Energy from Hydrogen

Making a cleaner world

7 November 2024

Most headlines after the recent UK Budget focused on taxation and increased governmental borrowing. Yet there were many supportive mentions in the Chancellor's speech for the UK's prominent role in developing clean energy solutions, including green hydrogen. Rachel Reeves confirmed that the UK is preparing to grant revenue support of up to £2.3bn for 11 green hydrogen projects that total 125MW in scale.

This summary paper is intended to raise understanding and awareness of hydrogen's potential, the science involved, and examples of diverse businesses in the UK seeking to commercialise it.

Already in widespread use

The global supply / demand picture for hydrogen is rapidly evolving as the world shifts toward cleaner energy solutions. Hydrogen is viewed as a critical component of this transition. The International Renewable Energy Agency (IRENA) states that the global production of hydrogen now stands at 75 Mt/yr of pure hydrogen, with an additional 45 Mt/yr as a mix of gases. Looking forward, the International Energy Agency (IEA) estimates that already announced projects could increase production by 50% by 2030 and meet up to 10-12% of global energy demand by 2050.

Most hydrogen currently produced is "grey hydrogen" due to its fossil fuel-based production methods, so the focus in relation to cleaner energy solutions is on: (1) "blue hydrogen" which is produced from natural gas but with carbon capture and storage, and (2) "green hydrogen" which uses renewable energy (solar, wind etc.) for water electrolysis.

By far the largest current demand for hydrogen comes from **heavy industrial sectors** such as steel, cement, refineries, chemical plants, and others. For activities that are difficult to electrify with batteries as they require energy-dense fuels, hydrogen (particularly 'green hydrogen') could provide a carbon-free fuel alternative.

Another area where hydrogen demand is forecast to increase rapidly is in **transportation**, particularly for heavy-duty vehicles, buses, trains, and even aviation where battery-electric solutions are likely to be impractical due to weight and range limitations. Hydrogen-powered fuel cells provide fast refuelling and longer ranges, making them a viable option in these areas.

When renewable sources like wind and solar produce excess electricity, hydrogen can in turn be produced via electrolysis and stored. This hydrogen can then be used in fuel cells or turbines to generate electricity during periods of low renewable energy production, **offering long-term energy storage options** that complement batteries.

Sourcing

Hydrogen can be produced from a variety of resources, including renewables, nuclear energy, and natural gas (with carbon capture). This flexibility offers countries the ability to diversify their energy sources and reduce dependence on fossil fuel imports, enhancing **energy security**.

Opportunity clear, hurdles to overcome

There can be little doubt that hydrogen is poised for significant growth in both supply and demand, but a successful transition to a large-scale hydrogen economy depends on a number of factors, including (1) reducing production costs, (2) building the required infrastructure such as pipelines, storage facilities and fuelling stations, (3) sustained support from national governments and international energy bodies, and (4) continuing technology developments.

Companies mentioned

ITM Power plc

Ceres Power plc

AFC Energy plc

GeoPura Ltd

Hydrogen Future Industries plc

Clean Power Hydrogen plc

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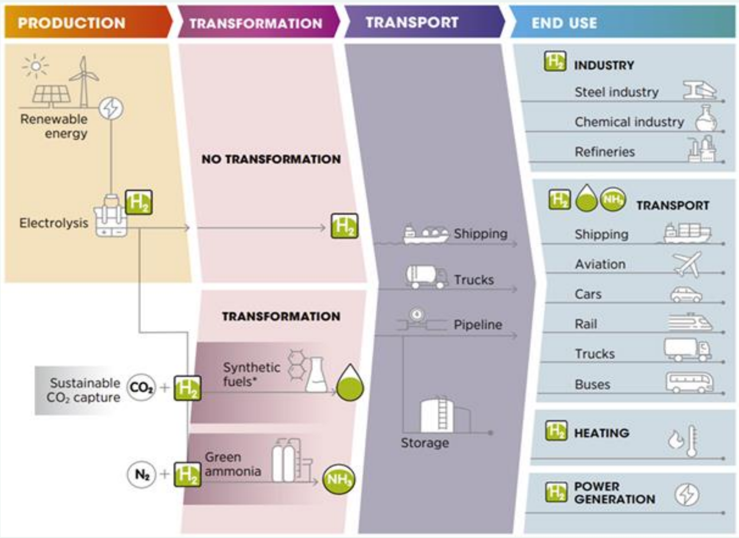
Hydrogen - Production

Hydrogen is a feedstock in the chemical and refinery sectors which is used in many industrial sectors, including steel production, heat and power generation. Global hydrogen production is about 120m tonnes per annum (*source: International Renewable Energy Agency / IRENA*) as either pure hydrogen or in a mix of gases, but most of this production is ‘grey’ i.e. derived from natural gas and coal without any capture of emissions.

Therefore, production of ‘green’ hydrogen, produced from electrolysis powered by renewable energy sources, is essential to help achieve challenging net zero targets by 2050.

While renewables, electrification and energy efficiency measures will be the main drivers of GHG (greenhouse gases) reduction, ‘green hydrogen’ can play a pivotal role in reducing the carbon emissions of not only heavy industry, but also other huge sectors such as long-haul transport and energy storage.

Path to end users



Source: IRENA website / Energy Transition

Hydrogen - Technologies

PEM (Proton Exchange Membranes)

Proton Exchange Membranes (PEMs), also known as Polymer-Electrolyte Membranes, are specialised polymer membranes that play a crucial role in devices like proton exchange membrane fuel cells (PEMFCs). They conduct protons (H^+) while acting as barriers to gases like hydrogen (H_2) and oxygen (O_2). In a fuel cell, PEMs separate the anode (where hydrogen gas is split into protons and electrons) from the cathode (where oxygen reacts with protons and electrons to form water).

The membrane allows protons to pass through from the anode to the cathode while forcing electrons to travel through an external circuit, generating electricity.

A Proton Exchange Membrane (PEM) is a key component in fuel cells and some electrochemical devices. It enables the conversion of chemical energy into electrical energy, so is vital in proton exchange membrane fuel cells (PEMFCs), which have widespread applications such as hydrogen-powered vehicles, stationary power generation, and portable electronics. The membrane’s primary role is to transport protons (H+) from one side of the fuel cell to the other while preventing gases, such as hydrogen and oxygen, from directly mixing.

