbonise applications in energy-intensive sectors such as steel, chemicals and refining. The UK government has set ambitious targets to develop a low-carbon hydrogen economy, aiming to establish 10GW of clean hydrogen production capacity by 2030, producing approximately 60TWh (1.8 million tonnes of H_2) with at least half of this coming from electrolytically produced hydrogen (green hydrogen).[1] This hydrogen generation is also projected to grow to 250-460TWh by 2050 to satisfy the demands of all sectors to reach net zero, equivalent to 20-35% of UK final energy consumption. However, current UK production is almost entirely via steam methane reforming without carbon capture (grey hydrogen) and amounts to 0.7 million tonnes annually, equating to around 27 terawatt-hours (TWh).[2] Therefore, achieving the Government's clean hydrogen production targets presents significant challenges, requiring investment, policy support and continued technological innovation.

This report outlines the importance of hydrogen generation to industrial decarbonisation and assesses key hydrogen production methods that will address the gap between current and required clean hydrogen production. It also highlights the research opportunities that can strengthen the UK's position in the global hydrogen economy, with a particular focus on the hydrogen generation research conducted through IDRIC.

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The role of hydrogen in industrial clusters

The UK's industrial emissions are concentrated in our main industrial clusters. These account for approximately 50% of industrial CO_2 emissions.[3] Alongside electrification, carbon capture and improved process efficiency, hydrogen is recognised as a crucial technology for decarbonising these industrial clusters, either through direct fuel substitution as a feedstock in industrial processes, or for large scale energy storage. The UK government's Industrial Decarbonisation Strategy (2021) and Hydrogen Strategy (2021) explicitly recognise hydrogen's role in reaching net zero.[4,5] Beyond the main industrial clusters, hydrogen is also expected to play a role in broader decarbonisation of decentralised industry, as well as other sectors including transport (e.g., heavy goods vehicles, shipping) and heating.[5]

1 The UK Government Department for Energy Security and Net Zero, Hydrogen Strategy Update to the Market: December 2024.
2 The Royal Academy of Engineering, The Role of Hydrogen in a Net Zero Energy System, Sep. 2022.
3 Industrial Decarbonisation Research and Innovation Centre (IDRIC), IDRIC Policy Synthesis Report: Next Steps for Decarbonising UK Industry, Dec. 2022.
4 Department for Energy Security and Net Zero and Department for Business, Energy & Industrial Strategy, Industrial Decarbonisation Strategy, Mar. 2021.
5 Department for Energy Security and Net Zero, "UK Hydrogen Strategy," Aug. 2021.

Key hydrogen production methods

Core to the role of hydrogen in achieving industrial decarbonisation is the development and adoption of clean hydrogen generation technologies, with low or even negative carbon emissions.[6] Although most current industrial hydrogen production in the UK does not achieve this standard, it does provide embedded experience of hydrogen handling and has enabled the establishment of safety protocols and engineering standards for hydrogen systems. The most likely methods to address the increasing requirement for clean hydrogen are electrolytic hydrogen using renewable electricity (*green hydrogen*) - including alkaline, proton exchange membrane, anion exchange membrane or solid oxide electrolysis, or thermochemical methods with carbon capture (*blue hydrogen*) – including steam methane or autothermal reforming, gasification or partial oxidation. Alongside these, bio-hydrogen from biological or bio-electrochemical means (such as microbial fermentation and microbial electrolysis) or thermochemical methods provide viable options for clean hydrogen at scale, with a possibility of capturing carbon to derive a carbon negative hydrogen production method.[7] In addition, there is also established interest in hydrogen and carbon capture from industrial syngas streams[8] or extraction from hydrogen carriers like ammonia.[9]

The research opportunities

Several core technical challenges remain across different hydrogen production pathways, providing the focus for further research and innovation attention. For green hydrogen, further improving electrolysis efficiency and developing durable, high-performance electrolysers remain key priorities, as do advances in electrolyser materials and system integration to enable rapid electrolyser response to renewable power fluctuations. Reducing capital and operating costs are important areas of ongoing innovation,[10] and effective utilisation of co-produced oxygen, or other electrolytic by-products such as hydrogen peroxide and persulfates offer opportunities to enhance process economics.[11,12] For blue hydrogen, improving carbon capture efficiency to exceed 95% CO_2 removal, minimising methane leakage from natural gas supply chains, and reducing costs are critical challenges, as are ongoing catalyst improvements, also applying to thermochemical gasification and purification technologies. Biohydrogen research focuses on increasing the efficiency and yield of microbial fermentation whilst bio electrochemical methods are at an earlier stage of development. Hydrogen production from industrial syngas streams presents a promising area for increasing process integration and hydrogen availability. Additionally, hydrogen carriers (like ammonia) could play a crucial role in efficient hydrogen distribution and storage, requiring development of effective recovery techniques. More broadly, successful hydrogen deployment in UK industrial clusters will require a comprehensive understanding of energy balances, environmental impacts and safety considerations.

Key technical challenges for the production of green and blue hydrogen

Green hydrogen	Blue hydrogen
Improving electrolysis efficiency.	Improving carbon capture efficiency to exceed 95% CO_2 removal.
Developing durable, high-performance electrolysers.	Minimising methane leakage from natural gas supply chains.
Advances in electrolyser materials.	Reducing capital and operating costs.
System integration to enable rapid electrolyser response to renewable power fluctuations.	Catalyst improvements also applying to thermochemical gasification and purification technologies.
Reducing capital and operating costs.	
Effective utilisation of co-produced oxygen, or other electrolytic by-products.	

6 Department for Energy Security and Net Zero, UK Low Carbon Hydrogen Standard: Greenhouse Gas Emissions Methodology and Conditions of Standard Compliance, Version 3, Dec. 2023.
7 The Royal Society, Options for Producing Low-Carbon Hydrogen at Scale, Jan. 2018.
8 D. P. Harrison, “Sorption-enhanced hydrogen production: A review,” Ind. Eng. Chem. Res., vol. 47, no. 17, pp. 6486–6501, 2008.
9 C. H. Christensen, T. Johannessen, and R. Z. Sørensen, “Towards an ammonia-mediated hydrogen economy?,” International Journal of Hydrogen Energy, vol. 31, no. 14, pp. 2293–2299, Nov. 2006.
10 O. Schmidt, A. Gambhir, I. Staffell, A. Hawkes, J. Nelson, and S. Few, “Future cost and performance of water electrolysis: An expert elicitation study,” International Journal of Hydrogen Energy, vol. 42, no. 52, pp. 30470–30492, Dec. 2017.
11 R. Wang, J. Ma, H. Sheng, V. M. Zavala, and S. Jin, “Exploiting different electricity markets via highly rate-mismatched modular electrochemical synthesis,” Nature Energy, vol. 9, no. 9, pp. 1064–1073, Sep. 2024.
12 Y. Zhao, H. Xue, X. Jin, B. Xiong, R. Liu, Y. Peng, L. Jiang, and G. Tian, “System level heat integration and efficiency analysis of hydrogen production process based on solid oxide electrolysis cells,” International Journal of Hydrogen Energy, vol. 46, no. 77, pp. 38163–38174, Oct. 2021.

