PLATINUM ESSENTIALS

Hydrogen 101 – An introduction for investors

Platinum demand is set for sustained long-term growth. With global decarbonisation on the agenda, this growth is fuelled by emerging demand from the hydrogen economy. In this edition of Platinum Essentials, we offer an overview of the hydrogen economy, its technologies, and its implications for platinum. This serves as a complementary piece to our latest hydrogen-related platinum demand forecast and offers a foundation for understanding the fundamental dynamics of the hydrogen market for platinum investors or those considering platinum as an investment asset.

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Hydrogen serves as a versatile energy carrier, capable of being produced from renewable energy sources and applied across various mobility and industrial sectors to facilitate decarbonisation. Despite this potential, the current 95 Mt per annum global hydrogen market primarily relies on fossil fuels for its production. Platinum and other PGMs are set to play a pivotal role through their inclusion in electrolysers, catalysing the production of hydrogen and oxygen via renewable energy – an emissions free process. Further, the commercial development of platinum containing Proton Exchange Membrane (PEM) fuel cells that utilise hydrogen to produce electricity have opened up the potential for hydrogen to remove fossil fuels from transport while the use of green hydrogen can decarbonise other sectors.

Hydrogen demand today is primarily for use as a feedstock in the chemical and petrochemical industries. However, the IEA estimates that hydrogen demand will increase to 150Mt by 2030 driven by energy transition related uses in fuel cells and novel industrial process' such as Direct Reduced Iron (DRI) steelmaking and use in gas turbine power stations. Electrolysers and carbon capture technology will be utilised to generate 60Mt of new supply, thereby displacing fossil fuel-based hydrogen production and decarbonising new sectors. Decarbonising the existing 95 Mtpa grey hydrogen market, would save 430 Mt of CO_2 emissions, or the equivalent of taking 120 million vehicles off the road for a year. According to the Hydrogen Council, by 2050 hydrogen could be responsible for up to 20% of global emissions abatement from its combined use with other applications.

Platinum demand within the hydrogen economy spans two key applications: PEM electrolysers for hydrogen production and PEM fuel cells for hydrogen use. While fuel cells are primarily deployed in Fuel Cell Electric Vehicles, their usage in marine, rail, off-road, and stationary power generation is expected to gain traction by 2030. 2024 marks a turning point in the hydrogen economy's growth, with hydrogen-related platinum demand projected to double year-on-year, propelled by advancing government policies and increasing financial support. Recognising hydrogen's pivotal role in achieving net-zero emissions, its integration into various sectors is inevitable. We anticipate sustained growth, with the hydrogen economy accounting for almost 875koz of platinum demand by 2030—approximately 10% of total platinum demand. Below, we present a summary of hydrogen-related demand, while our latest hydrogen outlook offers comprehensive analysis. This report focuses on essential hydrogen technology choices and their contribution to decarbonisation, aiding investors in grasping the key drivers of platinum demand in the latter half of the decade.

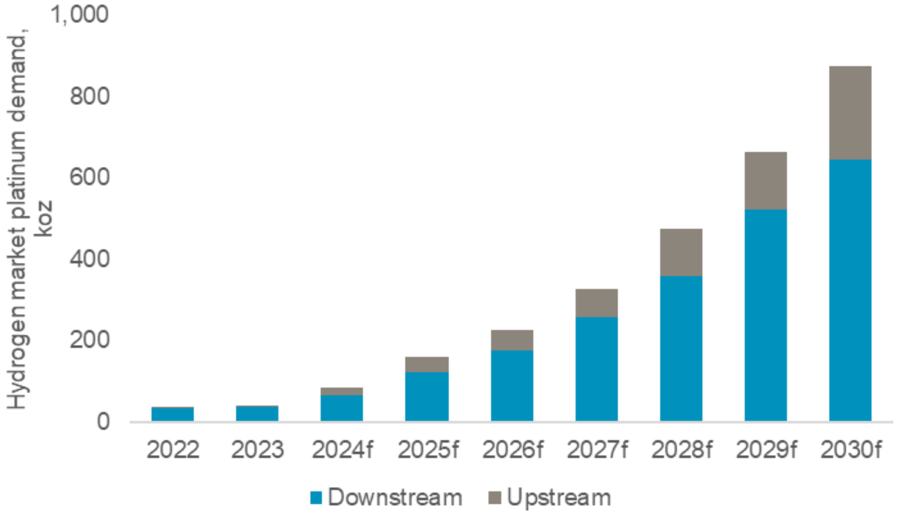
Figure 1. Hydrogen demand for platinum summary table

WPIC HYDROGEN-PLATINUM DEMAND ESTIMATES

Pt DEMAND (koz)	2022	2023	2024f	2025f	2026f	2027f	2028f	2029f	2030f
Mobility	**19**	**16**	**44**	**95**	**143**	**219**	**312**	**461**	**564**
- FCEV	19	15	42	93	138	208	293	427	505
- Rail	0	0	0	0	1	1	1	3	5
- Marine	0	1	1	1	2	4	8	14	24
- Off-Road	0	0	0	0	1	5	10	17	30
Electrolyser	**0**	**4**	**16**	**39**	**52**	**71**	**116**	**141**	**229**
Stationary Power	**17**	**20**	**23**	**27**	**32**	**39**	**48**	**61**	**81**
Total demand	**36**	**40**	**83**	**161**	**226**	**328**	**476**	**663**	**874**

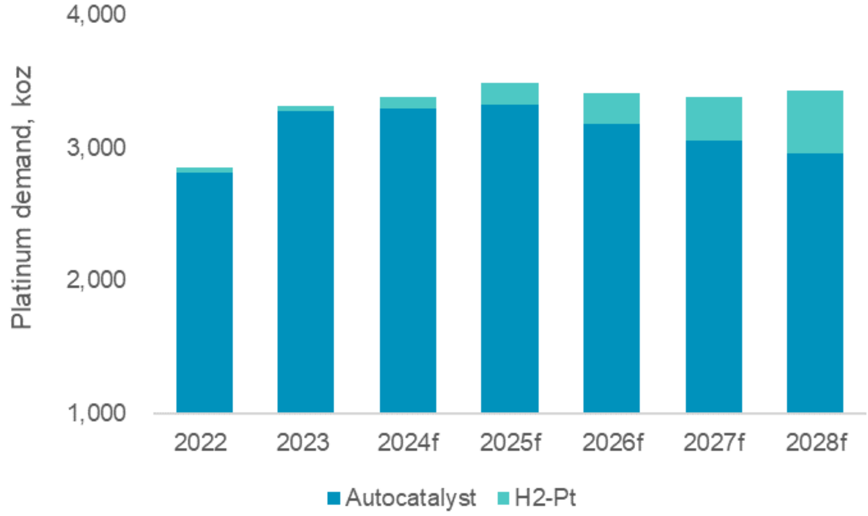
Source: WPIC research

Figure 2. Hydrogen linked platinum demand approaches 875 koz per annum by the end of the decade.



Source: IEA, Company data, WPIC research

Figure 3. Emerging platinum demand from hydrogen applications offsets lower ICE autocatalyst demand



Source: Metals Focus (2022 -2024f), WPIC research thereafter

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What is Hydrogen?

Hydrogen is the first element on the periodic table and gaseous hydrogen is the most abundant element in the universe. In its diatomic form, H_2, is an odourless, colourless, and tasteless gas. Its use stems from its high calorific value; hydrogen is ranked amongst the elements with the highest energy content per unit mass of combustible fuels. However, hydrogen is extremely light and difficult to handle. In order to be transported or utilised, it is often compressed or cooled to liquid form.

Hydrogen releases its energy potential through two means, namely, via direct combustion or through electrochemical reactions, in both cases recombining with atmospheric oxygen to create water. In fact, liquid hydrogen has been used in rocket launches since the mid-20th century, while platinum fuel cells were first used as on-board power supplies on the Gemini space mission service modules. Beyond fuel, hydrogen's main use in today's economy is as a chemical feedstock, particularly in ammonia production which is used for fertilisers in the global agriculture industry.

Figure 4. Fuel cell utilised in service module for command electrical power on the Gemini missions.

Source: National Air and Space Museum

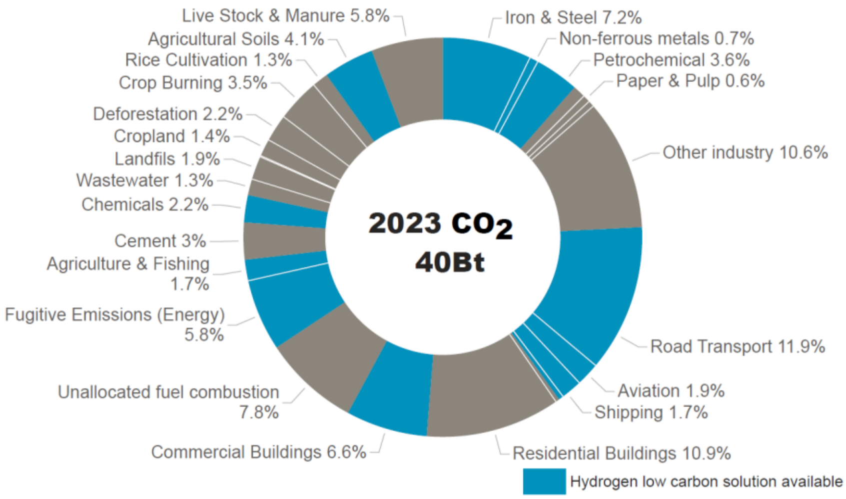
Why is hydrogen important for the energy transition?

Burning fossil fuels (coal, natural gas and oil) produces greenhouse gas emissions (GHG), which have been rising ever since the industrial revolution. GHG emissions are linked to climate change, most notably global warming. The Paris accord, signed in 2015, aims to limit global warming to less than 1.5 degrees Celsius by 2050 through the reduction of GHG emissions. Achieving this requires a fundamental shift in how human's generate energy, shifting from a fossil fuels based economy to a metals based economy, a change that is referred to as the energy transition. It is a complex socio-economic challenge requiring multiple technologies to be implemented to replace fossil fuels. Renewable energy (wind and solar) and battery technology will deliver most of the incremental reductions in GHG emissions. However, renewable energy and battery technologies are not applicable in a number of sectors where batteries would be too large and heavy, where high-capacity utilisation rates are required, or simply where electrification is not possible. Sectors like these, as described as being "hard-to-abate." Steel production - responsible for up to 10% of global CO_2 emissions - exemplifies this as coal and natural gas release GHGs when utilised as oxidisers in the chemical reaction to reduce iron. This is not a process that can be electrified using current technologies, therefore renewable energy cannot mitigate emissions from steel production, but hydrogen can. Hydrogen substitutes coal to reduce iron in a process called direct reduction, with water vapour replacing harmful GHGs as the main emission.

With hydrogen's versatility as a fuel, a chemical feedstock or energy carrier, it is increasingly seen as key to decarbonising hard-to-abate sectors. When produced via low or carbon free technologies, hydrogen reduces GHG emissions in mobility, heavy industry, and power generation. Below is the global contribution of industrial sub-sectors to total GHG emissions (figure 5). We have colour coded sectors in which hydrogen technology could be employed to illustrate the extent of viable applications. According to the

Hydrogen Council approximately 20% of the carbon abatement requirements by 2050 will be met by hydrogen use.

Figure 5. Hydrogen can decarbonise many of the worlds carbon intensive industries.



Source: Our World in Data, WPIC Research

What is the Hydrogen Economy?

Hydrogen is produced, transported, and utilised as a chemical energy carrier across various sectors. The expansive ecosystem of technologies and processes that contribute to hydrogen use is known as the 'hydrogen economy' (fig 6). The hydrogen economy can be segmented into upstream, midstream, and downstream. Here we will take the opportunity to briefly address each portion of the hydrogen economy, before expanding on the key technologies that drive it later on.