A PEM is typically a polymeric material that allows only protons to pass through it. In a PEM fuel cell, the membrane serves as the electrolyte, placed between the anode and cathode electrodes, as follows:

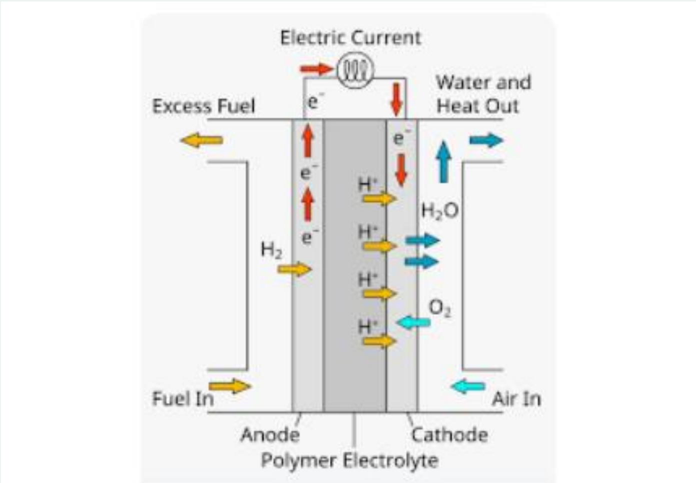
- **Hydrogen Splitting at the Anode**: At the anode of the fuel cell, hydrogen gas (H_2) is introduced and split into protons (H+) and electrons (e-) by a catalyst, usually platinum.

- **Proton Transport through the PEM**: The generated protons (H+) are then transported through the PEM from the anode to the cathode. The membrane only allows the protons to pass, preventing other molecules like hydrogen or oxygen from crossing over, ensuring the chemical reactions stay isolated.

- **Electron Flow through an External Circuit**: The electrons (e-) generated at the anode cannot pass through the PEM, as it is an insulating material for electrons, and are instead forced to travel through an external circuit, creating an electrical current that can be harnessed for power.

- **Oxygen Reduction at the Cathode**: On the other side of the fuel cell, oxygen (O_2) is introduced at the cathode. The protons transported through the PEM combine with the oxygen and the electrons arriving from the external circuit to form water (H_2O), completing the overall reaction.

PEM fuel cell graphic



Source: Wikimedia

There are several factors that can impact the performance of a PEM in a fuel cell:

- **Water Content**: PEMs require hydration to maintain high proton conductivity. If the membrane dries out, its ability to conduct protons diminishes significantly, leading to a drop in fuel cell performance. On the other hand, too much water can lead to flooding of the electrodes, which also hinders performance.

- **Temperature**: PEM fuel cells typically operate at temperatures between 60°C and 80°C. Higher temperatures increase proton conductivity but may cause water to evaporate more quickly, leading to dehydration of the membrane. This trade-off between temperature and hydration is a key consideration in the design and operation of PEM fuel cells.

- **Membrane Thickness**: Thinner membranes can enhance proton conductivity and reduce electrical resistance, but they are more prone to mechanical failure and gas crossover. Conversely, thicker membranes provide better durability but can impede ion transport and reduce overall efficiency.

- **Durability**: Over time, PEMs can degrade due to chemical and mechanical stresses. Factors such as exposure to high temperatures, impurities in the fuel, and mechanical stresses can reduce the lifespan of the membrane.

Solid Oxide Electrolysis (SOE)

SOE is a process that uses solid oxide electrolysers to produce hydrogen and oxygen from water. This electrochemical technique is part of the broader category of high-temperature electrolysis, operating at temperatures typically ranging from 700°C to 1,000°C. SOE systems are often used to generate hydrogen, but they can also be applied to produce other gases, such as carbon monoxide and syngas (a mixture of hydrogen and carbon monoxide) by co-electrolysing water and carbon dioxide.

The key component in this process is the solid oxide electrolyte, which conducts oxygen ions (O^{2-}) and is usually made from ceramic materials like yttria-stabilised zirconia (YSZ).

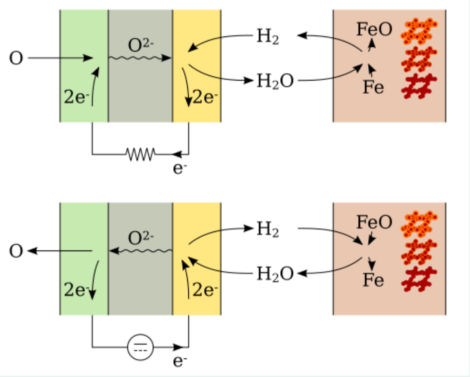
Solid oxide electrolysis is essentially the reverse of a solid oxide fuel cell (SOFC) operation. In an SOFC, fuel is consumed to produce electricity whereas in SOE electricity is supplied to drive a chemical reaction that produces hydrogen and oxygen. The overall reaction in SOE is the splitting of water (H_2O) into hydrogen (H_2) and oxygen (O_2), using electrical energy and heat. This reaction takes place in a cell that has three main components:

- **At the Cathode**: Water molecules (H_2O) are introduced and reduced by the input of electrical energy, producing hydrogen gas (H_2) and oxygen ions (O^{2-}).
- **Oxygen Ion Conduction through the Electrolyte**: The oxygen ions (O^{2-}) formed at the cathode migrate through the solid oxide electrolyte which is designed to allow oxygen ions to pass through efficiently while blocking other particles. The movement of oxygen ions from the cathode to the anode is driven by the applied electric potential across the cell
- **At the Anode**: The oxygen ions are oxidised, releasing electrons and forming molecular oxygen (O_2).

The combination of these reactions leads to the overall electrolysis of water into hydrogen and oxygen. Because solid oxide electrolysis operates at such high temperatures, a portion of the energy required for the process comes from thermal energy, which reduces the amount of electrical energy needed.

This makes SOE more efficient than low-temperature electrolysis methods, such as PEM electrolysis or alkaline electrolysis.