Research findings

The transition to a hydrogen-based energy system and the methods of generating hydrogen has received major research attention over several decades. Given the broad range of hydrogen production methods and their different levels of technological maturity, research efforts via IDRIC have been directed towards optimising electrolyser and system efficiency, reducing emissions, cost-competitiveness and ensuring the safe deployment of hydrogen production and distribution infrastructure at scale.

Nine IDRIC projects contributed to this report. They are referred to by their project IDs throughout.
→ See further information.

Project ID	Project name
MIP 7.1a	Evaluating the energy balance and efficiency of the large-scale deployment of a hydrogen energy system
MIP 7.1b	Environmental impacts of the large-scale deployment of a hydrogen energy system
MIP 7.1c	Guidance on the development of a safety case for the hydrogen value-chain
MIP 7.2	Electrolysis for green hydrogen and co-produced chemicals at scale
MIP 7.3	Utilisation of co-produced oxygen from electrolysis to enable deep decarbonisation
MIP 7.5	Reducing CO_2 emissions with improved hydrogen recovery processes
FF 1-1	High-efficiency green hydrogen production and compression for industrial decarbonisation
FF 3-2	Utilisation of industrial waste ammonia form steelmaking in solid oxide electrolysis cell technology for efficient and clean hydrogen production
FF 4-10	Feasibility of ammonia-to-hydrogen network in the Humber Cluster

IDRIC have directed its efforts towards optimising electrolyser and system efficiency, reducing emissions, cost-competitiveness and ensuring the safe deployment of hydrogen production and distribution infrastructure at scale.

This report synthesises findings from multiple research projects, highlighting key areas of investigation and their implications for the future of hydrogen energy. A major focus of the IDRIC research projects has been evaluating the energy balance and addressing the efficiency of large-scale hydrogen deployment within the UK's industrial clusters. Studies have also assessed the technical and commercial viability of hydrogen as a clean energy carrier, considering factors such as energy input requirements, conversion efficiencies and integration with existing energy networks. Additionally, IDRIC projects have assessed and provided advances in electrolysis technologies for green hydrogen production. Efforts have been directed at improving efficiency and enabling improved system economics through the co-production of oxygen and other valuable by-products, which could support deep decarbonisation in industrial applications.

Further IDRIC studies have explored innovative processes for hydrogen recovery from industrial streams aimed at reducing CO_2 emissions and improving industrial efficiency. This potential for resource recovery has included hydrogen generation from syngas streams using Sorption Enhanced Water Gas Shift (SEWGS) and producing hydrogen from industrial byproduct ammonia via solid oxide electrolysis cells. IDRIC research has also investigated the feasibility of an ammonia-to-hydrogen network to support industrial cluster decarbonisation

Safety remains a critical concern in the development of hydrogen generation and supporting infrastructure. IDRIC research has provided guidance on establishing comprehensive safety cases for throughout the hydrogen value chain. Alongside this, the environmental impacts of a hydrogen-based system have been investigated, particularly regarding greenhouse gas emissions, water usage and lifecycle sustainability.

Hydrogen pathways: Energy and efficiency

IDRIC project MIP 7.1a engaged with industrial clusters and stakeholders to evaluate the energy balance and efficiency of different hydrogen generation options. The overall assessment covered the entire value chain, from production to end use, to compare efficiencies, quantify energy intensity and determine associated CO_2 emissions. The approach adopted for hydrogen production focused on natural gas reforming techniques, evaluating steam methane reforming and autothermal reforming methods without carbon capture (grey hydrogen) and a range of carbon capture configurations. In addition, the investigation also examined electrolytic hydrogen generation (specifically alkaline and proton exchange membrane [PEM]), comparing current UK grid electricity feed with green hydrogen cases fed by wind-electricity.

The results from project MIP 7.1a indicate that the efficiency losses due to hydrogen production result in both blue and green hydrogen requiring more feedstock to deliver the same energy value as natural gas or direct use electricity. Nonetheless, greenhouse gas and local atmospheric emissions can be considerably reduced using hydrogen compared to current energy vectors.

The analysis indicated that over a full value chain and for the approaches investigated, blue hydrogen is a more efficient production method than green hydrogen (57.9% of total energy delivered vs. 49.2% respectively for the analysed value chain). However, blue hydrogen from locally produced natural gas was assessed to have approximately four times the greenhouse gas emissions impact of green hydrogen, and a further 40% more if LNG feedstock is used due to the energy-intensive nature of LNG processing and transportation. Compared to direct natural gas usage, blue hydrogen produced using autothermal reforming (ATR) with syngas capture offered approximately 80% reduction in greenhouse gas emissions. This emissions reduction, though, comes at the cost of a 38% increase in natural gas feedstock consumption due to process inefficiencies and the energy demands of CCS. Despite these challenges, blue hydrogen remains a practical option for industrial clusters where economies of scale can be realised through shared infrastructure. That said, the emissions savings must be weighed against the higher capital expenditure required for new facilities, the increased operational costs associated with higher natural gas consumption, and the potential volatility of natural gas prices.

Analysis from project MIP 7.1a indicates that green hydrogen – specifically alkaline electrolysis powered by wind energy – can reduce emissions by approximately 95% compared to direct natural gas usage, and has the key advantage that it can support industrial decarbonisation without the need for natural gas pipelines or CCS infrastructure. Green hydrogen generation provides a viable means to absorb excess renewable energy at scale, potentially mitigating grid intermittency issues where configuration and system controls allow. Furthermore, inherent high hydrogen purity makes it well-suited for direct fuel cell applications in transport and industry. Unsurprisingly, the overall energy efficiency of green hydrogen is significantly lower than that of direct electrification but can be the sensible choice for industrial decarbonisation in scenarios where electrification is not practical. Whilst normally associated with smaller-scale deployments, the rate of growth of green hydrogen technology is rapidly making large-scale application feasible.

Environmental impacts

In IDRIC project MIP 7.1b researchers evaluated the environmental impacts of large-scale hydrogen deployment. The research identifies key environmental challenges across the hydrogen value chain, structured around ISO 14001 impact categories. The analysis reveals inconsistencies in life cycle assessment (LCA) methodologies, system boundaries and functional units – which complicates direct comparisons. While emissions to air, particularly global warming potential, are well-documented, significant research gaps exist in other impact areas, including waste generation, land use and emitted energy. Hydrogen production is the most studied, whereas transmission, storage and direct use lack comprehensive assessment. Key recommendations include further research into fugitive emissions, life cycle impacts of hydrogen pipelines and detailed studies on alternative production pathways.