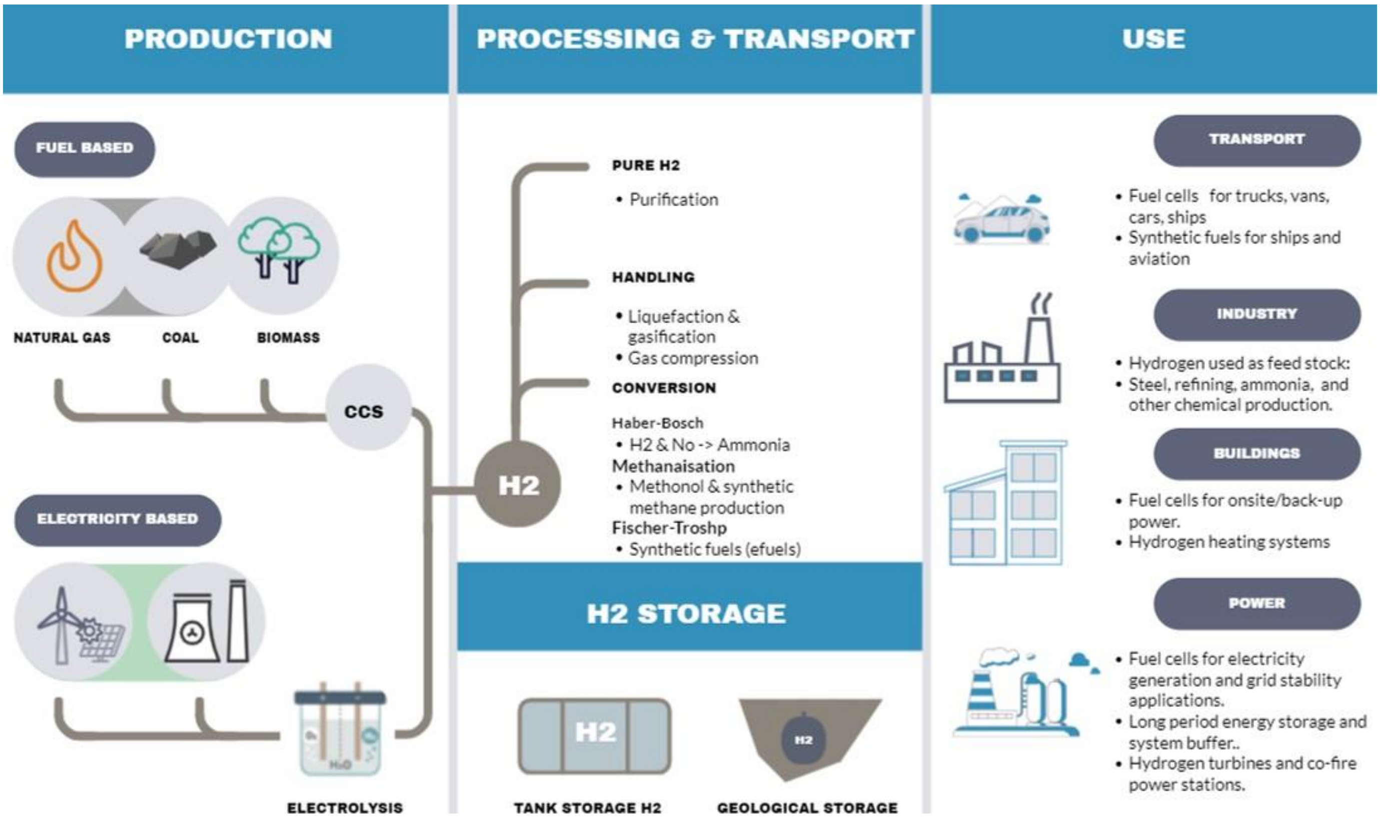
Upstream comprises hydrogen production, which today is a carbon intensive process typically utilising natural gas, oil or coal. This is the most cost-effective method of production. However, momentum is building towards low carbon and renewable production methods. It is expected that low carbon and renewable sources of production will grow to represent 50% of hydrogen supply by 2030. Electrolysis, the process of splitting water into hydrogen and oxygen utilising electricity, will be the primary technology to drive the shift away from fossil fuels.

Downstream encompasses hydrogen use. Today, hydrogen has three primary uses. It is used to produce, methanol – a base alcohol, ammonia – a fertiliser ingredient, key for global agriculture, or employed for its reactive properties in petroleum refining. Hydrogen plays a vital role in various refining processes, contributing to the production of cleaner, higher-quality fuels and meeting stringent environmental standards. Green hydrogen will be used to decarbonise these existing end uses of hydrogen that have hitherto been reliant on hydrogen from fossil fuels. However, as momentum builds in the energy transition, hydrogen's downstream uses will expand to new, low carbon applications such as the production of synfuels, and being used in platinum containing proton exchange membrane (PEM) fuel cells to generate electricity in mobility or stationary systems.

Connecting the upstream and downstream is the **midstream**, which describes the processing, transport, and storage of hydrogen. Today, hydrogen is typically produced and consumed in the same chemical facility. However, as the hydrogen economy evolves it will necessitate the transportation of hydrogen nationally and globally to connect production facilities with emerging end demand. Hydrogen can be transported as a pure gas, a liquid, or as a derivative product such as methanol, ammonia or using a liquid organic hydrogen carrier depending on the distance travelled and the end application.

Hydrogen can be stored either in tanks for short to medium term storage or in suitable naturally occurring geological formations for long time horizons. Long term storage is a key enabler for grid stability when utilised in combination with renewable energy sources. This amounts to a balancing factor, renewable energy sources are fickle, when there is an overabundance, the excess can be used to make hydrogen that can be stored, much like charging a battery, and then used as an energy source when renewable sources are insufficient.

Figure 6. The hydrogen economy contextualises the key segments of hydrogen use.



Source: WPIC Research

PGMS make hydrogen happen:

The hydrogen economy is driven by chemical and electrochemical process' that require PGM catalysts to facilitate or speed up reactions. The physiochemical properties of platinum make its use particularly essential for scaling the hydrogen economy and we estimate its expansion will support an additional platinum demand of 850-900 koz by 2030. This primer will explain the technologies utilised in the hydrogen economy and the roles played by PGMs and platinum specifically. Commencing with a high-level overview of where PGMs are utilised in the hydrogen economy:

Upstream

PGM catalysts provide the necessary surface reactivity in processes such as electrolysis and fuel cell electrochemistry, where efficient and rapid hydrogen conversion is crucial, platinum alongside iridium and ruthenium are key the catalysts employed in upstream production of hydrogen via electrolysis.

Electrolysis also creates indirect platinum demand. Platinum alloyed with rhodium is used in the bushings needed for fibreglass manufacturing, one of the main uses of which is as a key construction material for both wind turbines and photovoltaic solar panels. As demand grows for renewable energy to power hydrogen production, so will glass linked platinum demand.

Midstream

Midstream uses for platinum include loading hydrogen into a liquid organic hydrogen carrier (LOHC) for transportation and purifying hydrogen from electrolysers. Impurities in hydrogen gas can negatively impact the performance and lifespan of fuel cells, making the use of effective catalysts critical.

Downstream

Platinum, palladium, and rhodium have been used for decades in hydrogenation reactions involved in petroleum refining and chemical processing, which make up ~6% of platinum's industrial demand (2023). Similarly, a platinum gauze is utilised in the Haber-Bosh reaction to promote the efficient production of ammonia.

New downstream platinum demand is ascribed to fuel cells for mobility or stationary power applications, with solutions available across road, marine and off-highway sectors. Other downstream hydrogen applications such as green steel and synthetic fuels do not directly require platinum, but they do in-directly increase demand through promoting the need for increased electrolyser manufacturing and low emission hydrogen production.

Figure 7. PGMs employed in the Hydrogen economy.

Production *(Upstream)*	**Processing & Transport** *(Midstream)*	**Use** *(Downstream)*
Electrolysis • **Pt, Ir, Ru** Fibreglass Production • **Pt, Rh**	Hydrogen Purification • **Pt, Pd** Ammonia Production • **Pt, Ru, Pd** LOCH • **Pt, Ru**	Fuel Cells Mobility • **Pt** Fuel Cells Stationary • **Pt**

Source: WPIC Research

The Role of Policy Setting

Policy plays a crucial role in assisting industries in their infancy by providing a supportive environment for growth, innovation, and sustainability. Various challenges face the green hydrogen economy in its infancy, including high production costs, technological uncertainties, and lack of infrastructure.

With the global goal of decarbonisation in-mind, supportive policy action is required to ensure the successful growth of the hydrogen economy. As of the end of 2023, a total of 61 governments have adopted hydrogen strategies, representing over 80% of global energy related CO_2 emitters. Global strategies are in various ranges of maturity, ranging from non-binding hydrogen production targets to policy intervention for demand creation and mitigating investment risk. Figure 8 details the national hydrogen roadmaps of select countries highlighting a range of strategies and targets. Key uses of hydrogen have been targeted at a national level, spanning industrial decarbonisation to synthetic fuel production.

Figure 8. Select summary of government hydrogen targets.

Country	Description
United States	10 Mt of "clean" hydrogen production by 2030, 20 Mt by 2040 and 50Mt by 2050.
European Union	10 Mt of hydrogen domestically produced and 10Mt imported by 2030. 42% of hydrogen used in industry to be renewable by 2030, rising to 60% in 2035.
China	Province based production targets, combined 2025 target of 1.1Mt.
Germany	Install 10 GW of electrolysers by 2030, increase industrial and mobility hydrogen demand. Replace reliance on natural gas via hydrogen, 1,800km hydrogen pipeline.
India	5 Mt of "green" hydrogen by 2030 and 125 GW of renewable energy additions. Plans to expand to 10 Mt/yr so include development of exports.
United Arab Emirates	1.4 Mt of hydrogen by 2030, 7.5 Mt by 2040 and 15 Mt by 2050. Mix of electrolysis and SMR with CCS production.
Panama	Utilise hydrogen derivative fuels for 5% of maritime bunkering by 2030.
Japan	3 Mt of hydrogen by 2030, 12 Mt by 2040 and 20 Mt by 2050. Further, target to replace 1% of gas supply in existing pipelines with synthetic methane, rising to 90% by 2050. Targeting industrial hydrogen use in steel and petrochemical industries.
Korea	Targeting 2.1% of total electricity generation via hydrogen and ammonia by 2030, rising to 7.1% by 2036.

Source: Government press releases, WPIC Research

Strategic targets are largely unbinding and serve to provide the intended direction of a government's decarbonisation plans. Whilst helpful, they do not provide investors with demand motive or reassurances regarding investment. A lack of a robust policy has led to stagnation in largescale hydrogen development in recent years. However, momentum is building around mandatory target setting, combined with major fiscal support in key jurisdictions such as the European Union and the United States. Binding targets send a clear signal to industry about the future marketplace. In the EU 42% of hydrogen demand is required to be produced via renewable hydrogen by 2030, creating demand for low carbon investment.

Hydrogen technology costs are high in their infancy and require both R&D and economies of scale to bring costs in-line with traditional carbon-based alternatives. This takes time. Governments are introducing various financial tools to bridge the gap and provide medium to long term stability to the entire value chain. We have listed below some of the key funding mechanisms available, although, it should be noted the space is evolving quickly:

- **Grants & subsidies:** Direct funding is commonly employed to reduce hydrogen project capex , lowering barriers for entry. Examples include Hydrogen Headstart, an AUD 2 billion Australian federal government program to support large scale renewable hydrogen projects.