Cell reactions in a high temperature metal oxide battery



Source: Wikimedia

Challenges that SOE has in the past faced include:

- **High Operating Temperatures**: operating at 750C to 850C can increase material stresses and reduce the lifespan of the electrolyser components. Over time, thermal cycling can lead to mechanical failure in the ceramic electrolyte, electrodes, or other components. However, new SOE technologies have developed recently that are based on ceria, operating at low (550C to 650C) temperatures and using less expensive raw materials – see Ceres Power on pages 12-13.

- **Material Degradation**: At elevated temperatures, the materials used in the electrodes and electrolyte may degrade due to reactions with contaminants or through physical wear.
- **Cost**: The materials used for high temperature SOE, especially the ceramic electrolytes and electrode catalysts, can be relatively expensive. This, combined with the need for heat insulation, drove up the overall cost of earlier SOE systems.

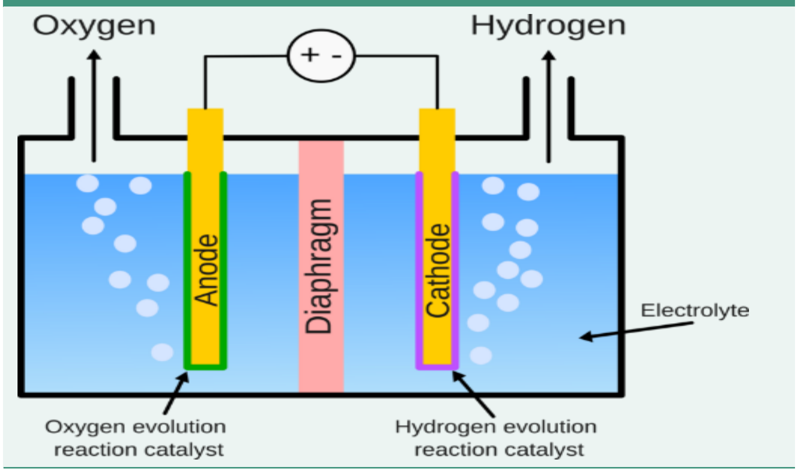
Alkaline Water Electrolysis (AWE)

AWE is a well-established method for producing hydrogen and oxygen by splitting water molecules using an electric current. This technology has been **in use for decades,** primarily for industrial-scale hydrogen production, and operates at relatively low temperatures (50-80°C). AWE uses an alkaline electrolyte solution, usually potassium hydroxide (KOH) or sodium hydroxide (NaOH), to enable the transport of hydroxide ions (OH^-) between an anode and a cathode. The system relies on a direct current (DC) power supply to drive the electrochemical reactions.

In AWE, water is broken down into hydrogen (H_2) and oxygen (O_2) by applying electricity to the electrodes submerged in the alkaline solution. The electrolysis cell consists of three key components: the cathode, the anode, and a separator (typically a diaphragm) that divides the two electrode chambers. The separator allows the passage of ions but prevents the hydrogen and oxygen gases from mixing.

- **At the Cathode (Hydrogen Production)**: Water molecules accept electrons from the external circuit and are reduced to hydrogen gas and hydroxide ions (OH^-). The hydrogen gas is released as bubbles at the cathode, while the hydroxide ions remain in the electrolyte and migrate towards the anode.
- **At the Anode (Oxygen Production)**: The hydroxide ions are oxidised, releasing oxygen gas, water, and electrons that flow back through the external circuit to complete the circuit. Oxygen gas is released at the anode and collected as a by-product.
- **Role of the Electrolyte**: The electrolyte serves to conduct the hydroxide ions between the two electrodes. The concentration of the electrolyte is usually high, around 20-30%, which enhances ion conductivity and ensures efficient transport of ions. The electrolyte does not participate in the overall reaction but facilitates the movement of hydroxide ions between the anode and cathode, enabling the electrochemical reactions to proceed smoothly.
- **Role of the Diaphragm**: A diaphragm or separator is placed between the anode and cathode compartments to physically separate the gases produced, hydrogen at the cathode and oxygen at the anode. This stops a dangerous recombination of these gases, which risks explosions or inefficiencies.

AWE reactions



Source: Wikimedia

Some of the challenges and limitations of AWE are:

- **Low Current Density**: AWE systems generally operate at lower current densities compared to PEM electrolysis, which limits their power output for a given size, making them less efficient for compact applications.
- **Startup Time**: Alkaline electrolysers take longer to start up and respond less quickly to changes in electrical input, which can make them less suitable for applications where rapid demand changes are required.
- **Gas Purity**: AWE systems typically produce hydrogen with slightly lower purity compared to PEM electrolysis, often requiring additional purification steps if very high purity hydrogen is needed.

Comparison of all 3 key technologies

In the table below we compare the three technologies, reviewing the pros and cons of each in a commercial setting. Inevitably, aspects of space availability and cost will be critical factors considered when making a commercial choice.

PEM electrolysis looks the most suitable for large scale production of hydrogen with a high purity, although PEM is costly in comparison to AWE which is the most cost-friendly methodology due to its mature but effective technology.

Strengths and weaknesses

Technology	Positives	Negatives
PEM	High power density	Limited tolerance to water impurities
	Fast starting time	High upfront costs
	Small carbon footprint producing high purity hydrogen	More energy intensive
SOE	High operating temperatures providing higher efficiency lowering renewable energy consumption and total cost	High manufacturing costs
		Hydrogen needs to be separated and purified from water (steam)
		High temperatures can cause accelerated ageing
AWE	Mature technology	Large footprint
	Utilises cost-effective catalysts that have a longer operational life	Lower purity hydrogen output than PEM
	Materials used are widely available	Not always suitable for small scale application due to cells needing to be in stack form
	Not reliant on water purity to run	Slow starting from cold