Hydrogen safety

As part of project MIP 7.1c, researchers analysed safety case development for UK hydrogen projects, including hydrogen generation, as well as distribution and storage. The report highlights hydrogen's unique hazards, including its rapid dispersal, wide flammability range and potential for material embrittlement. Storage risks vary by method – gaseous, cryogenic, or liquid carriers. UK regulations cover offshore (SCR 2015) and onshore (COMAH, DSEAR, planning laws) safety. Pipeline integrity falls under PSR, while transportation follows CDG 2009. Gas safety laws, originally methane-focused, are evolving to accommodate hydrogen. Environmental permits remain bespoke due to regulatory gaps. Case studies investigated in project MIP 7.1c reveal legislative challenges in hydrogen networks, offshore production and refuelling stations. While the UK framework is strong, refinements are needed for hydrogen blending, offshore safety and refuelling standards. Overall, project MIP 7.1c concludes that UK regulations provide a solid foundation but require targeted updates for full hydrogen sector integration.

While the UK safety framework is strong, refinements are needed for hydrogen blending, offshore safety, and refuelling standards.

Advancements in electrolysis for green hydrogen

IDRIC project MIP 7.2 emphasised the advantage of electrolysers being highly modular, making them suitable for deployment at various scales, including individual businesses. However, the project found that scaling up potentially offers more limited cost savings than for other technologies, due to individual stack size limitations. Current electrolysers range in size from 1 MW for solid oxide technology to 150 MW for alkaline systems, with rapid growth across all types. Manufacturing capacity is also expanding, with several gigawatts added globally each year. While planned deployment suggests continued expansion, uncertainties remain about whether supply will outpace demand or vice versa, and whether all proposed projects will materialise. However, growing research and industry interest are driving progress toward commercial viability. Solid Oxide high-temperature electrolysers improve efficiency by using waste heat, replacing up to 20% of electrical energy with thermal energy. Industrial synthesis processes, such as methanol and ammonia production, generate heat that could offset electrolysis energy costs. Newer technologies are also emerging. Anion Exchange Membrane (AEM) electrolysis offers a balance between the efficiency of PEM and the low-cost materials of AWE. It enables the use of non-precious metal catalysts and safer, less caustic electrolytes, potentially lowering costs and simplifying system design. AEM still faces ongoing challenges in membrane durability and long-term performance.

Electrolytic co-generation

With growing focus on hydrogen production via electrolysis, maximising resource use and value will be essential. Conventionally chemicals like chlorine and sodium hydroxide have been co-produced with hydrogen at scale through electrolysis. Co-production of oxygen provides an obvious, often neglected example of potential added value for electrolytic hydrogen developments. Whilst oxygen is traditionally and economically produced from cryogenic or adsorptive air separation, the potential co-production of nine tonnes oxygen for every tonne of hydrogen generated via water electrolysis presents a possible additional revenue stream. IDRIC project MIP 7.3 investigated the potential for added value from co-produced oxygen from green hydrogen production for use in industry, in particular wastewater treatment and steel production sectors (Figure 1).

Historically, steel manufacturing has been a major consumer of industrial oxygen, with primary steelmaking consuming thousands of tonnes per day of oxygen. In the UK, Tata Steel closed their blast furnaces and basic oxygen steel making (BOS) plant in Port Talbot in 2024 and British Steel in Scunthorpe have indicated the planned closure of their two blast furnaces and BOS plant (although still operational at the time of writing). Whilst the demand for oxygen is shifting and the industry is transitioning to electric arc furnaces, they still consume roughly half the amount of oxygen per tonne of steel, meaning there is still further downstream use of oxygen in secondary steelmaking. Looking further ahead, if a transition to hydrogen based direct reduced iron production takes place, there is an opportunity for at-scale use of both hydrogen and oxygen.

Project MIP 7.3 also investigated the promising use of co-produced oxygen in wastewater treatment plants. Such facilities commonly use aerobic biological treatment to remove organic pollutants, usually in the form of energy-intensive aeration. The alternative to use pure oxygen offers improved oxygen dissolution, higher biomass concentration, reduced sludge production, and enables lower plant footprint and capital costs. To date, oxygen costs have limited widespread adoption. Co-produced oxygen from electrolysis presents an opportunity to enhance wastewater treatment efficiency while reducing emissions and supporting sustainability.