- **Tax incentives:** Tax credits and rebates such as the US's $500 bn Inflation Reduction Act (IRA) which includes tax credits of up to $3 per kg of hydrogen produced.
- **Contracts for Difference (CfD):** Such as the United Kingdom's low-carbon hydrogen agreement. This model aims to provide revenue support to hydrogen producers when production costs are high. It provides the difference between the operating cost of low-carbon and high-carbon fuels via a 15-year contract.
- **Competitive bidding schemes:** Such as the European Union's €800m Hydrogen Bank pilot project. Bids are placed to receive revenue payments per kilogram of hydrogen produced over a certain number of years, with up to €4.5 per kg of hydrogen produced to be available for 10 years.

Robust government targets for hydrogen helps generate demand. When combined with strong financial support, it provides a base to build the hydrogen economy for investors and project developers.

How is Hydrogen Produced?

Despite hydrogen's abundance it rarely exists alone in a useable form. Generally, it exists in combination with other chemical elements such as in water, where it is combined with oxygen, and in organic compounds where it is combined with carbon, as in natural gas. Producing hydrogen therefore requires physical or chemical processes to strip it away from the source molecule.

From a technical standpoint, commercial hydrogen production processes are fundamentally categorised into two main pathways. The first involves a **thermal process**, wherein a hydrocarbon fuel such as natural gas, oil or coal undergoes splitting (producing hydrogen and carbon dioxide). The second employs an **electricity-based** system, utilising electrical energy to chemically separate water, known as electrolysis. Other processes such as Biological, thermochemical and photolytic processes can produce hydrogen, though currently these are limited in scale.

Fossil-Fuel Based Thermal Systems:

Steam Methane Reformation & Coal Gasification

Hydrogen demand today is near exclusively met (99.9% of supply) via production with fossil fuels. Hydrogen is abundant and produced at low cost (~$1-1.5/kg H_2) when utilising fossil fuel production methods such as coal gasification, partial oxidation and steam methane reforming (SMR).

SMR involves reacting a light hydrocarbon, generally methane (CH) with steam (H_2O) at high temperatures and pressures, producing hydrogen (H_2) and carbon monoxide (CO). SMR is an established technology that is preferred for its efficiency, and reliance on easily accessible natural gas feedstock. It is cost-effective, but carbon dioxide is a byproduct.

Coal gasification is an alternative method, leveraging coal as a feedstock for hydrogen production. Coal is converted into synthesis gas (syngas) through high-temperature reactions with oxygen and steam. Syngas contains hydrogen, carbon monoxide, and other gases, which can then be separated into different product streams.

Typically, SMR will be utilised in conjunction with petrochemical process due to the colocation of supply making it cost effective for large scale hydrogen production. Coal gasification provides an option when producing hydrogen for chemical feedstocks when coal resources are abundant. It offers diversity in feedstock, but it can be less preferred in some regions due to higher CO_2 emissions. Coal gasification is widely employed in China, with SMR taking preference in the US and EU.

On some estimates, fossil fuel based production of hydrogen is responsible for up to 3.5% of global CO2 emissions. Considering the global drive for decarbonisation, regions will look to phase out high carbon intensity production. Instead favouring, low carbon fuel-based production and eventually renewable electricity-based production.

Low Carbon Fuel Based Production

Low carbon and potentially carbon neutral fuel-based production methods are emerging. Three technologies currently present as potential viable hydrogen production pathways, namely, SMR followed by carbon capture and storage (CCS), methane pyrolysis and biomass gasification. CCS is a relatively mature technology and is positioned as the preferred pathway to decarbonise fossil fuel based hydrogen production. Whereas methane pyrolysis and biomass gasification are at earlier stages of development, with some challenges to overcome.

CCS is an additive technology to SMR or coal gasification. Carbon dioxide is captured and stored or utilised in other industrial process'. This reduces the release of CO_2 into the atmosphere by about 75%, lowering the CO_2 intensity of the process. This approach proves attractive as it leverages existing fossil fuel infrastructure and boasts lower costs compared to renewable energy-derived hydrogen (at current prices). Nevertheless, a significant drawback is its continued reliance on natural gas as well as its non-zero CO_2 footprint, leading many nations to view it as a transitional method toward the ultimate goal of green hydrogen production.

Methane pyrolysis refers to a process in which methane (CH_4), the primary component of natural gas, is broken down into its constituent elements, primarily hydrogen (H_2) and solid carbon. Methane pyrolysis is considered a low-carbon process. The solid carbon produced in the process can be captured and stored, preventing it from being released into the atmosphere as carbon dioxide (CO_2), reducing the overall carbon footprint. Additionally, the hard carbon produced holds market value and finds applications in products such as car tires, black inks, and graphite.

The process is not yet economically competitive with SMR or electrolysis. Scaling of the technology combined with supportive policy could see this method gain traction in the future.

Biomass gasification. Biomass refers to organic materials derived from plants or animals, and biomass gasification involves converting these materials into a gas mixture known as syngas (synthesis gas), which contains hydrogen (H_2), carbon monoxide (CO), carbon dioxide (CO_2), and other gases. Syngas produced from biomass can then be processed to extract hydrogen. Biomass gasification is considered a potentially carbon-neutral process because the carbon released during gasification is initially sequestered by the plants during their growth. However, the overall carbon balance depends on factors such as the sustainability of biomass sourcing, transportation, and the efficiency of the conversion process.

Electrolysis – Electricity based system:

Renewable hydrogen is the fundamental value add in the global challenge of decarbonisation. The primary pathway to renewable, 'green', hydrogen production is through a process called electrolysis. Electrolysis utilises a piece of equipment called an electrolyser to produce hydrogen.

An electrolyser is a device that splits water molecules (H_2O) into its constituent oxygen and hydrogen elements by breaking the bonds. There are various competing electrolyser technologies that have each have strengths and weaknesses, however the underlying concept remains the same; electrical energy is utilised to split water and produce a useable hydrogen product and dependent on where the electricity is sourced will impact the classification of the hydrogen produced. We elaborate on the different electrolyser technologies later in this report.

Today, electrolytic hydrogen costs around twice as much to produce as fossil fuel-based hydrogen. However, the technology is in its commercial infancy representing only 0.1% of global supply. The technology is set so scale and it is estimated that by 2030 some projects will be able to produce hydrogen at a comparable price point to SMR and coal gasification.

Native Hydrogen Deposits

There are also a number of ways in which hydrogen can form naturally. The main process involves the interaction of ground water with iron-rich minerals such as olivine. This causes the water to be naturally split into oxygen, which binds with the iron, and hydrogen. Whilst chemically possible, hydrogen was not known to concentrate in enough magnitude to be economically exploitable.

However, this was disproven by chance. In 1987 a bore hole in Mali was drilled for water, but instead of water emerging an odourless flammable gas was released. The bore was capped and forgotten about until 2012, when prospectors drilling for natural gas re-intercepted and confirmed an abundance of hydrogen beneath West Africa. The hydrogen now powers the village of Bourakébougou in western Mali. Confirmation of the existence of economic concentrations has kickstarted a wave of exploitation for the element. Native hydrogen appears to be a highly optimistic production method, but it must be stressed that exploration and extraction studies are at a very early stage.

The Hydrogen Rainbow

As discussed, hydrogen as a fuel comes from a number of possible sources with varying levels of green credibility and challenges. In order to quickly distinguish between different sources of hydrogen, the varieties have allocated colours. This is the “hydrogen rainbow” and is commonly referred to in industry to describe the hydrogen produced.

Green hydrogen: Green hydrogen is produced through the electrolysis of water using renewable energy for a minimal CO_2 footprint as well as being low in impurities.

Yellow hydrogen: Produced by the electrolysis of water using mixed-origin grid energy, or renewables when available and grid when not, to maximise capacity utilisation. Medium CO_2 footprint but also low in impurities.

Pink hydrogen: Produced through the electrolysis of water using nuclear power for a minimal CO_2 footprint and low impurities.

Turquoise hydrogen: Produced from the pyrolysis of natural gas or methane, produces solid carbon as a by-product. Minimal CO_2 footprint and low in impurities.

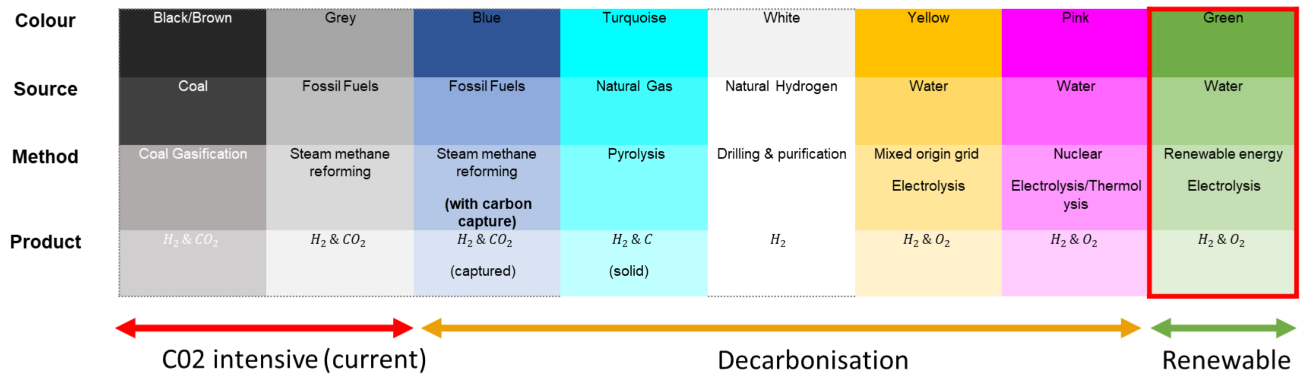
Blue hydrogen: Produced by steam reformation of natural gas or coal with CO_2 capture and sequestration. Low to medium CO_2 footprint with entrained impurities.

Grey hydrogen: Produced by steam reformation of natural gas without CO_2 abatement. Medium to high CO_2 footprint with entrained impurities.

Brown and black hydrogen: Produced by the gasification of brown or black coal without CO_2 abatement. High CO_2 footprint with entrained impurities

White hydrogen: Refers to naturally occurring hydrogen.

Figure 9. The hydrogen rainbow contextualises the shift in carbon intensity via various hydrogen production methods.



Source: WPIC Research

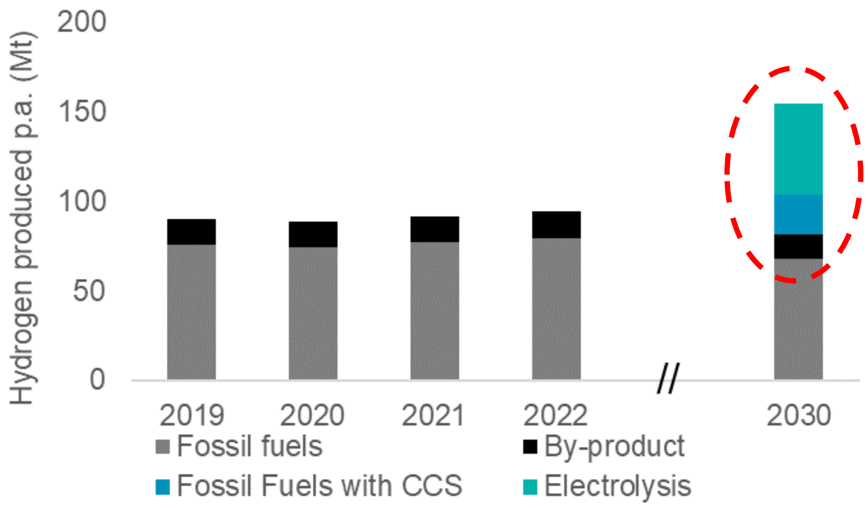
Hydrogen supply side trends and technological winners

Having identified how hydrogen can be produced, which technology pathway for production will prevail? The existing 95 Mt hydrogen market is almost exclusively supplied via fossil fuel-based production. However, the market is poised for change. Over the next decade there will be an emergence of new energy transition applications in transport, power and industry that will require dedicated hydrogen offtake. Whilst hydrogen is abundant and supply elastic, new offtake will most likely be mandated to be low emission hydrogen. As such its viability and the ultimate supply trajectory is governed by the cost of production via low carbon technologies.