Source: Equity Development, various

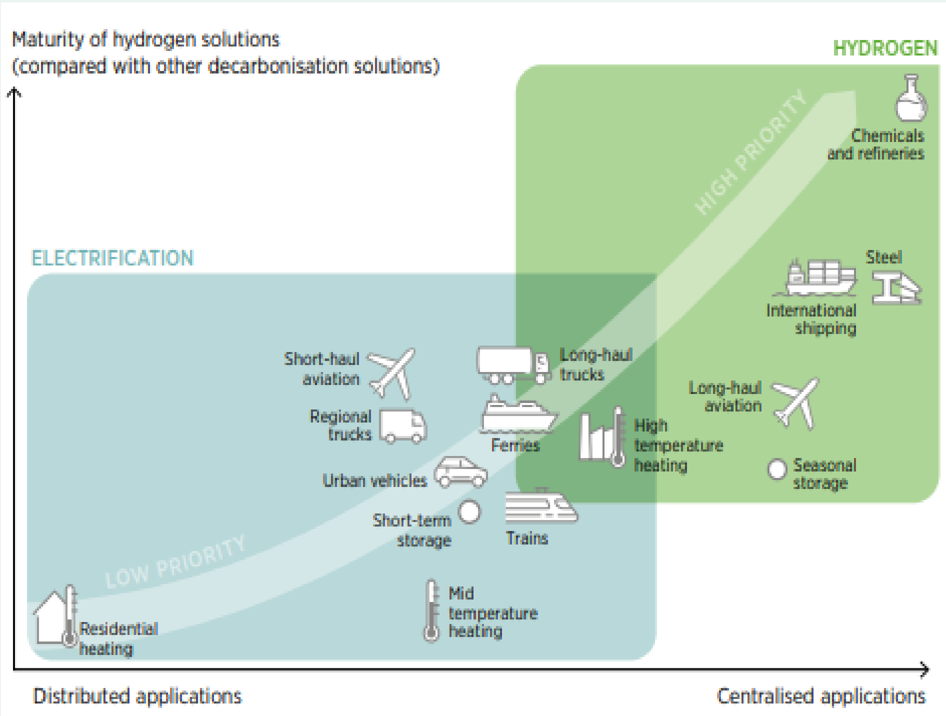
Regulation & Legislation

The use of green hydrogen is being driven by growth in the number of opportunities and applications in both industrial and domestic settings for which IRENA has created policy recommendations to support electrolyser use in support of the reduction of greenhouse gases.

We have already mentioned the major barriers to large scale adoption, yet green hydrogen is viewed as one of the most important drivers of GHG reduction in hard-to-decarbonise industrial segments - given the relatively maturity of the technology and lack of alternative solutions.

The chart below highlights industries that are prioritised for hydrogen use. To date, different countries and their governments have developed independent policies (hydrogen roadmaps) for leadership in clean technology and manufacturing.

Industries prioritised for hydrogen use



Source: IRENA

There is worldwide recognition of the need to rapidly increase and prioritise the generation of renewable power and green energy.

As such, diverse countries and governments are increasingly developing their own roadmaps which lay out measures which need to be taken to achieve a net-zero economy by 2050.

IRENA thinks that clean hydrogen production needs to rise to 518 million tonnes per annum by 2050 to achieve a net-zero economy, from 0.5m tonnes per annum in 2024.

Looking at these different approaches by region:

USA

The Inflation Reduction Act (IRA) of 2022 was landmark legislation to address climate change, healthcare costs, and inflation. The IRA aims to tackle pressing issues like reducing carbon emissions, making healthcare more affordable, and improving economic stability by addressing inflationary pressures. The key provisions in relation to Climate and Energy include:

The IRA allocates approximately **$369 billion over the next decade** to investments in clean energy, making it the largest federal investment in combating climate change in US history. It provides tax incentives for renewable energy projects such as wind, solar, and geothermal energy, and promotes energy efficiency in homes and businesses. There is also significant support for the manufacturing of electric vehicles (EVs) and energy storage technologies.

A key feature of the climate provisions is the extension of tax credits for clean energy producers, aimed at stimulating innovation and reducing the cost of producing clean energy. The IRA also incentivises domestic production of batteries and other components vital to the clean energy transition, addressing concerns over reliance on foreign supply chains.

Additionally, it introduces measures to reduce emissions from sectors such as transportation and manufacturing, with a goal of **cutting US GHG emissions by roughly 40% from 2005 levels by 2030**.

The Energy Infrastructure Reinvestment (EIR) programme is part of the 2022 IRA, aimed at modernising US energy infrastructure by repurposing aging fossil fuel facilities for cleaner energy solutions. With a significant allocation of $5 billion, the EIR provides loan guarantees to encourage investment in projects that transition existing energy assets, like coal and natural gas plants, into renewable energy sources and technologies.

Working alongside the IRA, the **US National Clean Hydrogen Strategy and Roadmap**, released by the Department of Energy in 2022, outlines a comprehensive framework for the development and deployment of clean hydrogen technologies across the USA. The strategy aims to position the USA as a leader in clean hydrogen production, use, and infrastructure, with a focus on reducing GHG emissions and enhancing energy security. Its key components are:

- **Hydrogen Production**: The strategy emphasises the importance of producing hydrogen using low-carbon methods, such as electrolysis powered by renewable energy and natural gas with carbon capture, utilisation, and storage (CCUS).
- **Infrastructure Development**: It calls for investment in hydrogen infrastructure, including pipelines, storage facilities, and refuelling stations, to facilitate the widespread adoption of hydrogen across various sectors.
- **Sector Applications**: The roadmap identifies key sectors for hydrogen deployment, such as transportation, industrial processes, and power generation, aiming to replace fossil fuels and reduce emissions.
- **Research and Development**: The strategy supports increased R&D funding to advance hydrogen technologies, making them more efficient and cost-effective.
- **Collaboration and Partnerships**: It encourages collaboration among federal, state, and local governments, private industry, and academic institutions to foster innovation and deployment of clean hydrogen solutions

The EU

REPowerEU

REPowerEU is an initiative launched by the European Commission in 2022 aimed at accelerating the EU's transition to renewable energy and reducing dependency on fossil fuels, particularly in the wake of geopolitical tensions and energy supply challenges, notably exacerbated by the war in Ukraine. The latter highlighted to the EU the need to diversify energy sources given its dependence on Russia which supplied 45% (2021) of the gas imported by the EU, compared to 15% in 2023. REPowerEU's key objectives are:

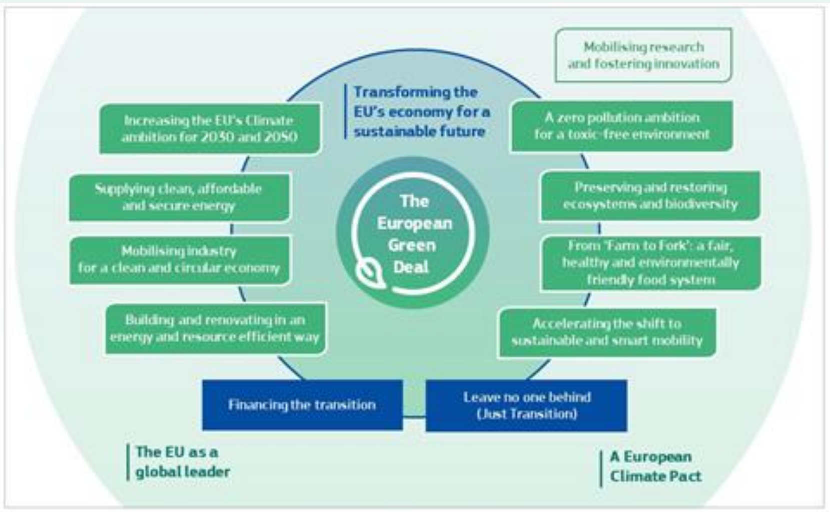
- **Energy Independence**: REPowerEU seeks to diversify energy sources and reduce reliance on Russian fossil fuels by increasing the use of renewable energy, such as solar and wind power.
- **Investment in Renewable Energy**: The initiative includes plans for substantial investments in renewable energy infrastructure, including the expansion of solar panels, wind farms, and hydrogen production.
- **Energy Efficiency**: It promotes improving energy efficiency across sectors, which is essential for reducing overall energy demand and emissions.
- **Infrastructure Development**: It emphasises the need to enhance energy infrastructure, including electricity grids and interconnections, to support the integration of renewable energy sources.
- **Regulatory Framework**: It proposes regulatory reforms to streamline the permitting process for renewable energy projects and increase public and private investments in clean energy technologies.

EU Green Deal Industrial Plan (GDIP)

The Green Deal Industrial Plan is a key initiative of the EU Green Deal, to support the achievement of zero net-emission of greenhouses gases by 2050, increasing the competitiveness of the net-zero industry alongside accelerating the transition to climate neutrality. The GDIP aims to provide a *more supportive environment for the scaling up of the EU's manufacturing capacity* alongside allowing the EU to sharpen its competitive edge.

The EU Green Deal intends to promote sustainable and economic growth while reducing greenhouse gases impacting climate change. This plan is built upon **four key pillars**: a predictable and simplified regulatory environment, faster access to funding, enhancing skills and open trade for resilient supply chains.

EU Green Deal summary



Source: GDIP

Reliant on large public investment, along with significant efforts in directing private capital toward climate and environmental action, the GDIP builds on previous initiatives, as well as being heavily reliant on the strength of the EU Single Market.

The initial pillar of this Plan; a predictable and simplified regulatory environment, utilises three different initiatives: the Net-Zero Industry act, the Critical Raw Materials Act, and reform of the electricity market design.

The Net-Zero Industry Act identifies goals for industrial capacity to be net-zero, thereby creating an efficient framework that is simple and quickly deployable. Complementing the Net-Zero Industrial Act, the Critical Raw Materials act and reform of the electricity market design aim to ensure trouble-free access of raw materials as well as lower renewable costs for consumers.

Regulatory summary

Below we list the key objectives of the legislations implemented to support net zero objectives. Through the common objective of achieving net-zero carbon emissions by 2050, each country will achieve clean energy through the utilisation of different technologies.

At the same time, the consideration of which technology to use must be aligned with the expectation for the regulation to also the deliver most cost beneficial process.

Comparison of key regulations

USA		
	IRA – Inflation Reduction Act	• Enacted in 2022 the IRA aims to achieve a net-zero economy by 2050
		• To date, the IRA is the largest single investment in climate & energy
		• IRA utilises clean energy incentives through tax incentives
		• Funding into Loan Programs & Greenhouse gas reduction to reduce industrial carbon footprint and promote use/production of renewables
EUROPE		
	REPowerEU	• Launched in May 2022, in response to the Russian attack on Ukraine
		• Removal of imported Russian fossil fuel transitioning to clean energy
		• 3 key aims: save energy, diversify energy supply and produce clean energy
	EU Green Deal Industrial Plan	• Launched in 2023
		• Build upon the withstanding EU Green Deal and REPowerER
		• Consists of 4 key pillars: a predictable and simplified regulatory environment, faster access to funding, enhancing skills and open trade for resilient supply chains.

Source: Equity Development

Diverse hydrogen companies in the UK

This next section is not intended to be a comprehensive list, but more an opportunity to show that the UK has nurtured very different business models and technologies – all driving growth in the use of hydrogen in clean energy:

ITM Power plc (ITM.L / AIM) View company website

Founded in 2000 in Sheffield, ITM Power specialises in hydrogen energy solutions. The group designs and manufactures electrolysers based on proton exchange membrane (PEM) technology to produce green hydrogen, the only net zero energy gas, using renewable electricity and water.

At the time of writing, ITM Power had a market capitalisation of £249m and reported revenue of £16.5m in its financial year to 30 April 2023.

The company's core mission is to enable the transition to a clean energy economy by developing technology that produces hydrogen using renewable electricity. Its key historical milestones include:

Foundation and Early Years (2000–2010)

- ITM Power initially focused on R&D, particularly electrolyser technology to split water into hydrogen and oxygen using electricity.
- The company went public on AIM in 2004 to raise capital for its research.
- During this time, it worked on creating cost-effective electrolyser solutions and filed technology patents

Developing Commercial Technology (2010–2015):

- ITM Power shifted focus from R&D to the commercialisation of its hydrogen technology. Its core product became the PEM (Proton Exchange Membrane) electrolyser.
- The company's first commercial product launch came in 2010 when it started offering hydrogen generation systems for industrial applications.
- In 2015, ITM Power became one of the leading players in the hydrogen refuelling sector, opening the UK's first public hydrogen refuelling station in London as part of a push for hydrogen-powered vehicles.

Strategic Partnerships and Growth (2015–2020):

- ITM Power entered significant partnerships with major companies, including Royal Dutch Shell, Linde, and National Grid, to develop hydrogen infrastructure.
- The company secured projects to integrate hydrogen into the energy grid for storage and balance, a concept called Power-to-Gas (P2G), particularly in Germany.
- ITM Power's product offerings expanded to large-scale electrolysers for industrial use and refuelling stations, capitalising on the rising interest in hydrogen for decarbonisation.