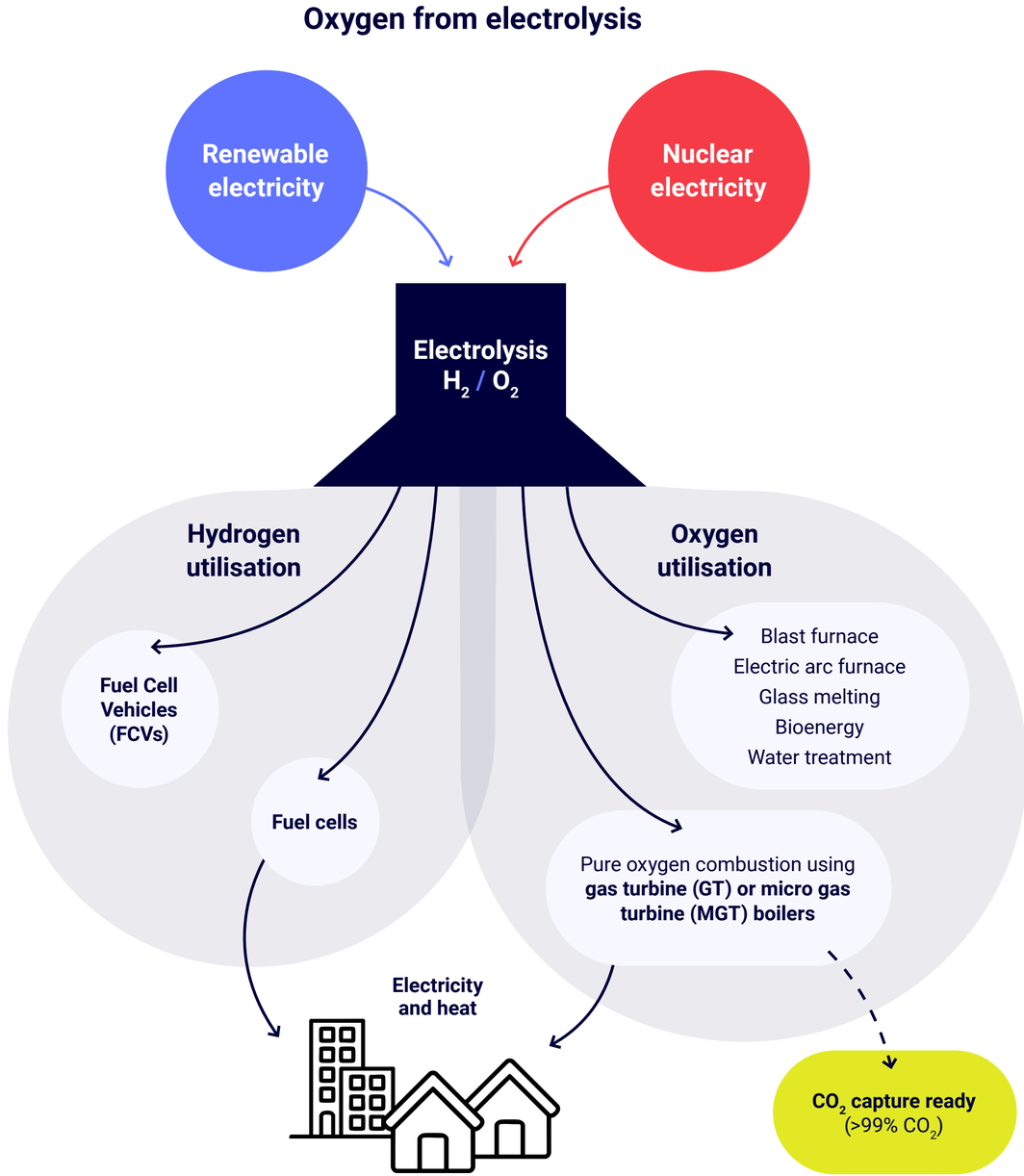
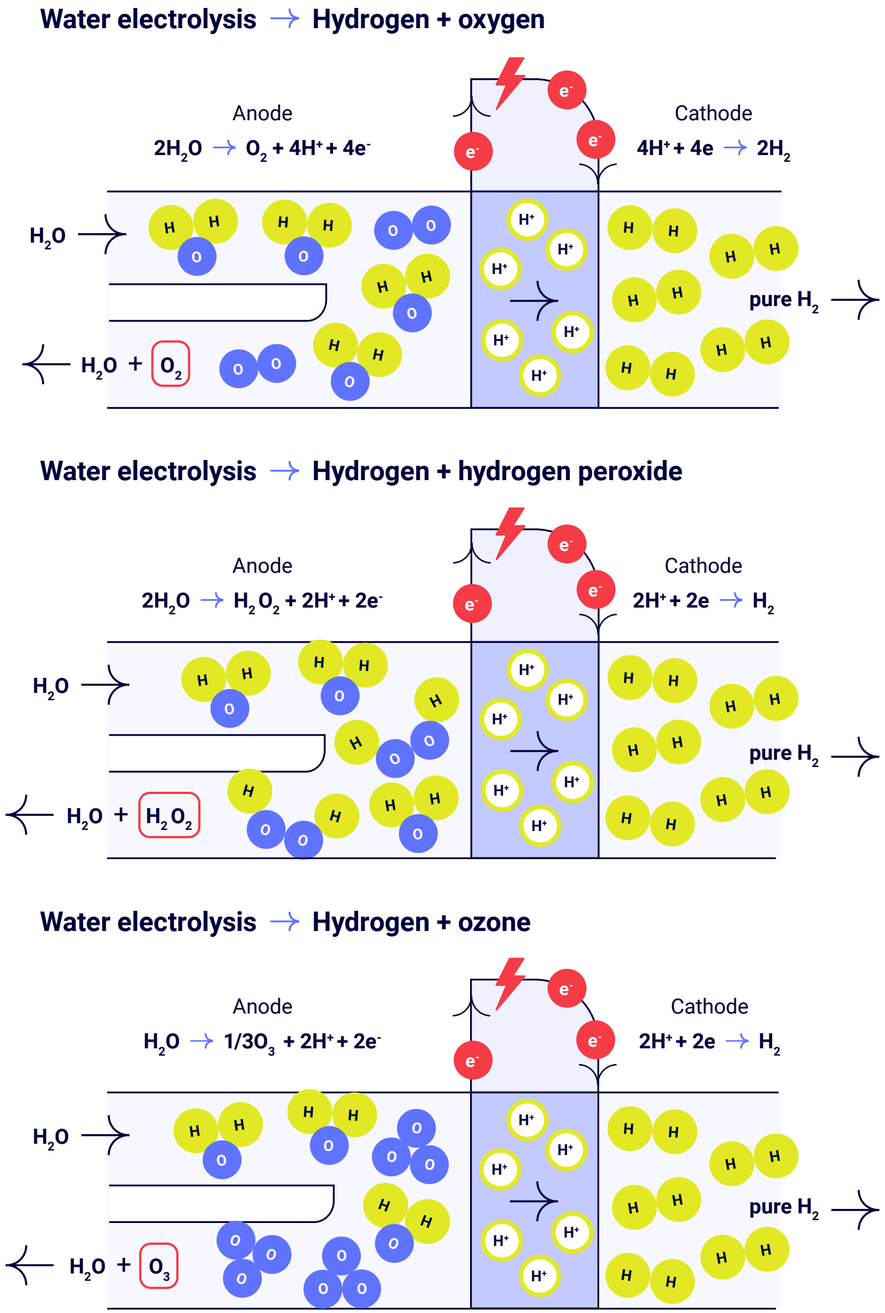


Figure 1

Pathways for utilisation of electrolytically co-produced oxygen [MIP 7.3].



Alternative co-products of low temperature electrolysis

IDRIC project MIP 7.2 explored the co-production of high-value oxidants alongside hydrogen as a more economically attractive alternative to traditional oxygen co-production from water electrolysis The long-established chlor-alkali process, which co-produces chlorine and sodium hydroxide with hydrogen, serves as an existing large-scale example of this approach and the investigation highlights hydrogen peroxide, ozone, persulphates and fluorine as promising candidates for such co-production (Figure 2). These oxidants have significant industrial applications. Hydrogen peroxide is used in bleaching processes, the production of other oxidising agents, chemical synthesis and water treatment. Ozone is useful in potable water production, wastewater treatment and wood pulp bleaching. Persulphates (such as sodium, potassium and ammonium persulphate) are currently used as bleaching agents, dyes for textiles, etching of copper and in detergents. Lastly, fluorine is used in the production of uranium hexafluoride and sulphur hexafluoride. Producing these higher-value chemicals alongside hydrogen could improve the overall economics of electrolytic hydrogen production.

Figure 2

The co-production of high-value oxidants alongside hydrogen can offer more economically attractive alternatives to traditional oxygen co-production from water electrolysis [MIP 7.2].

Co-production with high temperature electrolysis

Project MIP 7.2 also explored co-production with high temperature electrolysers (HTEs). As the thermodynamics of water splitting is more favourable at higher temperatures, HTEs operate at higher efficiency than low temperature electrolysers. Waste heat from exothermic reactions can offset electrical energy demands and improve the electrical efficiency of HTEs by producing steam for the electrolyser or by substituting a portion of the electrical energy needed for water splitting with thermal energy. Since oxygen is transported across the solid oxide electrolyte, as well as converting steam into hydrogen, HTEs can also convert CO_2 into CO and mixtures of CO_2 and steam mixtures into syngas – a vital chemical precursor. The ability of HTEs to produce carbon-containing molecules makes them well-suited for industries requiring syngas, including the UK chemicals sector.