The IEA forecasts global hydrogen supply to increase by 50% by 2030 (fig 10). Electrolysis and carbon capture technologies will become the primary methods of production, overtaking unabated fossil fuel-based production after 2030. This forecast will be underpinned by rising demand, but will require key enablers to scale the industry in its infancy:

- **Policies, incentives, and regulatory frameworks** set by governments can have a substantial impact on hydrogen production. Subsidies, grants, and supportive regulations can encourage increased production.
- **Subsidies/carbon pricing:** The implementation of carbon pricing mechanisms and a growing focus on reducing carbon emissions can drive the adoption of low-carbon and zero-carbon hydrogen production methods. Carbon pricing is applied to emission emitting technologies, making them and their products more expensive and less competitive. On the other hand, Subsidies are applied to green technologies to help reduce early development costs and make their products more commercially attractive. Combined they act as mechanisms to promote energy transition technologies.
- **International collaboration:** Collaboration between countries and international organisations can facilitate the global trade of hydrogen, impacting its supply. Agreements for cross-border transportation and trade infrastructure are essential.
- **Technology development:** The upfront investment for electrolysers and Carbon Capture and Storage (CCS) plays a pivotal role in the current high cost of low-carbon hydrogen. As economies of scale come into play and technology matures, there is potential for improvement in Capex, contributing to an increase in suppliers willing to enter the market.
- **Renewable Power Availability:** The largest cost component of green hydrogen is the electricity cost and utilisation limitations of renewable energy. Key to lowering the cost of hydrogen and increasing supply is pairing electrolysers with renewable energy instillations in cost advantaged regions.

Figure 10. According to the IEA, electrolysis is set to underpin a 50% increase in hydrogen supply by 2030.



Source: IEA, WPIC Research

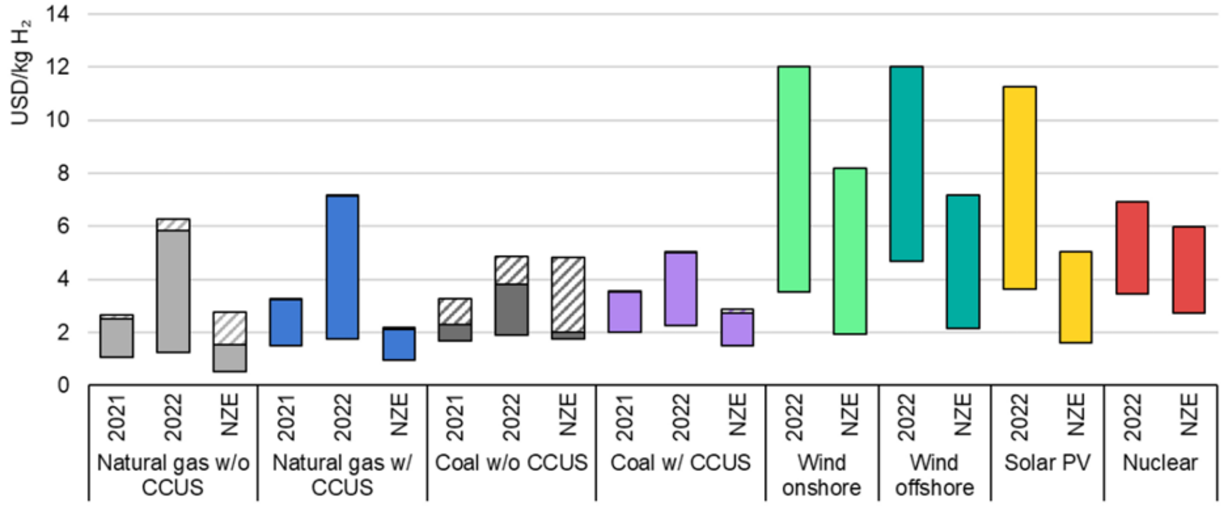
CCS VS ELECTROLYSIS

Fossil fuel production with carbon capture technologies and electrolysis are the two primary future pathways for producing low carbon hydrogen. According to the International Energy Agency (IEA) by 2030, approximately 70% of new hydrogen supply is expected to come from electrolysis, with the remaining 30% from Carbon Capture and Storage (CCS). CCS is viewed as a transitionary technology, capturing CO_2 but relying on fossil fuel extraction for production. In light of COP 28 agreements to phase out fossil fuel use, there is an anticipated decline in CCS applications post-2030. Early indications of this shift are evident in the EU Hydrogen Second Delegate Act (2023) mandating 42% renewable hydrogen by 2030, increasing to 60% by 2035. There is a long-term goal to eliminate the combustion of non-sustainable fuels, even with carbon capture. One expected pathway is for a tightening of the definition criteria of what constitutes low-carbon hydrogen based on greenhouse gas intensity over time.

Currently CCS offers the advantage of being lower cost, negating the use of expensive electrolyser and renewable energy costs. Additionally, it makes use of existing coal and gas infrastructure, providing simpler supply chains. Regionally it is favoured in areas with traditional oil and gas industries, with strong uptake of the technology in the US, UK and Netherlands (fig 11). Furthermore, CCS benefits from subsidies as a low carbon method of hydrogen production in both the US and EU.

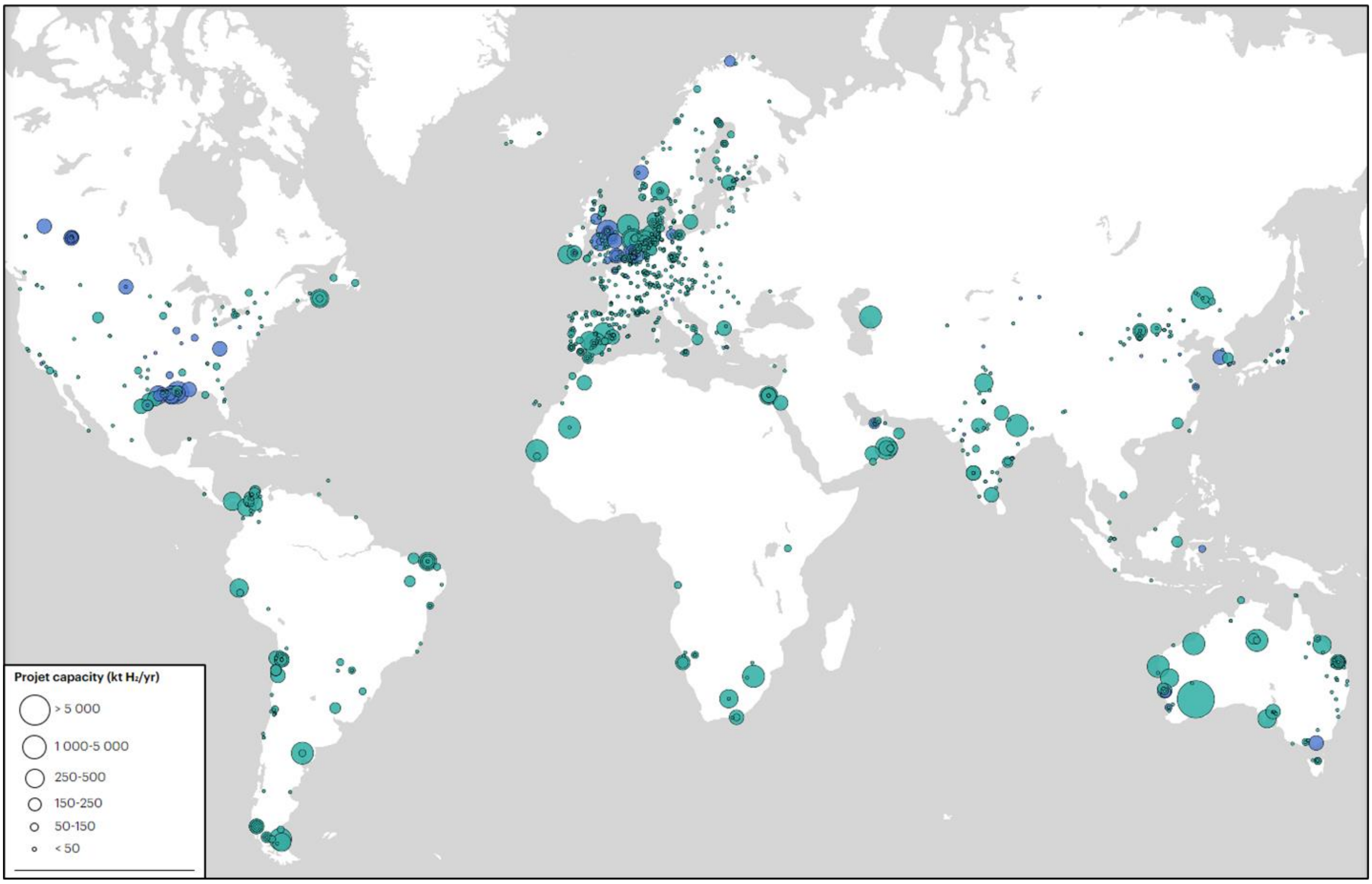
Nevertheless, it's widely acknowledged that the costs of electrolysers are anticipated to decrease with increasing economies of scale. When strategically located in regions with cost-advantageous renewables, electrolysers have the potential to reach cost parity with CCS (fig 10). In essence, blue hydrogen is viewed as a transition technology that facilitates industry growth. This is particularly pertinent when the costs of renewable hydrogen remain high, serving as an effective means to decarbonise fundamental hydrogen applications.

Figure 11. Cost of hydrogen by production method in 2021, 2022 and forecast 2030 (EIA Net Zero Emissions by 2050 scenario).



Source: IEA

Figure 12. Map of planned Electrolyser (Green) and CCS (Blue) projects to be commissioned by 2030.



Source: IEA

Types of electrolysers and the impact for platinum

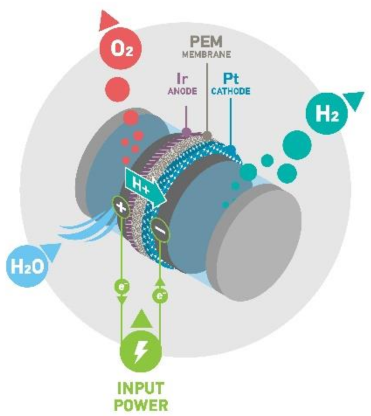
Electrolysers represent the major share of new hydrogen production by 2030. At present, alkaline electrolysers (AEL) and platinum containing proton exchange membrane (PEM) electrolysers are relatively mature and have been commercialised. However, anion exchange membrane (AEM) electrolysers and solid oxide electrolysers (SOEC) electrolysers, which have great development potential, are still less commercially mature.

Below we outline the major electrolyser technology choices as a guide before discussing deployment scenarios and future trends:

Proton Exchange Membrane (PEM): technology splits water into hydrogen and oxygen using a gas-tight solid polymer-based membrane as an electrolyte. Although less mature than alkaline technology and with higher capital costs, PEM electrolysers are much better at cycling in reaction to variable power supplies, which makes them better suited to pairing with intermittent renewables. As manufacturing scales up, PEM costs are expected to significantly decrease.