Gigafactory and Major Expansion (2020–Present):

- In 2020, ITM Power opened the world's largest electrolyser factory, called the ITM Gigafactory, in Sheffield. The factory aims to significantly increase the production of electrolyser units, helping meet growing demand for green hydrogen.
- In the same year, ITM Power formed ITM Linde Electrolysis GmbH, a joint venture with Linde, a global industrial gas company. This partnership accelerated the commercialisation and deployment of green hydrogen solutions worldwide.
- The company has focused on large-scale projects for hydrogen production, including initiatives tied to the EU's and UK's green recovery plans.

Ceres Power plc (CWR.L / LSE) View company website

Ceres Power specialises in fuel cell technology, notably in solid oxide fuel cells (SOFCs) and solid oxide electrolysis cells (SOECs). These fuel cells generate electricity through a clean, efficient process using various fuels, including natural gas, hydrogen, and biogas. Its current market capitalisation is £377m and in the financial year to 31 December 2023 it had revenues of £22.3m.

Founded in 2001, the company has evolved into a key player in the global clean energy sector, able to offer both SOFC and SOEC solutions as shown by this corporate video . Group key historical milestones include:

Founding and Early Development (2001–2010):

- Ceres Power was founded as a spin-off from Imperial College London, based on research into solid oxide fuel cell technology. The company was set up to commercialise this fuel cell technology, which promised highly efficient, low-emission energy production.
- Early on, Ceres focused on developing SOFCs that could operate at relatively low temperatures (500–600°C), compared to traditional SOFCs that typically require much higher temperatures.
- In 2004, Ceres Power went public on AIM, raising funds to advance its technology from research into commercialisation.

First Commercial Attempts and Challenges (2010–2015):

- During the early 2010s, Ceres Power focused on developing a fuel cell product for residential combined heat and power (CHP) applications, aimed at providing homes with both heat and electricity from a single system.
- The company partnered with British Gas for a residential CHP unit, which integrated Ceres' fuel cells with domestic boilers. However, technical challenges, including difficulties in scaling the technology and achieving the necessary cost reductions, caused delays.
- In 2011, after facing commercialisation setbacks and a failed initial rollout, the company underwent restructuring and changed leadership to refocus on developing its core SOFC technology for broader applications.

Shift in Strategy and Technological Breakthroughs (2015–2018):

- Under new leadership, Ceres Power shifted its strategy from developing complete systems (like CHP units) to focusing on licensing its SOFC technology to major energy and industrial companies. This shift allowed Ceres to concentrate on improving and scaling the core technology, while leveraging partners for manufacturing and distribution.
- The company developed its flagship SteelCell® technology, a low-cost, high-performance SOFC that can run on various fuels, including hydrogen, natural gas, and biofuels. This technology was unique because it used conventional steel, making it cheaper and easier to manufacture than traditional ceramic-based SOFCs.
- Ceres Power began securing partnerships with large global players, including Bosch and Weichai Power, to co-develop fuel cell applications for power generation, transportation, and other industrial uses.

Strategic Partnerships and Global Expansion (2018–2020):

- In 2018, Ceres Power formed a major partnership with **Bosch**, which took a 4% equity stake in Ceres and became a licensee of the SteelCell® technology. Bosch has since increased its stake to over 17%, becoming a significant shareholder and partner in the deployment of SOFC technology.

- Ceres Power also entered a strategic partnership with **Weichai Power**, a leading Chinese automotive and equipment manufacturer, which aimed to use Ceres' technology in commercial vehicles and power generation. Weichai has also become the largest shareholder in Ceres and played a crucial role in expanding the company's presence in China's fast-growing fuel cell market.
- The company continued to build on these partnerships, securing additional contracts and collaborations to commercialise its SOFC technology across various industries, from residential heating to data centres and transportation.

Scaling and Global Leadership (2020–Present):

- Ceres Power has positioned itself as a leading provider of SOFC technology globally, with its focus on high-efficiency, low-emission power generation.
- In 2020, it opened a new manufacturing facility in the UK to boost production and satisfy Ceres' needs regarding innovation and prototyping. Its strategy revolves around licensing its technology to industrial partners like Bosch, Doosan, and Weichai Power, which handle mass production and distribution.
- With hydrogen gaining momentum as a critical part of the global energy transition, Ceres Power expanded its focus to include hydrogen-powered systems, which are essential for decarbonising industries and energy generation.
- In 2021 Ceres raised £180m of equity finance to accelerate its SOEC business which soon signed major global manufacturing partners under license (Delta and Denso). Indeed, the group's leading technology means the SOEC business within Ceres appears to have considerable momentum .
- Recently, the company has broadened its applications beyond stationary power generation to areas such as heavy-duty transportation, aiming to use its fuel cells in trucks, buses, and marine vessels.

AFC Energy plc (AFC.L / AIM) View company website

AFC Energy is a leading provider of hydrogen power and ammonia cracking solutions. The company's core proposition focuses on fuel cell generators (hydrogen into power) and fuel processing (ammonia into hydrogen). Financial revenues in the year to 31 October 2024 were c. £4.0m, its market capitalisation at time of writing was £86m.

The company provides clean energy solutions, primarily through hydrogen-powered fuel cells, which can be used in off-grid power generation, electric vehicle charging, and industrial applications. Its key historical milestones include:

Founding and Early Development (2006–2010):

- AFC Energy was founded in 2006, its focus was to develop an alkaline fuel cell system using hydrogen to produce clean electricity. Alkaline fuel cells (AFCs) are among the most efficient types of fuel cells, using a solution of potassium hydroxide (an alkaline electrolyte) to conduct electricity.
- In 2007, AFC Energy was listed on AIM, raising capital to further develop its hydrogen fuel cell technology.
- By 2009, AFC Energy had successfully completed its first operational trials of the fuel cell system, validating its potential to produce low-cost, clean energy.

Partnerships and Early Commercialisation (2010–2015):

- The group formed several partnerships with industrial companies and research organisations to accelerate the development of its fuel cells. These included collaborations with chemical and energy companies to test the technology in real-world industrial settings.