Production of methanol is an interesting case which illustrates the potential for coupling with HTEs. HTEs can reduce steam to hydrogen, but they can also reduce CO_2 to carbon monoxide, or combinations of steam and CO_2 to a mixture of hydrogen and carbon monoxide known as syngas. Methanol can be synthesised from reaction of hydrogen with CO_2, or from syngas. Methanol production from CO_2 and hydrogen generates little heat (2.3 kWh/kg H_2). By contrast, the syngas route for methanol production is more exothermic (6.3 kWh/kg H_2), closely matching the 6.7 kWh/kg H_2 needed for steam generation, making the coupling high temperature electrolysis producing syngas with methanol production 11% more efficient than the hydrogen and CO_2 route.

Similarly, ammonia synthesis is one of the major uses of hydrogen. As an exothermic process, ammonia synthesis could potentially provide heat to improve the efficiency of HTEs. Coupling of heat from ammonia synthesis with HTEs has the potential to reduce electrical energy requirement for ammonia production by 10% compared to not using that heat, and by 32% compared to low temperature electrolysers which are not capable of this form of coupling.

Industrial hydrogen recovery, ammonia and resource efficiency

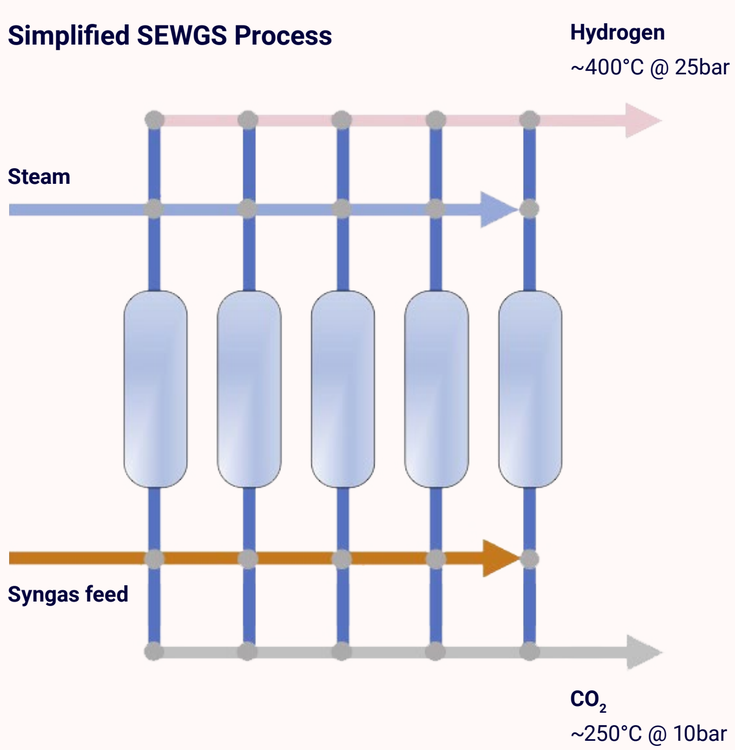
IDRIC project MIP 7.5 investigated sorption-enhanced water gas shift (SEWGS) for hydrogen production and CO_2 Capture. SEWGS is a promising process innovation in hydrogen production from industrial syngas (including biomass gasification streams) that integrates in-situ CO_2 capture, with enhanced reaction efficiency (Figure 3). The process builds upon the traditional water gas shift (WGS) reaction but incorporates solid sorbents that selectively capture CO_2, shifting the equilibrium towards higher hydrogen yields. The specific aim of project MIP 7.5 was to optimise reactor configuration, as well as investigating integration of SEWGS technology with various feedstocks, thereby increasing understanding of SEWGS for hydrogen production. A process modelling approach was adopted, incorporating kinetic and thermodynamic modelling to optimise operating conditions such as temperature, steam-to-carbon ratio and pressure to maximise H_2 production while minimising unreacted CO.

Findings confirmed that lower operating temperatures, combined with continuous CO_2 removal, create a thermodynamically favourable environment for hydrogen production and recovery. The integration of bifunctional catalysts, which simultaneously catalyse the WGS reaction and capture CO_2, further enhances hydrogen production by shifting equilibrium toward higher H_2 yields. This dual functionality reduces process complexity, improves reactor compactness and increases overall efficiency, making SEWGS a promising for low-carbon hydrogen production where suitable feed streams are present.

Figure 3
Simplified SEWGS process diagram [MIP 7.5].

Sorption Enhanced Water Gas Shift (SEWGS) steps

1. Adsorption/ Reaction
2. Steam Rinse
3. Equalisation
4. Blowdown
5. Purge
6. Equalisation
7. Repressurisation



Hydrogen and ammonia

IDRIC project FF 3-2 investigated the use of industrial waste ammonia as a feedstock to solid oxide electrolysis cell (SOEC) technology for hydrogen production. Currently, ammonia waste from steelmaking is primarily disposed of through incineration, which contributes to NOx emissions and also to SOx emissions due to the presence of sulphur-containing compounds. The project developed methods for SOEC testing and enhancement of anodes via sintering with precious metals, followed by experimentation of the conversion of ammonia in a commercially available solid oxide electrolysis cell for hydrogen production and impurity conversion. The project concluded that SOEC technology is a promising approach to produce hydrogen from ammonia, exhibiting high efficiency and low emissions. Metal sintering onto the anode was shown to increase the durability and production of hydrogen.

Project FF 4-10 also investigated the feasibility of hydrogen from ammonia, but in this instance using ammonia as a hydrogen carrier in preference to the distribution of hydrogen in gaseous form. The work investigated the potential for an ammonia distribution network in the Humber Cluster, indicating the potential cost benefit of a decentralised network, with small scale ammonia cracking on or adjacent to the point of use, compared with a centralised, large-scale ammonia cracking facility. The heat integration potential of a decentralised approach suggests further benefits by reducing primary energy use for the cracking process.

Recommendations to industry

Based in IDRIC’s research into hydrogen production, we make the following recommendations to industry to support their decarbonisation through a transition to hydrogen.

Key recommendations

1 Optimise hydrogen production efficiency and emissions

2 Improve sustainability and environmental performance

3 Invest in safety and risk management

4 Utilise electrolytic co-products

5 Accelerate adoption of high temperature electrolysers (HTE)

6 Support Innovation in hydrogen recovery

7 Explore ammonia-based hydrogen systems

Assess emissions intensity of feedstocks and maximise efficiency in hydrogen production

Industry should **carefully consider the source and associated emissions intensity of any natural gas feedstocks** utilised in the production of blue hydrogen, especially when considering LNG imports, as this can significantly impact the overall emissions reduction benefits.

We recommend industry aims for **greater heat integration in blue hydrogen production processes** to maximise efficiency of CO_2 capture. For green hydrogen, **co-location of electrolysers with new renewable generation** is crucial to achieve high efficiency.

Additionally, **continued scaling of electrolyser manufacturing and optimisation of both alkaline and PEM technologies** are also essential to meet the anticipated future demand, along with capital and operational cost improvements.

Improve sustainability and environmental performance

Industry is recommended to **improve Life Cycle Assessment (LCA) transparency and data collection**. It is also critical that companies address **fugitive hydrogen emissions** – a key contributor to indirect global warming – and **manage brine waste from saline electrolysis**. Where used as a hydrogen carrier, fugitive ammonia emissions are also a key consideration.