PEM electrolysis employs platinum and iridium as coated catalysts, offering similar efficiencies to alkaline electrolysers but with a much smaller footprint - up to 5 times smaller. This compact design is advantageous for offshore wind farms or urban spaces. PEM electrolysers produce 99.99% pure hydrogen, directly usable in fuel cell applications, eliminating the need for additional purification steps. Furthermore, in contrast to other electrolysis technologies, PEM electrolysers typically operate at higher pressures, up to 200 bar. This lowers the balance of plant costs compared to other technologies as subsequent compression needs are reduced. While platinum and iridium are the primary catalysts used in PEM electrolysis, ruthenium is being introduced to reduce the amount of iridium that is needed for a given power output. In general, it is fair to assume that the catalyst requirements will decline with technological improvements in time – this is termed ‘thrifting’.

Figure 13. Schematic of PEM electrolyser which utilises Pt. and Ir. to produce H_2.



Source: WPIC Research

Alkaline electrolysers (AEL) are the oldest electrolyser type, using an alkaline electrolyte with metal electrodes to split water into hydrogen and oxygen. In contrast to the highly corrosive acidic conditions in PEM electrolysers, alkaline conditions in AEL electrolysers allow for electrodes to be made of non-noble and therefore less expensive metals. This contributes to lower capital expenditure compared to PEM. The oxygen-producing anode is typically nickel-coated stainless steel, while the hydrogen-producing cathode is an activated nickel alloy, commonly nickel sulphide, nickel-molybdenum, or nickel-tin blends. Additionally, a key difference is AEL utilises a porous membrane to sperate hydrogen and oxygen. This separator provides for cheaper construction but can lead to performance issues when coupled with renewable energy sources, as some gasses can pass through the barrier.

Despite platinum being a superior catalyst for the hydrogen evolution reaction in an alkaline electrolyser due to its lower overpotential, nickel alloys are often chosen for a cost-performance trade-off. One drawback is nickel alloys are more prone to increased degradation when the electrolyser is exposed to start-stop operation. This leads to decreased hydrogen conversion efficiency over time. Some manufacturers have begun to incorporate **platinum catalysts in high-performance alkaline electrolysers** to enhance performance, including allowing for higher current densities, and lifespan.

Anionic exchange membrane (AEM): is a newer alkaline technology that behaves similarly to PEM. The system is designed to utilise a non-porous membrane and operate at a higher pressure, like PEM. The purpose is to remove cross-over losses that result in shutdowns and increased maintenance. As with PEM, AEM does not utilise an electrolyte, removing environmental material handling concerns surrounding corrosive leakage. This design change also reduces size and weight.

The electrodes are manufactured from low-cost transition metals (Fe, NI, Co) offering cost advantages against PEM, although, some manufactures are including small amounts of platinum to boost performance. The technology still has technical challenges to overcome before realising commercialisation. Firstly, anion conductivity is significantly lower than cation conductivity utilised in PEM which impacts hydrogen and oxygen production rates. Secondly, there is lower durability of the membrane impacting stack life. These issues will likely be improved over time and commercial units are available and being scaled.

Solid Oxide: Solid oxide emerges as a promising and nascent electrolyser technology. Operating at high temperatures between 500 and 850 degrees, heat is used to split water, achieving an efficiency of around 90%. Comparatively AEL and PEM currently achieve 60% to 80%.

Despite its potential, the solid oxide electrolyser currently boasts the highest capital cost among available technologies and incurs substantial maintenance expenses due to harsh operating conditions that degrade internal components. The feasibility of high-temperature electrolysis becomes challenging if electric sources are used for heating. However, when integrated with industrial processes providing waste heat, the required additional input energy significantly decreases, offering one of the lowest electrical input costs per kilogram of H_2 produced, comparable to fossil fuel-based grey hydrogen.

A particularly promising application involves coupling Solid Oxide Electrolysis Cells (SOEC) with nuclear power to produce pink hydrogen. This innovative pairing of low-cost, low-emission nuclear electricity with waste heat has the potential to generate hydrogen at a discount compared to green hydrogen. Furthermore, SOEC integration proves advantageous in industries like steel or ammonia production, where waste heat is readily available.

Figure 14. Technical summary of electrolysis technology.

	Alkaline	PEM	SOE	AEM
Electrolyte	Aqueous potassium hydroxide	PFSA membranes (e.g. Nafion)	Yttria Stabilised Zirconia (YSZ)	Anion exchange ionomer
Cathode	Nickel, Nickel – Molybdenum alloy	Platinum, Platinum – Palladium alloy	Nickel/YSZ	Nickel and Nickel alloys, Platinum
Anode	Nickel, Nickel – Cobalt alloys	Iridium oxide, Ruthenium oxide	YSZ	Nickel, Ferrous Cobalt oxides.
Operating Temperature	60 - 80	50-80	500-850	50-60
Operating Pressure	30	70	1-25	1-30
Stack Lifetime (h)	60-80k	60-80k	<10k	
Technology Readiness	Matured	Commercialised	Demonstration	Large prototype
Capital Cost	USD 500-1400/KW	USD 1000-1800/KW	USD 2800-5600/KW	

Source: Centre for Energy Finance, WPIC Research

Electrolysis deep dive: Alkaline vs PEM

Installed global electrolyser capacity surpassed 1GW in 2023 and based on announced projects could reach over 250 GW by 2030. Europe and China currently lead development. However, the impact of the Inflation Reduction Act (IRA) in the United States is likely to change this picture, commanding a larger share of total installed capacity than can be seen in the announced projects today. It should be noted that the Inflation Reduction Act faces political opposition in the US, and it may be at risk of being revoked if Donald Trump wins the 2024 election.

The realisation of announced projects is still highly uncertain, as less than 20% of the capacity of all announced projects with pre-2030 delivery targets have reached a final investment decision (FID), let alone commenced construction. Although this is not uncommon with many projects up to 6 years away from name plate commissioning. Promisingly, 50% have completed a feasibility study, highlighting a commitment capital to planning and announced projects increased 74% on 2022. Whilst not all projects will be constructed, momentum is building. As regional policy matures, announcements and FIDs will increase.

Alkaline and PEM are the commercially available electrolysers globally, representing close to 95% of disclosed capacity to 2030. Understanding the technology split is important as although platinum catalysts are beginning to be used in alkaline electrolysers the scale of their use is not yet known and most current assumptions are that it is only or primarily PEM that directly contributes to platinum demand. Before explaining our view on the technology outlook, it is worth providing a high-level overview of the drivers into electrolyser choice.

Drivers of Electrolysis Choice

Producers strategically choose electrolyser technologies that maximises return on investment. The determination of the lowest hydrogen cost involves aggregation of operational expenses, primarily renewable electricity, and the annual capital repayment over the hydrogen yield. Given equal energy costs for a project location, three variables exist in minimising hydrogen production costs: Capex, opex, and utilisation, with each technology offering different benefits and drawbacks which will be examined in the following segment. Typically, PEM has a higher capex than AEL (fig 15), but technical considerations during operation such as lower maintenance and higher utilisation can balance against this in lowering opex and unit costs.

Capital Cost Drivers

As new technologies emerge, initial costs tend to run high. However, there are three key avenues to drive down capital expenses: economies of scale, economies of numbers, and innovation.

Economies of scale: Scaling up operations yields significant cost benefits. As a plant or project size scales large, fixed costs can be spread over a larger output and savings can be made from bulk purchasing power, and synergies in construction and engineering. In the chemical industry for example, a plant ten times larger may only have a five times higher capital cost. As electrolyser projects become bigger the capital cost per unit of capacity is expected to decrease.

Economies of numbers: "Economies of numbers" refer to the phenomenon where producing more units of the same product results in cost reduction due to automated manufacturing and supply chain optimisation.

Innovation: Meanwhile, innovation serves as the third driver of cost reduction. It encompasses enhancements in manufacturing design, leveraging economies of number and scale, as well as advancements in underlying technology to enhance performance and lower hydrogen production costs.

By integrating these concepts, ongoing research and development refines technology, industry expansion boosts scale, and construction of large-scale projects drives down costs. This iterative process is commonly referred to as the learning curve.

Bringing the discussion back to technology selection, alkaline electrolysis is a more mature technology, positioned further along the learning curve compared to PEM (Proton Exchange Membrane) systems. This maturity translates into a greater degree of embedded innovation and the ability to undertake larger projects. Typically, a single alkaline stack can now be scaled to 10MW versus 5MW for PEM, and, on average, constructing an alkaline system cost approximately half as much as a PEM system (figure 15).

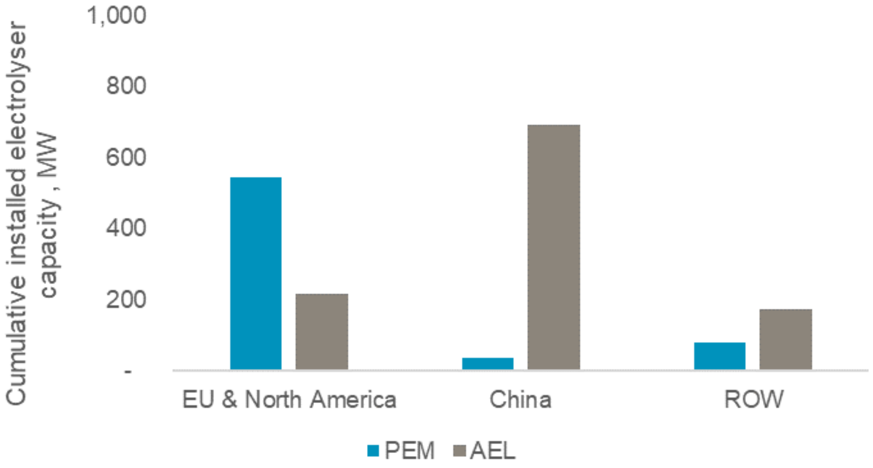
This cost disparity is even more pronounced regionally. In China, where alkaline manufacturing has seen significant advancements, electrolysers can be procured at a remarkable 60% discount compared to the global average (although, anecdotally, there may be a penalty in terms of operating stability, output and opex). Conversely, PEM systems incur roughly triple the cost within China (fig 15). This stark contrast underpins the early dominance of AEL electrolysis globally, which boasted an estimated 65% market share of installed global capacity by the close of 2023 compared to PEM systems.

Figure 15. Technical summary of electrolysis technology.

	2022 uninstalled capital cost ($/ Kw)		
	Global Avg.	China Avg.	**Delta**
PEM	1,000	630	**-0.4x**
AEL	500	210	**-0.6x**
Delta	**2.0x**	**3.0x**	

Source: U.S. Department of Energy, CEDC, WPIC Research

Figure 16. AEL is dominant technology in China & ROW, leading to a 65% market share (2023). PEM is more popular in the EU & North America.



Source: IEA, WPIC Research

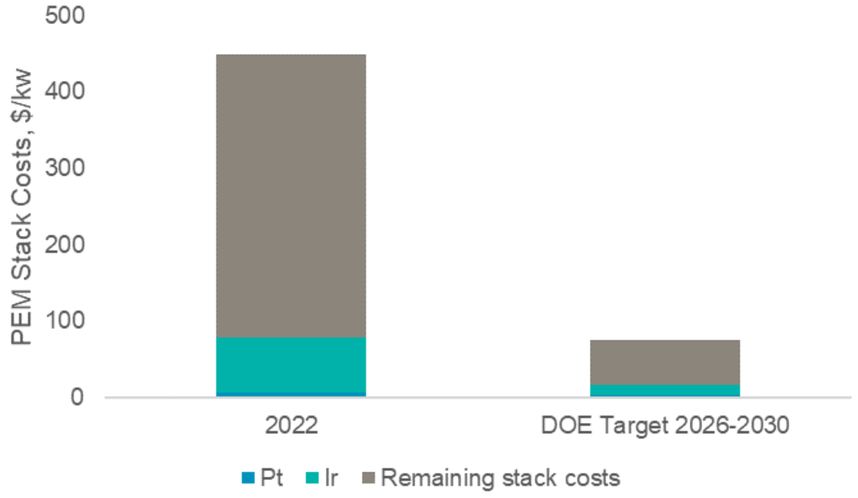
While PEM is less developed with less embedded innovation than AEL, this also means that there is more scope for future innovation that will reduce costs. A learning curve starts with a steep gradient with large savings accrued in a short time, before shallowing out as gains become incrementally harder to achieve. Solar instillations in their infancy were extremely expensive, however, over a decade their cost reduced by 90%. Whilst savings of this magnitude may not be achievable for PEM, solar innovation does provide a parallel. Alkaline technology has been around for 100 years and is further along the curve so whilst cost savings will likely occur, it is expected that PEM costs will fall much more quickly. Many technical commentators suggest that PEM cost parity with AEL is possible by 2030, outside of China.