- In 2011, AFC Energy signed a partnership with AkzoNobel, a global chemicals company, to deploy fuel cells at a chlor-alkali plant in Germany. The plant produced hydrogen as a byproduct, making it an ideal location to test AFC's technology for producing clean electricity from hydrogen.
- By 2015, AFC Energy successfully completed the world's largest alkaline fuel cell installation at Stade, Germany. This 240kW system demonstrated the viability of using hydrogen as a fuel to generate clean electricity on a commercial scale.

Strategic Shifts and Focus on Hydrogen Economy (2015–2020):

- AFC Energy pivoted its focus towards leveraging its fuel cell technology for the growing hydrogen economy, particularly in off-grid applications and industrial power generation.
- In 2016, the company began exploring new markets, including electric vehicle (EV) charging. AFC Energy's alkaline fuel cells were promoted as a solution to power remote EV charging stations, helping to overcome limitations in EV infrastructure.
- In 2019, AFC Energy launched its HydroX-Cell(L) fuel cell system, a modular and flexible fuel cell that could be used in a range of applications, including data centres, EV charging, and industrial power generation.

Expansion into New Markets and Sustainable Solutions (2020–Present):

- With hydrogen becoming a key pillar of global decarbonisation strategies, AFC Energy positioned itself as a leader in providing fuel cell systems for sustainable power generation.
- In 2020, AFC Energy unveiled its H-Power EV charger, a hydrogen fuel cell-powered electric vehicle charging system. This innovation addressed the growing demand for clean and reliable charging infrastructure, particularly in locations where grid access is limited.
- The company secured multiple strategic partnerships to expand the adoption of its technology. Notably, it partnered with ABB to integrate fuel cells into EV charging and industrial power systems. The collaboration aimed to address the growing demand for sustainable energy solutions in transportation and heavy industries.
- AFC Energy continued to expand its global presence by entering into partnerships in the Middle East and Europe, focusing on integrating its fuel cell technology into large-scale infrastructure projects, including clean energy solutions for ports, data centres, and off-grid industrial sites.
- The company has also focused on the maritime industry, offering fuel cell systems as a clean alternative for powering ships, contributing to efforts to reduce emissions in the sector.
- AFC Energy and Speedy Hire plc announced in November 2023 the launch of 'Speedy Hydrogen Solutions Limited' - a 50:50 joint venture company with a dedicated hydrogen powered generator plant hire business promoting sustainable, zero emission, temporary power solutions designed specifically for the off-grid generation market.
- On 4 November 2024 the group released a well-received update on its financial year to 31 October 2024 indicating that it expected to report group revenues of c. £4.0m i.e. slightly above existing market expectations and had unaudited cash and cash equivalents of £15.4 million.
- In January 2025 John Wilson will assume the role of CEO. John appears well placed to lead AFC Energy at this stage of its development as has considerable experience in leading technology-driven businesses through periods of material growth and transformation.

GeoPura Ltd. (Private) View company website

GeoPura was founded in 2019 to enable the production, transport and use of zero emission fuels with innovative and commercially viable technology to decarbonise our global economy. Having operated in the hydrogen industry since its launch, the group already has vast experience in the production, storage and transportation of hydrogen as a fuel for its HPU, hydrogen powered generators.

Its focus is on **GeoPura HPU** (Hydrogen Power Units) which harness green hydrogen to provide zero-emission electricity, augmenting the grid where the local supply is insufficient and replacing diesel generators delivering reliable, large-scale power, with the only byproduct being water. The commercial HPU2 product is already in manufacturing planning, with the prototype complete.

The HyMarnham Power project in the East Midlands, a joint venture between GeoPura and JG Pears, is one of those projects listed in the Budget for funding - to cover up to 9.3MW capacity.

How GeoPura delivers Energy-as-a-Service

The company's aim is to deliver hydrogen-fuelled clean energy to replace diesel generators and decarbonise customers in off-grid and grid augmentation situations. This is achieved by:

- using a contracted energy-as-a-service business model, whereby GeoPura leases HPUs (Hydrogen Power Units) to customers and provides regular hydrogen supply
- operating under a revenue model that includes a weekly rental fee for the HPU and per unit cost of hydrogen supplied, and
- using hydrogen sourced from third parties and owned electrolysers, with plans to bring more production in-house via High Marnham Power

GeoPura's end-to-end solution for clients is well illustrated by this company graphic:

From hydrogen production to client usage

Source: GeoPura

Blue-chip supporters

Although a private company, the attraction of GeoPura's model means it has raised **over £100m** in funding over the last 18 months via a Series A placing, a Convertible Loan, and Asset-backed Debt.

Adding to the long-term support of The UK Infrastructure Bank (now known as The National Wealth Fund), GeoPura has attracted an impressive array of industry experts, lenders and investors including Siemens Energy, General Motors, Barclays, SWEN Capital Partners, Close Brothers, BNP Paribas, HSBC, and Siemens Financial Services.

Hydrogen Future Industries plc (HFI / AQSE) View company website

Hydrogen Future Industries (HFI) was founded in July 2021 with the aim of reducing green hydrogen costs, as well as increasing hydrogen accessibility to create a cleaner environment. HFI is currently a pre-revenue business, and its shares started trading on the AQUIS Stock Exchange Growth market in December 2021.

The group has a market capitalisation today of £0.93m and is pre-revenue. However, licensing and project-based revenues are expected to accrue as they deliver on deals already signed.

HFI's wind-based hydrogen production system utilises an anion exchange membrane electrolyser alongside a wind turbine designed for efficient and green hydrogen production, thereby bypassing historic challenges associated with electricity grids. They are developing their unique wind harnessing technology to enable the group to target companies of material scale (e.g. in the mining industry) to supplement their high energy demands through green hydrogen production.

The aim is to produce green hydrogen at a cost of $2/kg. HFI's research and development to date shows they should be able to generate three times the energy that a traditional open rotor turbine design does.

Wind Turbines

HFI's patented system includes a Smart Hydraulic Drive and Dynamic Tower which allows for a much lighter and height adjustable turbine configuration.

The turbine's unique features include a smart hydraulic drive that improves efficiency and reduces the cost of energy production, the ability to generate energy over a broader range of wind speeds, and versatile energy output in hydraulic, DC, or AC forms without the need for additional AC to DC rectifiers for hydrogen production. Significantly, the turbine can be raised and lowered for optimal wind capture, thereby reducing maintenance and installation costs as servicing can be performed at ground level.