Collaboration with regulators will help to close data gaps and ensure hydrogen aligns with long-term environmental and sustainability goals.

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Industry – particularly within industrial clusters or hubs – are recommended to explore the potential for co-production of green chemicals alongside green hydrogen using high temperature electrolysers.

Accelerate the adoption of high temperature electrolysers (HTE)

IDRIC's research illustrates that the **UK chemicals industry represents a key synergistic market for high temperature electrolysers (HTEs)** due to its need for carbon-containing molecules, exothermic processes and operation at elevated temperatures.

Industry, particularly within industrial clusters or hubs and within the hydrogen supply sector, are recommended to **explore the potential for co-production of green chemicals** alongside green hydrogen using HTEs, particularly **targeting building block chemicals like ethylene or methanol, or ammonia**.

Industries located in coastal clusters with good access to offshore wind resources should consider **electrolysis for green chemical manufacturing**, potentially **negotiating favourable electricity prices for curtailed energy**.

Dispersed industrial sites would benefit from **assessing the feasibility of appropriately sized local electrolysers** for decarbonisation, especially where electrification is challenging.

Invest in safety and risk management

Industry is recommended to **adopt stringent risk management for hydrogen projects**. This includes:

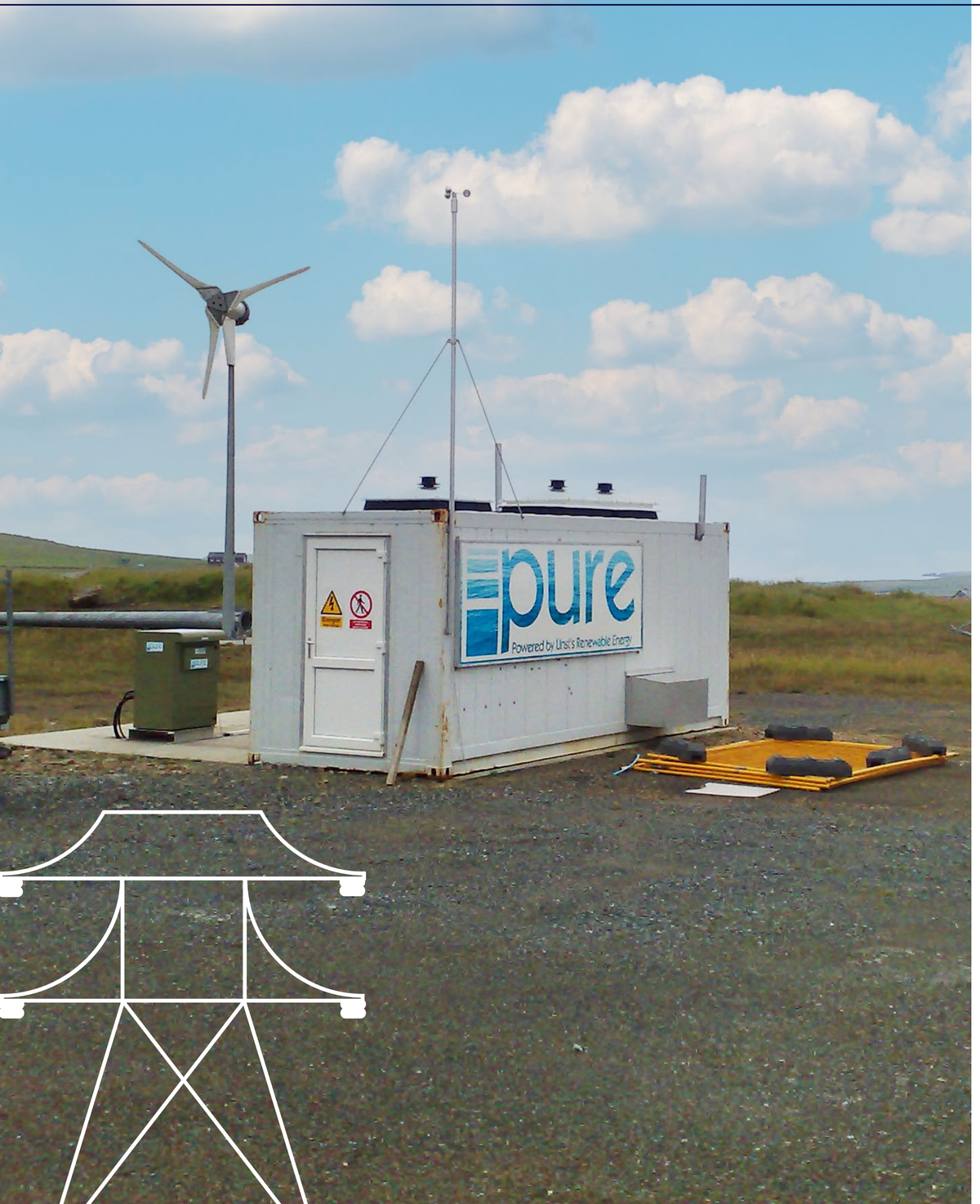
- → Addressing embrittlement risks by selecting materials carefully and complying with DSEAR hazardous zone requirements.
- → Proactive engagement with regulators to clarify environmental permitting and COMAH compliance.
- → Integrate early safety case development in offshore projects for smoother SCR 2015 approval.
- → **I**nvesting in advanced monitoring technologies, such as leak detection, to improve safety and regulatory alignment.
- → Participating in refining hydrogen refuelling and pipeline standards.

Knowledge sharing through industry consortia will help establish best practices and ensure efficient, compliant hydrogen deployment across various infrastructure projects.

Utilise co-produced oxygen from electrolysis

The **oxygen co-produced during electrolytic hydrogen production** represents a valuable opportunity to **support decarbonisation with minimal system modifications**. Industrial clusters and specific sites across the UK should explore the integration of this form of oxygen supply in sectors like **wastewater treatment and steel production to reduce energy use and operational costs**.

End users and hydrogen supply businesses should **assess this opportunity through techno-economic evaluations** to enhance sustainability and process efficiency.



Accelerate the commercial viability of hydrogen capture and recovery technologies

To accelerate the commercial viability of hydrogen capture and recovery technologies, including sorption-enhanced water-gas shift (SEWGS), we recommend **industrial effort focuses on investigation of process integration and scalability**.

Supporting **investment in high-performance bifunctional catalysts** that combine CO_2 capture with catalytic activity will **enhance efficiency while reducing process complexity. Continuous research into sorbent regeneration techniques**, such as steam-assisted regeneration or chemical looping, can improve long-term stability and lower operational costs.

Industrial-scale pilot projects can be used to validate SEWGS in real-world applications, with a focus on optimising reactor designs using computational fluid dynamics (CFD), supported by techno-economic modelling. Opportunities for **development of modular SEWGS systems should also be explored**, allowing for scalable and flexible deployment across various industrial sectors.