Low hanging fruit will drive cost reductions for PEM, specifically manufacturing automation in combination with the developmental improvement of catalysts, which will likely include thrifting of precious metals. One engineering consultancy (Wood Group) disclosed at a recent hydrogen conference that

PEM stacks are currently manufactured with a high degree of manual labour. Two full time personnel and two days are required to assemble a stack. However, an automated production line can build the product in 2.5 hours, offering evident advantages.

Precious metals (platinum and iridium), currently constitute approximately 15% of the material costs of PEM electrolyser stack designs. Thrifting is likely to occur as catalyst support design matures, prolonging catalyst life and efficiencies, whilst minimising metal content. An 80% thrift is expected in iridium by 2030, which has recently been trading at an elevated premium (~4x) to platinum and constitutes much of the precious metal content costs. Platinum loadings will also decrease albeit likely at a lesser pace. Having already experience high levels of thrifting given their maturity, it is expected that catalyst R&D focus will be on high-cost iridium. The key takeaway is to understand that iridium, not platinum, is the primary expense associated with precious metal catalysts utilised in PEM.

Figure 17. Iridium thrifting to help bring down capital costs. There is currently lower motivation to aggressively thrift platinum due to its price discount.



Source: Heraeus, DOE, Johnsen Mathey, WPIC Research

Finally, innovation will play a pivotal role in enhancing electrolyser performance. As shown in figure 18, the US Department of Energy forecasts that by 2030, advancements in PEM (Proton Exchange Membrane) technology will enable it to match the cost and lifespan of alkaline technology. Crucially, PEM systems are poised to achieve cost parity while delivering superior performance.

PEM electrolysers are targeted to achieve higher efficiencies and greater current densities compared to alkaline systems. This translates to a PEM electrolyser being able to produce a larger volume of hydrogen using less electricity and occupying a smaller footprint. These advantages are particularly beneficial in offshore and urban environments, where space constraints are prevalent, and efficiency is paramount.

Figure 18. PEM and Alkaline performance targets by 2030 in the US where the Department of Energy is targeting cost and performance parity with alkaline by 2030

		Alkaline		PEM	
Characteristic	**Units**	***2022***	***2030***	***2022***	***2030***
Performance	*A/cm^2*	*0.5*	*2*	*2*	*3*
Efficiency	*kwh/kg H_2*	*51*	*45*	*51*	*43*
Lifetime	*Operation h*	*60,000*	*80,000*	*40,000*	*80,000*
Capital Cost (Stack)	*$/kw*	*250*	*50*	*450*	*50*
System Cost	*$/kw*	*500*	*150*	*1,000*	*150*

Source: DOE, WPIC Research

Operational cost drivers & renewable energy compatibility

Next, we consider both technologies compatibility with renewable energy sources. Both PEM and AEL are currently deployed in producing green hydrogen. Yet notably, their performance in terms of hydrogen production and operating costs can vary massively dependent on the renewable energy source. Alkaline electrolysers are designed to operate at a consistent power, whereas PEM can tolerate a higher level of flexibility. These differences are engrained into the system design.

With renewable power intermittency, such as when the wind isn't blowing or clouds obstruct the sun, the available power to directly coupled electrolysers diminishes, termed as operating under partial load. Alkaline electrolysers utilise a porous membrane that limits but doesn't entirely prevent the mixing of hydrogen and oxygen streams. Operating at partial load increases this mixing, raising the risk of combustion or explosion when gas concentrations surpass 4% (e.g., 96% oxygen and 4% hydrogen). To mitigate this risk, the electrolyser system initiates a shutdown at a safety factor below 4%. This typically translates to when the power drops below 25-30% of its rated capacity, halting hydrogen production. This initiates two future challenges:

- **Extended Restart Time**: Restarting an alkaline electrolyser takes longer compared to PEM, prolonging shutdowns beyond the time needed to restore the power source to 25% of nominal power (approximately +30 minutes compared to PEM).
- **Electrode Aging**: Frequent alkaline electrolyser shutdowns/start-ups accelerate electrode aging, diminishing equipment lifespan, and increasing maintenance and capital costs. For instance, the nickel electrodes used in alkaline electrolysers show significant degradation after 5,000 to 10,000 start/stop cycles.

The combination of these factors effectively reduces the amount of hydrogen produced by alkaline electrolysers within a given timeframe compared to PEM when utilising renewable energy sources. This, in turn, amplifies the total cost per kg of H_2 produced.

This issue can be mitigated by incorporating solutions like absorbing power fluctuations through an intermediary energy storage device such as a battery or implementing advanced electrolyser stack system management. However, both approaches come with added costs and limitations. Another strategy involves balancing the renewable electricity supply by linking electrolysers to the grid to maintain a steady load, but this can impact the hydrogen product definition (e.g. renewable/green or fossil/grey) based on the grid electricity source, and potentially impact qualification for subsidies. While popular in regions like China, this method may not find widespread application in the West due to stringent policies.

On the other hand, compatibility with renewable energy sources is a standout feature of Proton Exchange Membrane (PEM) technology. It can be directly coupled with renewables as it can operated down to a lower partial range from 0% to 10%. What this means is the system can handle load drops to 10% before shutting down - or not at all, depending on system design. PEM systems respond faster to load increases and restarts compared to other electrolysis systems. While PEM may have higher upfront costs, it balances this with system advantages and potential operational cost reductions.

Policy Drivers

Outside China, operators prefer PEM for its flexibility and responsiveness with fluctuating power sources such as solar and wind. As US & EU policy matures it appears that electrolysers will have to be directly or virtually – through a Power Purchase Agreement (PPA) – coupled to a renewable energy project. The EU Renewable Energy Directive set out strict additionality and temporal correlation rules regarding utilising electrolysis to generate renewable hydrogen in 2023 – and similar legislation is being drafted in the US (45V tax credit regulations). These rules must be met to classify they hydrogen product as renewable or green. In turn, this impacts the taxes, subsidies and potentially the available end market and price of the hydrogen produced:

Additionality: *Use of existing grid mix; or the requirement to build 'additional' renewable energy. In the EU by 2027 electricity must be sourced from a renewable energy project constructed no less than 3-years earlier than the electrolyser*.

Temporal Correlation: *electricity utilised for hydrogen production must be supplied within the same 1-hour period as the renewable energy instillation under a PPA.*

What this means is that from 2027 in the EU the electricity used to power electrolysers has to be powered in two ways. First by a dedicated and direct coupled renewable source. Or second, by a new renewable source connected via a grid connected PPA. When utilising the second option the power from the grid must only be utilised whilst the renewable source is running, in effect this is a direct coupled electrolyser. As a result, even grid connected electrolysers will experience fluctuations and partial load.

Temporal correlation suits flexible electrolysers that can quickly respond to power generation from the underlying renewable asset, favouring platinum containing PEM electrolysis. Responsive electrolysers enable higher utilisation by closely tracking fluctuations in feed-in power compared to AEL, whilst also potentially reducing downtime for maintenance in such operational scenarios. Moreover, rapid startup times facilitate options to increase operational hours from other power sources. This can be done through the utilisation of curtailed grid electricity or enable the provision of frequency containment reserve services to grid operators. Under a control reserve agreement, grid operators compensate electrolyser operators for operating and drawing power during periods of surplus electricity and low demand to stabilise the grid. Enhanced utilisation, in conjunction with such agreements, contributes to the increase in project NPV, potentially offsetting the initial capex advantage of AEL. Additionally, subsidies of up to €4.5 per kg of hydrogen produced are anticipated through the Hydrogen Bank in 2024, further amplifying the advantages of increased utilisation and hydrogen production.

Non-PEM electrolysers outside of China will largely be made up of regions and projects where **alkaline electrolysers can be operated consistently**. Countries or regions with a highly renewable grid or low carbon nuclear zone can power electrolysers directly from the grid to produce low carbon hydrogen. Additionally, some renewable energy sources such as hydropower and geothermal heat sources or a mixture of complimentary renewables can be suitable for alkaline technology as they supply power more consistently. When consistent power is supplied and there are no space constraints, alkaline technology is currently the preferred choice for cost effective hydrogen production.

Pulling it all together – the East-West trend.

Regional trends in electrolyser deployment are already evident (fig 19), with alkaline dominating in China and other regions such as Africa, South America, and Australia, while PEM holds a larger market share in Europe and North America. We anticipate this regional preference to persist, with Alkaline maintaining dominance but PEM gaining ground to reach a 38% global market share by 2030 (fig 17).

By 2030, we project that over a third of global electrolyser capacity will be installed in China, where Alkaline technology is expected to maintain a market share of 90-95%, buoyed by capital discounts over PEM. Meanwhile, PEM technology is set to experience growth in North America and Europe, driven by stringent renewable hydrogen policies and its advantageous compact footprint for land use and long-term expansion.

Figure 19. 2023 Regional split of Alkaline and PEM electrolysis.

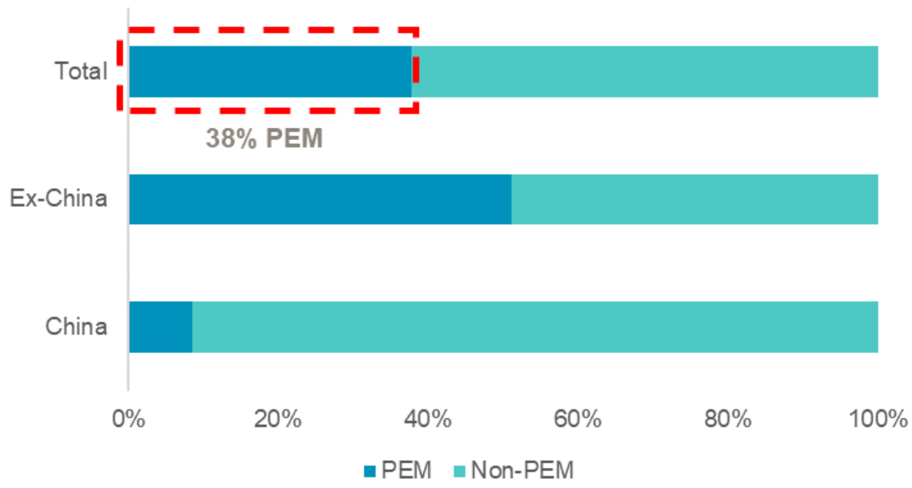
	PEM	ALK
US & EU	70%	30%
China	5%	95%
Rest of the World	30%	70%

Source: IEA, WPIC Research

Whilst picking PEM today incurs higher costs, it could add strategic value. In contemplating power installations with decades-long project lifespans, PEM's operational costs may currently be higher. However, with electrolyser stack replacements every 10-15 years, the next generation is forecasted to deliver enhanced performance, increased utilisation of renewables, and comparable costs in Western regions. Subsequent replacements on the same site footprint could enable the installation of significantly larger capacity projects, yielding higher hydrogen output and scalability of revenue, compared to alkaline technology.

Considering the growing availability of renewable energy projects and the rise in excess off-peak renewable power, investing in PEM technology today offers the opportunity to build experience and unlock long-term strategic value. This strategic outlook positions PEM as a compelling choice for forward-thinking energy projects aiming for sustainable growth and flexibility. That being said the industry is rapidly evolving and technology choice is highly dependent upon innovation and scaling.