Anion Exchange Membrane Water Electrolyser

HFI claims AEMWE is a step forward in power efficiency, longevity, and cost-reduction for green hydrogen production. Testing has shown a **cell efficiency of 97%,** much higher than the 80-85% of rival technologies.

Constructed without platinum group metal catalysts, the AEMWE utilises more affordable and accessible materials, resulting in a projected cost that is 50% lower per kW than PEM electrolysers. It is designed to deliver high efficiency even with variable energy supply typical of renewable sources, and it features a unique system where individual cells can be replaced without halting hydrogen production.

The AEMWE's catalysts are chemically attached to the electrodes, preventing wash-off and ensuring durability. The ongoing patent applications aim to protect the unique IP developed around this technology.

Commercial progress

HFI has entered several Memorandums of Understanding (MoU) to support its R&D efforts, including with the University of Bristol and an Australian renewable microgrid partner (Capricorn Clean Energy Limited).

The Capricorn deal allows access to a target market, facilitating the identification of potential opportunities in line with the Australian Renewable Energy Agency's (ARENA) Renewable Microgrid Programme ("RMP"). The latter has earmarked A$125m in funding by the RMP to support the creation of demand from green energy sources: hopefully creating opportunity and demand for HFI technology.

In July 2024, HFI announced a long-term licensing deal in Ireland generating up €2.25m. The creation of HFI Ireland has been put in place to install a pilot system for displaying the technological concept to potential users. With a license over 20 years, HFI will have a 30% equity interest in HFI Ireland plus the potential to raise that to 40% following the expected investment of €1m into the pilot system.

Clean Power Hydrogen plc (CPH2 / AIM)

View company website

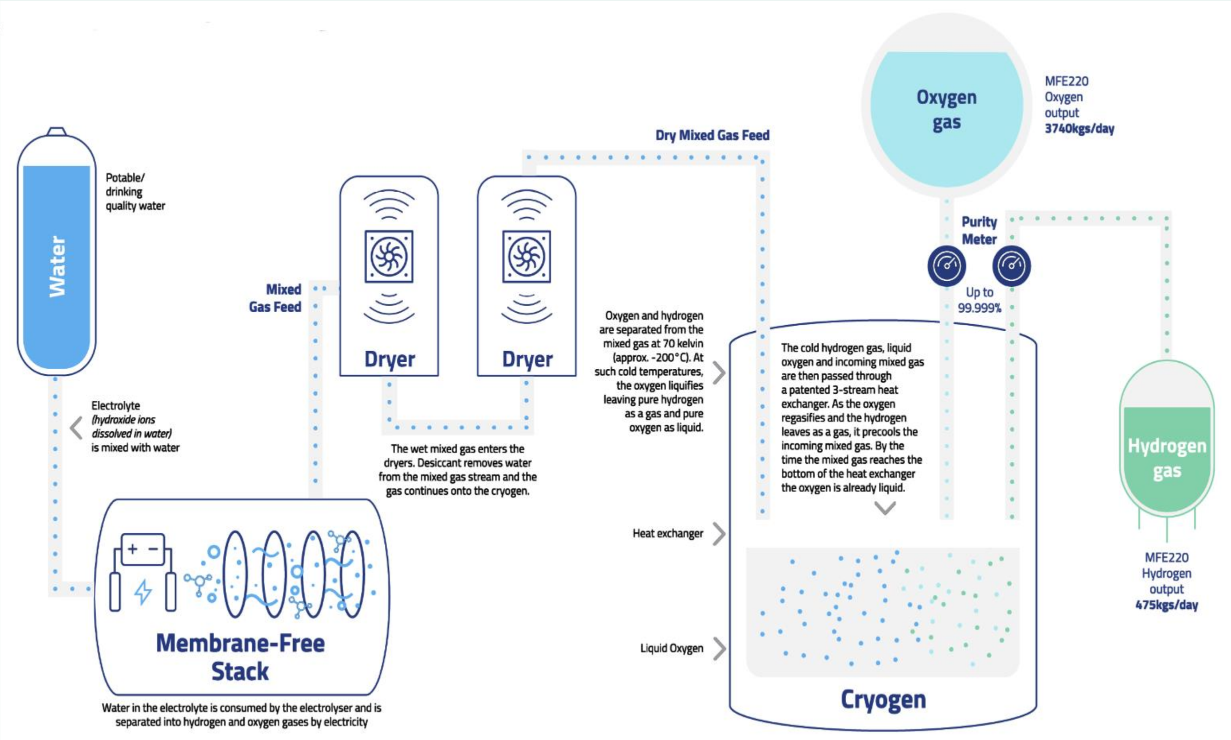
Clean Power Hydrogen plc (CPH2) is a UK-based company that specialises in developing innovative green hydrogen technology. CPH2 was founded by Dr Nigel Williamson and Joe Scott in 2012, and in February 2022 its shares were listed on AIM. Its current market capitalisation is £30m.

Founded in 2012, CPH2 has focused on advancing hydrogen and oxygen production through its membrane-free electrolyser technology. This technology provides a cost-effective and robust alternative to conventional systems, making hydrogen production more efficient and environmentally sustainable.

Membrane-free Electrolyser

CPH2's technology is based on water electrolysis without needing a membrane, separating hydrogen and oxygen gases using cryogenics later in the process rather than at the start. This approach provides flexibility in applications as oxygen and heat can be harvested by re-engineering the primary product (hydrogen).

CPH2 process



Source: Clean Power Hydrogen plc

CPH2's MFE110 electrolyser successfully passed its Factory Acceptance Test (FAT) in 2024. This marked a significant step toward commercial rollout, as the electrolyser demonstrated its ability to produce hydrogen and oxygen at commercial standards. The MFE110 is set to be deployed to Northern Ireland Water for full installation and commissioning.

CPH2 is currently a pre-revenue business and had cash and cash equivalents of £4m as at 30/06/24. On the 4 November 2024 it announced a new License Agreement with Lisheen H2 Energy Park, as well as a contract to deliver Lisheen one of CPH2's 1MW MFE220 electrolyser units.

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