Explore alternative hydrogen production methods and integrated ammonia-to-hydrogen systems

We recommend industry **invests in alternative production methods like pyrolysis and gasification**.

They are also recommended to consider **detailed investigation of deployment of integrated ammonia-to-hydrogen systems** utilising ammonia cracking and solid oxide electrolysis cells (SOECs). **Investment should focus on modular reactors for distributed hydrogen production** from green ammonia and **enhancing catalyst efficiency in ammonia decomposition**. Industrial support to **further solid oxide cell development** will further enhance efficiency of this operation.

Improve hydrogen storage solutions

There is a need to **enhance hydrogen storage solutions, particularly for liquid hydrogen and SAF applications**. See IDRIC's Frontiers Report on Hydrogen Transport and Storage for more information.

Recommendations to policymakers

Based in IDRIC’s research into hydrogen production, we make the following recommendations to policymakers to support industry in decarbonising through a transition to hydrogen.

Key recommendations

1 Establish clear and long-term policy frameworks

2 Standardise Life Cycle Assessment (LCA) methods

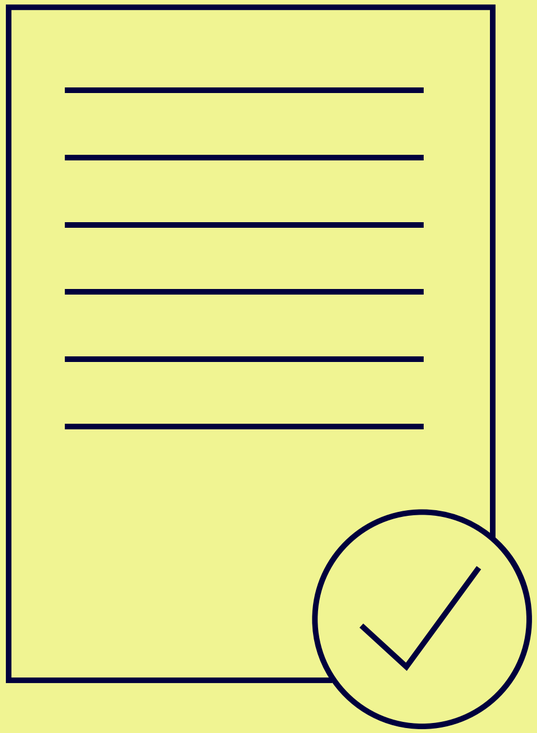
3 Refine and strengthen regulation

4 Encourage use of electrolysis co-products

5 Advance hydrogen recovery technologies

6 Clarify policy on ammonia as a hydrogen carrier

To support a successful industrial transition to hydrogen, policymakers must prioritise the development of clear and robust policy frameworks.



Establish strong policy frameworks to support the adoption of low-carbon hydrogen

To support a successful industrial transition to hydrogen, policymakers must **prioritise the development of clear and robust policy frameworks**.

Encouraging hydrogen **adoption in industrial clusters can significantly cut emissions**. Funding innovation and subsidies for early adopters will accelerate deployment. Infrastructure support – including pipeline retrofitting and storage research – will be essential.

We recommend governments **ensure green hydrogen is strictly defined as renewables-based** and introduce carbon pricing to incentivise low-carbon production. **International cooperation on hydrogen certification** and trade will **help establish a global market** and secure sustainable supply chains.

Standardise life cycle assessment (LCA) methods and improve environmental performance

LCA methods should be standardised for consistent hydrogen assessments and full impact evaluations, including transport and storage. See IDRIC's Frontiers Report on Life Cycle Assessment (LCA) for more information.

Policies which enable research on pipeline emissions can help to **create regulations to address leakage risks** and incentivise sustainable hydrogen production. **Cross-sector collaboration should be encouraged to improve data access**, while clear guidelines should define hydrogen's role in decarbonisation.

Refine and strengthen regulation

Key regulatory updates are needed to facilitate hydrogen deployment. **Updating GS(M)R will facilitate hydrogen blending**, while **streamlining EPR permits will accelerate project approvals. Offshore hydrogen production needs clearer regulatory pathways** under SCR 2015.

Hydrogen refuelling station regulations need to be expanded to cover dispenser testing, metering and vehicle safety. Strategic policy support, including incentives for hydrogen storage and infrastructure, will accelerate deployment.

Funding further research into material compatibility and emergency response protocols will enhance industry preparedness. **Aligning UK hydrogen regulations with international standards will promote consistency** and position the UK as a leader in the global hydrogen economy.

Support co-product use and electrolyser deployment

IDRIC's research has demonstrated how integration of electrolysis co-products, including oxygen and others, offer a promising alternative to help in decarbonisation and potentially improving project economics. **Policy mechanisms for hydrogen should consider the opportunities for co-products** and **should support the deployment of electrolysers near offshore renewable facilities** to mitigate grid connection limitations and curtailment.

Given that the cost of electricity significantly impacts the economics of electrolysis, we recommend **policy continues to focus on developing grid infrastructure to connect renewable energy sources and energy-intensive users**. Recognising that a significant portion of UK industrial emissions and employment is outside major clusters, **policies also need to address the decarbonisation needs of dispersed industries, through incentives for local hydrogen production with co-products**.

Furthermore, supporting research and development in **electrolytic co-production of high-value oxidants like ozone and persulphate could lead to significant reductions in green hydrogen costs**.

Encourage innovation in hydrogen recovery technologies

Governments can **support hydrogen recovery processes**, such as SEWGS as part of a broader clean hydrogen strategy by **encouraging R&D in catalysts, sorbents and reactor design**, along with **offering incentives for pilot and commercial-scale projects**, to advance the technology. Further development of support for CO_2 transport, storage and hydrogen infrastructure would further aid integration into industry.

Clarify policy on ammonia as a hydrogen carrier

Policy on ammonia as a **hydrogen carrier is in its early stages, but it would be beneficial for governments to consider the role that green ammonia has as a hydrogen carrier** across sectors and including for industrial use.

Support for **R&D for green ammonia technologies, SOECs and more efficient ammonia cracking** would all be positive steps. The **regulatory framework enabling ammonia as a transportable hydrogen vector needs to be explored**, especially as there are potential cross-sectoral benefits and strategic alignment between industrial use, maritime and grid storage decarbonisation pathways.

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Next steps and further research

This section outlines the most pressing further research required to accelerate industrial decarbonisation and the establishment of a thriving hydrogen economy.

Research into improving electrolyser efficiency and scaling carbon capture in blue hydrogen is required to accelerate industrial decarbonisation through a transition to hydrogen. More studies on hydrogen transport economics, including pipeline conversion and cryogenic storage, are needed. Expanding research into alternative carriers, such as ammonia, will help optimise long-range transport. Policy analyses on hydrogen's economic impact and job creation are crucial. Real-world pilot projects in domestic heating, transport and industrial applications will inform implementation. Addressing safety and public acceptance through education and outreach remains a key research priority.

Additional research is needed to quantify and clarify emissions beyond carbon dioxide equivalents, including better understanding of the impact of fugitive hydrogen emissions and their indirect warming effects.