Figure 20. Alkaline will maintain a dominant market share due to its low capex. PEM will gain market share in regions where direct coupling to renewables occurs.

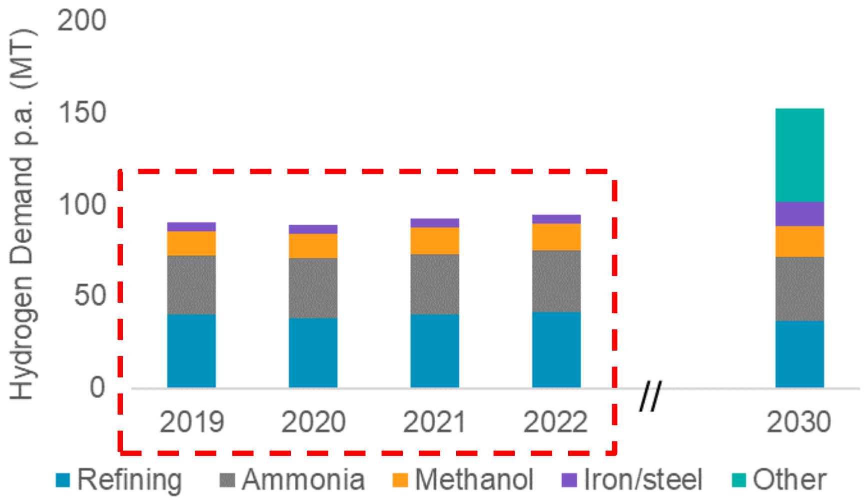


Source: IEA, The orange group, WPIC Research

What is Hydrogen Used For?

Hydrogen demand can be split into traditional and future uses. Traditional hydrogen markets use hydrogen produced and used onsite as a byproduct of fossil fuel operations and utilised onsite to produce petrochemical or agricultural derivatives. Current demand of 95 Mt is predominantly met by grey hydrogen production and is mostly hard to abate uses that actually need hydrogen itself as a feedstock. Traditional hydrogen demand segments (e.g. ammonia and refining) will be flat to 2030, but new demand segments (e.g. FCEVs and DRI steel) will underpin the vast majority of additional demand growth at 37% CAGR (fig 21).

Figure 21. Traditional demand for hydrogen in chemical and petrochemical production has remained flat since 2019.



Source: IEA

Traditional Hydrogen uses

Petroleum Refining:

Hydrogen plays a crucial role in petroleum refining processes by serving as a reactant, catalyst, and carrier of hydrogenation reactions. Its use enables the production of cleaner fuels with improved performance characteristics, meeting regulatory requirements and market demands for high-quality refined products. Some of the main uses of hydrogen in petroleum refining include:

Hydrocracking: Hydrogen acts as a catalyst in hydrocracking reactions, facilitating the conversion of long-chain hydrocarbons into smaller molecules such as gasoline, diesel, and jet fuel.

Hydrotreating: Hydrotreating, also known as hydrodesulfurization (HDS), is a process used to remove sulphur, nitrogen, and other impurities from petroleum fractions.

Catalytic Reforming: Catalytic reforming is a process used to convert low-octane naphtha fractions into high-octane gasoline.

Hydrogenation: Hydrogenation reactions can be used to convert unsaturated compounds such as olefins and diolefins into more stable and valuable products, such as paraffins.

Isomerisation: Hydrogen is used as a reactant in isomerization reactions to facilitate the rearrangement of molecular structures and improve the quality of gasoline.

Chemical Production

Ammonia production is hydrogen's second-largest traditional demand segment. It's a crucial chemical building block, especially vital for agricultural fertilisers. Ammonia is primarily produced through the Haber-Bosch process, which involves the reaction of nitrogen (N_2) and hydrogen (H_2) under high pressure and temperature conditions.

Ammonia also holds a lot of promise to be utilised as an energy carrier or directly as a fuel. Work is underway to test its suitability to transport hydrogen via shipping as well as an energy source for fuel cells and internal combustion engines.

Methanol is an essential chemical in various industries and applications. Methanol is typically produced via reacting carbon monoxide and hydrogen together in the presence of a catalyst (typically copper-zinc oxide).

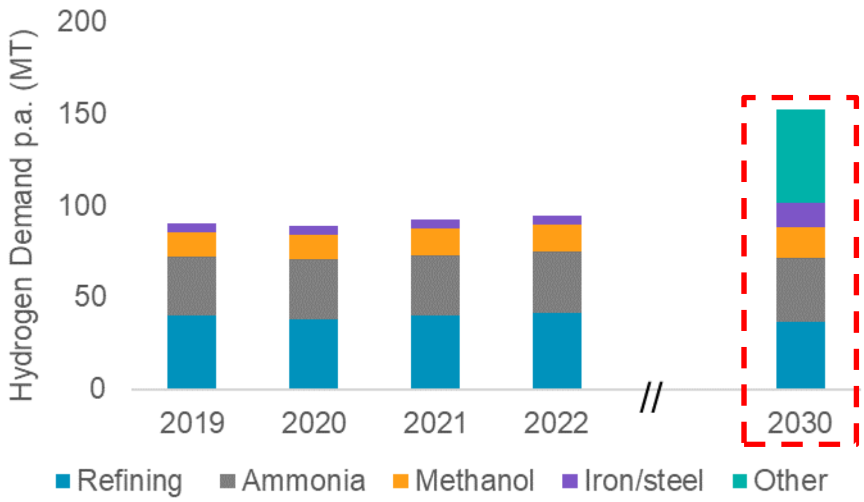
Hydrogen for decarbonisation

Hydrogen's role in decarbonisation is twofold. To displace grey hydrogen with green hydrogen in the traditional industries described above. Second, new demand will be generated with the underlying purpose of decarbonising polluting industries through the application of low carbon hydrogen as an alternative energy source to those already in use.

We address this more fully later on, but as a short aside, decarbonising the 95 Mt of grey hydrogen used in traditional end uses today, would save 430 Mt of CO_2 emissions, or the equivalent of taking 120 million vehicles off the road for a year.

Further, new demand must satisfy two conditions to be viable. First, there is a requirement to reduce the intensity of an applications CO_2 emissions. Second, the solution hydrogen offers must be economically competitive to its current use and any alternatives to offer scale and commercialisation. One methodology that assists in quantitatively assessing novel applications for hydrogen is the 'hydrogen ladder'.

Figure 22. New demand such as FCEVs and e-fuel production will drive an incremental increase in annual hydrogen demand of ~50%.



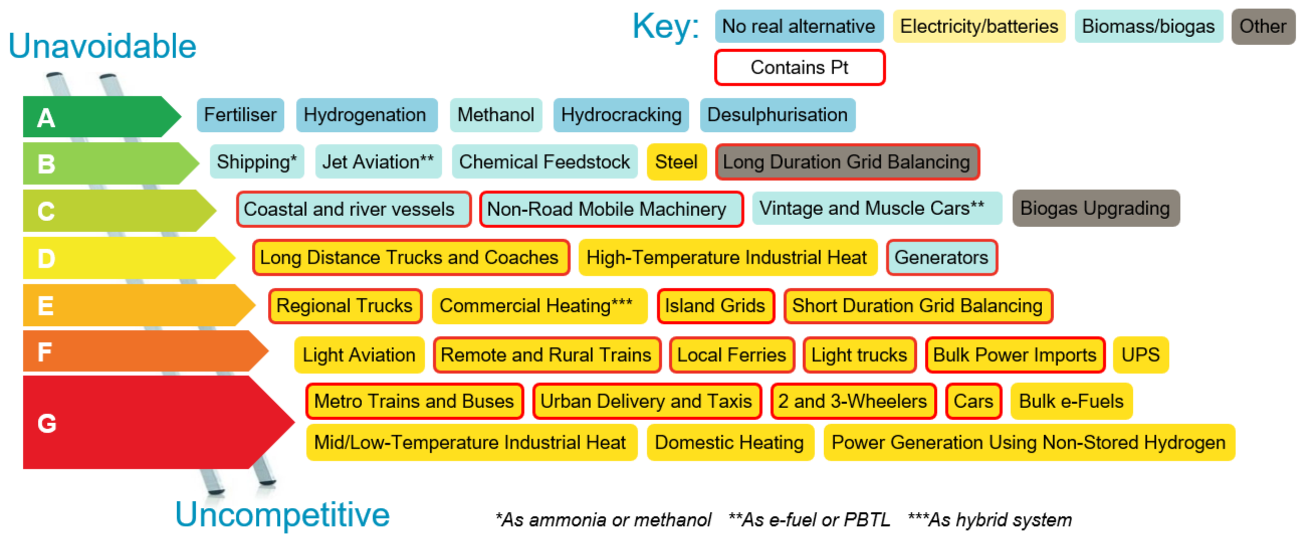
Source: IEA

The Hydrogen Ladder

The hydrogen ladder methodology identifies applications in which hydrogen could be technically employed as part of decarbonisation efforts. The ladder ranks applications based on the likelihood of becoming a significant market user of hydrogen by 2035 considering factors driving technology uptake and alternative decarbonisation technologies.

Applications are ranked from unavoidable at the top to uncompetitive at the bottom. Unavoidable effectively means that either hydrogen has to be used as a process input, or there are no technological alternatives to hydrogen at present. At the uncompetitive end of the scale, hydrogen can be used but is currently outcompeted by alternative technologies. Notably, an unavoidable use of hydrogen does not necessarily mean that demand is increasing, instead it is that hydrogen use is key to that application and must be considered when forecasting hydrogen demand scenarios.

Figure 23. New demand such as FCEVs and e-fuel production will drive an incremental increase in demand of ~50%.



Source: Michael Liebreich/Liebreich Associates

The top row (A) consists of primary functions of hydrogen today that cannot be substituted (e.g. ammonia production). Current demand for hydrogen is produced near exclusively via fossil fuels and is responsible for ~2% of global GHG emissions. These industries will be decarbonised first. Platinum is set to benefit through a mandated shift from grey to green hydrogen, requiring platinum containing electrolysers.

Moving down, the ladder highlights markets which do not use hydrogen currently, but which could adopt hydrogen to decarbonise (B to G). These are new demand sectors. Ranging from "e-fuels" where green hydrogen and captured carbon are combined for aviation to "cars" powered by fuel cells.

Before unpacking these new applications, we will take a moment to consider the impact on these new applications on platinum.

Niche applications generate large platinum demand:

Red bordered boxes in figure 23 directly contribute to platinum through the use of fuel cells and electrolysers. Most platinum containing applications sit in groups C to G representing "some market share" to "niche applications in some geographies". This is important to understand. The hydrogen economy sits alongside other technologies to support a holistic decarbonisation effort, and, as highlighted in figure 23, battery/electric alternatives are available (yellow).

It must be acknowledged that hydrogen technology, due to its lower energy efficiency compared to Battery Electric Vehicle (BEV) technology, will be primarily reserved for high-capacity, high-utilisation cycle applications. In instances where batteries would be excessively large and the recharging times impractical, hydrogen becomes the viable alternative.

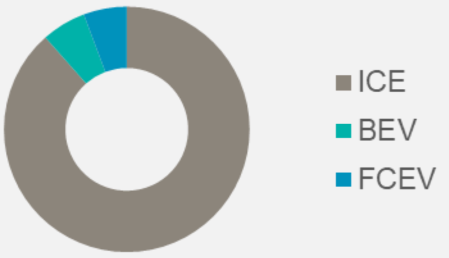
Figure 24. New what areas of hydrogen demand such as FCEVs and e-fuel production will drive an incremental increase in demand of platinum by ~50%.