Hydrogen safety

There is a need for further research into hydrogen safety, especially material degradation and embrittlement. Improved safety standards for refuelling, pipelines and offshore production are essential. Aligning UK regulations with global best practices remains a priority. Additional case studies will provide practical insights. Expanding emergency response protocols, training and simulations will enhance preparedness for hydrogen-related incidents, ensuring safe infrastructure expansion in the UK.

Environmental impact and life cycle assessment LCA)

Future research should focus on addressing the identified gaps and improving full environmental impact assessment of the hydrogen supply chain. Additional research is needed to quantify and clarify emissions beyond carbon dioxide equivalents, including better understanding of the impact of fugitive hydrogen emissions and their indirect warming effects. Investigating further impacts from hydrogen production including waste generation, land use implications and emitted energy impacts across the value chain will be crucial. Collaboration between industry, academia and policymakers is essential to develop a comprehensive and standardised approach to assessing hydrogen's environmental footprint and using this in the decision-making process. Ultimately, ensuring that hydrogen contributes positively to net-zero goals requires a more holistic and evidence-based understanding of its environmental impacts across all deployment stages.

Electrolyser development and maximising use of co-products

To unlock the full potential of co-electrolysis, further research is needed to optimise electrolyser designs to selectively produce alternative oxidants alongside hydrogen. In addition, there is a requirement for greater understanding of enhanced economic models for integrating hydrogen electrolysis and co-products with existing chemical production industries. Further research is needed to optimise the integration of high temperature electrolysers (HTEs) with specific chemical synthesis processes to maximise efficiency gains from waste heat utilisation.

A detailed quantification of the value and current uses of waste biomass is required to assess its potential as a CO_2 source for green chemical production via electrolysis. The economic viability and scalability of direct air capture (DAC) for providing CO_2 to electrolysis-based chemical production in low-electricity-cost regions needs further investigation, considering its high energy demands. More data is required on the performance and cost reductions of larger scale Solid Oxide Electrolysers (SOEs) as deployment increases. Investigation into improving the current efficiency of electrolytic ozone production beyond 35% is crucial for its wider adoption as a valuable co-product.

Advancing ammonia and alternative hydrogen carriers

Ammonia as a hydrogen carrier offers high hydrogen density and ease of liquefaction, making it a promising vector for long-distance transport. Future research on ammonia must focus on improving system efficiency, scalability and sustainability to support the development of a robust hydrogen economy. However, key challenges remain in efficient ammonia synthesis using green hydrogen and in hydrogen release via catalytic cracking, or via solid oxide electrolysis. Advances in metal-based catalysts – particularly those operating at lower temperatures – are crucial to improving ammonia decomposition efficiency. More broadly, research is needed to optimise ammonia storage and transport infrastructure, addressing safety concerns and minimising energy losses.

Alternatives, like liquid organic hydrogen carriers (LOHCs) and methanol continue to be explored for their compatibility with existing fuel infrastructure. Comparative studies assessing lifecycle emissions, energy efficiency and economic feasibility will all be critical in determining the optimal role of hydrogen carriers within a diversified hydrogen supply chain. Continued research focus on improving thermodynamic efficiency and longevity of SOECs under real-world operating conditions and catalyst optimisation for low-temperature ammonia cracking.

Future research on ammonia must focus on improving system efficiency, scalability, and sustainability to support the development of a robust hydrogen economy.

Hydrogen recovery and advanced capture processes

Further work is required to explore the potential for hydrogen recovery from industrial syngas streams to improve resource utilisation. Advancing SEWGS requires material innovation, process optimisation and large-scale validation. Research should enhance sorbent stability and regeneration. Machine learning can optimise reactor conditions, improving efficiency.

Integrating SEWGS with electrolysis and biomass gasification will boost flexibility. Demonstration plants will ensure scalability, while industry-academia collaboration drives modular units. Life-cycle assessments will clarify environmental impact, supporting SEWGS as a sustainable hydrogen solution.

Contributing projects

IDRIC projects included in this report

IDRIC ran three complementary strands of projects:

1 In-depth research projects embedded within nine Multidisciplinary Integrated Programmes (MIPs), each programme tackling a key challenge or pathway for industrial decarbonisation;

2 Shorter-term Flexible Fund (FF) projects designed to rapidly address emerging or urgent opportunities identified directly by industrial clusters;

3 Impact Accelerator (IA) projects aimed at maximising the impact of existing IDRIC projects.

Projects discussed within the report are referred to by their project ID.

◗ – Principal investigator

Project ID	Project name	Researchers	
MIP 7.1a	Evaluating the energy balance and efficiency of the large-scale deployment of a hydrogen energy system	Martin Maeso ◗, Mark Scanlon, Toni Needham, Amaia O'Reilly	Energy Institute
MIP 7.1b	Environmental impacts of the large-scale deployment of a hydrogen energy system	Martin Maeso ◗, Mark Scanlon, Toni Needham, Amaia O'Reilly	Energy Institute
MIP 7.1c	Guidance on the development of a safety case for the hydrogen value-chain	Martin Maeso ◗, Mark Scanlon, Toni Needham, Amaia O'Reilly	Energy Institute
MIP 7.2	Electrolysis for green hydrogen and co-produced chemicals at scale	Nigel Brandon ◗, Anthony Kucernak, Paul Boldrin, Colleen Jackson	Imperial College London
MIP 7.3	Utilisation of co-produced oxygen from electrolysis to enable deep decarbonisation	John Andresen ◗, Susana Garcia, Manuel Ojeda	Heriot-Watt University
MIP 7.5	Reducing CO_2 emissions with improved hydrogen recovery processes	Jon Madd ◗	Heriot-Watt University
FF 1-1	High-efficiency green hydrogen production and compression for industrial decarbonisation	Sumit Roy ◗, Andrew Smallbone, Tony Roskilly, Shivaprasad Vijayalakshmi	Durham University
FF 3-2	Utilisation of industrial waste ammonia form steelmaking in solid oxide electrolysis cell technology for efficient and clean hydrogen production	Kleitos Panagi ◗, Christian Laycock, Alan Guwy	University of South Wales
FF 4-10	Feasibility of ammonia-to-hydrogen network in the Humber Cluster	Eni Oko ◗	Newcastle University
		Alex Ibhadon	University of Hull
		Tohid Borhani	University of Wolverhampton

Project ID	Project name	Outputs	
MIP 7.1	Large-scale deployment of a hydrogen energy system	Review of directives/regulations relevant to the safe and environmentally compliant production, transportation, and storage of hydrogen - Executive summary	Report
		Application of life cycle assessment methodology to the understanding of the energy balance and efficiency of hydrogen value chain building blocks - Executive summary	
FF 4-10	Feasibility of ammonia-to-hydrogen network in the Humber Cluster	Comparative energy and exergy analysis of ortho-para hydrogen and non-ortho-para hydrogen conversion in hydrogen liquefaction	Journal

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