Application	Use Case	% Market Share 2030	Koz Pt. 2030
FCEV Cars	*Premium SUV/ First mover countries*	*0.3%*	*91*
FCEV Trucks/Vans	*Range extender/ cold storage*	*1%*	*42*
FCEV Heavy Duty	*High utilisation cycles*	*6%*	*372*

Source: OICA, WPIC Research

The comparatively high amount of platinum contained in electrolysers and fuel cells means that only small rates of growth in these segments can have an outsized impact on total platinum demand. For example, our forecast is for light-duty, light-duty commercial, and heavy-duty FCEVs to capture market shares of 0.003%, 1%, and 6%, respectively by 2030. Despite these limited market shares, this translates to a projected FCEV demand for platinum exceeding 500 Koz by 2030, compared to total ICE demand for platinum of ~3,000 koz in 2023. Growth is expected to continue thereafter with medium and heavy-duty fuel cell trucks to hold a market share in the mid-teens by 2040.

Figure 25. Heavy-Duty FCEV market penetration to exceed 6% by 2030.



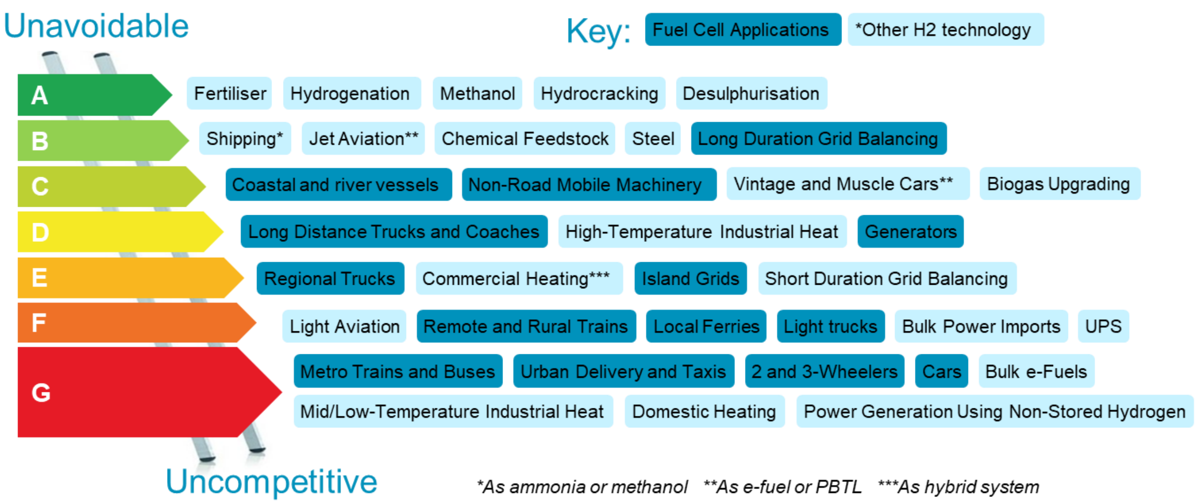
Source: WPIC Research

Hydrogen Fuel Cells

With global CO_2 reduction on the agenda, fuel cells can replace carbon emitting combustion in variety of applications such as replacing diesel generators used for backup power or marine auxiliary power to general mobility and freight applications (highlighted dark blue, fig 26).

Fuel cells are devices that consume hydrogen to produce electricity through an electrochemical reaction by combining hydrogen and oxygen, with heat and water as the only by-products. Fuel cell technology is mature and has been converting hydrogen into electricity and water for over 100 years.

Figure 26. Many technically feasible fuel cell applications exist within the hydrogen ladder (dark blue).



Source: Michael Liebreich/Liebreich Associates

Fuel cells have diverse applications (fig 27), spanning portable, mobile, and stationary categories, each accommodating different power ranges and fuel cell types (shown below). Platinum stands out as a catalyst in mobile fuel cell applications, facilitating optimal reactions between hydrogen and oxygen. Its stability withstands the challenging chemical environment and high electrical current density, ensuring long-term efficiency.

In the realm of mobility, promising sectors include automotive fuel cell vehicles, as well as off-road applications such as rail, marine, and mobile heavy machinery. These sectors present significant development potential, driving forward the adoption of fuel cell technology in hard-to-electrify applications alongside battery technology.

Figure 27. Many types of fuel cells are available. Typically, PEM fuel cells are utilised for mobility applications, and the others are utilised for stationary power generation.

Name	Acronym	Common uses	Industries	Operating Temp °C	Electrical Eff. (%)	Contains platinum?
Proton exchange membrane fuel cell	PEMFC	Portable, mobile	Road transport, Consumer	<120	~55%	**Yes**
Phosphoric Acid Fuel Cells	PAFC	Stationary	Stationary power	120-150	~40%	**Yes**
Alkaline Fuel Cell	AFC	Stationary, mobile	Stationary power	<100	~65%	**Some**
Molten Carbonate Fuel Cell	MCFC	Stationary	Stationary power	600-700	~55%	**No**
Solid Oxide Fuel Cell	SOFC	Stationary	Stationary power	500-100	~60%	**No**

Source: WPIC Research

Automotive FCEV Applications

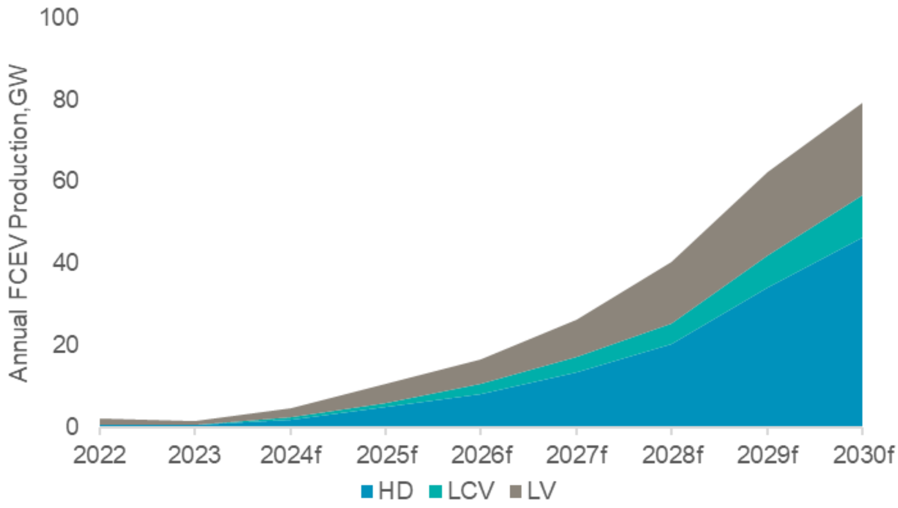
A fuel cell electric vehicle (FCEV) has similarities with both battery electric vehicles (BEV) and mild-hybrid electric vehicles (MHEV). Like a BEV, the motive power is provided by one or more electric motors, with the energy source being a fuel cell, rather than a large heavy battery pack. The fuel cell consists of a 'stack' or Membrane Electrode Assembly (MEA), where each membrane is sandwiched between a cathode and an anode, both dosed with platinum, with the membrane acting as a solid electrolyte. Hydrogen gas is channelled to the anode where it reacts with the platinum catalyst causing each hydrogen atom to separate into an electron and a proton. The electrons flow to the cathode as an electrical current which provides propulsion. Whilst the protons flow across the membrane to combine with oxygen from air channels into the cathode, and the current of electrons to produce pure water as the vehicle's emission.

Aside from the fuel cell, FCEVs typically share ~80% of the components and systems found in a BEV. Like a MHEV, a FCEV also has a supplementary but relatively small battery to store energy from regenerative braking, also making it available to the motor during heavy acceleration, although the prime motive power is from the electric motor rather than an internal combustion engine (ICE). Importantly, FCEVs are 'off-grid' in that they do not need to be plugged in to be charged, a significant advantage in inner city locations where consumers may not have access to off-street parking and home charging points. Further, FCEVs offer faster refuelling times, comparable to ICE (3 to 5 minutes), longer driving ranges, and a significantly lighter total system weight.

To date FCEVS models have been developed for passenger, light-duty commercial, and heavy-duty transportation. The global FCEV car park stood at around 72,000 units by the end of 2022 with 80% being passenger vehicles, 1% being light commercial and 19% being truck and buses. Although FCEV fleets are currently small, they are forecast to expand rapidly, as large multinationals such as Hyundai, Toyota & Bosch commit capital to manufacturing. Our bottom-up analysis outlined in our hydrogen outlook indicates over 2,000,000 FCEV vehicles of all types could be on the road by 2030 based upon manufacturer capacity expansions.

Future demand growth for FCEVs will predominantly emerge from the heavy-duty sector, especially in the near term (fig 28). In the EU, heavy-duty vehicles account for approximately 25% of road transport greenhouse gas (GHG) emissions, which is broadly similar to the world as a whole. The heavy-duty transport industry's needs to change, and its commercial nature enables environmentally minded organisations to make streamlined changes across a concentrated group of participants, unlike the intricate landscape of influencing consumer choices in the passenger segment.

Figure 28. Automotive fuel-cell demand will be driven by heavy-duty applications.



Source: WPIC Research

Commercial vehicle applications typically require high-capacity utilisation rates, long-distance capability, and high load carrying capacities. Considering the distinct characteristics of Fuel Cell Electric Vehicles (FCEVs) and Battery Electric Vehicles (BEVs), the choice of technology for decarbonisation varies by transport application, as outlined below.

Heavy Duty Vehicles (HD): Fuel cell systems in heavy-duty vehicles are significantly lighter than the equivalent battery required for the same power output. According to the Clean Air Task Force, a Class 8-sized US battery electric vehicle (BEV) freight truck could experience a reduction in carrying capacity of between 10% and 20% compared to diesel trucks, whereas a fuel cell electric vehicle (FCEV) would only incur a loss of less than 5%. This mitigates the loss of capacity and payload associated with the large, heavy batteries needed by BEVs for haulage purposes. Additionally, FCEVs can typically travel much longer distances, ranging from 500km to 1,000km, and can be refuelled quickly and off-grid, providing a considerable advantage over BEV counterparts for long-distance haulage in remote locations and minimising downtime required for battery recharging.

Light Commercial fuel cell applications are also emerging. Two primary use cases are emerging. First in refrigerated vehicles where the required battery size would be unsuitably large to meet the power requirements. Secondly, to utilise a small fuel cell in vans and light trucks to act as a range extender to a BEV. The idea is to ensure high utilisation and minimise losses in commercial applications. Further, reports of commercial BEV struggling with towing and range at higher payloads lends support to a fuel cell system. Symbio, a joint venture between Stellantis, Faurecia and Michelin aim to produce 200,000 LCV FCEVs per annum by 2030 utilising this set up.

Passenger: There are currently two commercially available passenger vehicles, the Hyundai Nexo and Toyota Mirai. Battery technology is a substitute for fuel cells in passenger vehicles. BEV market share has quadrupled since 2020 to 12% in 2023 with technology advancements, improved charging availability, government subsidies, and new model rollouts. Despite some consumer pushback, BEVs appear to be entrenched as the incumbent route to decarbonise passenger vehicles, and in the near term we expect FCEV market penetration growth to be modest globally.

Figure 29. BMWiX5 Hydrogen SUV & Hyundai Nexo

Source: BMW, Hyundai

In the longer term, with the development of hydrogen refuelling infrastructure for commercial applications, the emergence of niche passenger Fuel Cell Electric Vehicle segments is conceivable. A glance back to 2016 illustrates how rapidly markets can evolve or diminish. Diesel vehicles in the EU once held a 50% market share of light-duty vehicles. However, by 2023—eight years later—following the Diesel-gate scandal and a downturn in consumer sentiment, this share had decreased to approximately 15%. Conversely, during the same period, the production share of light-duty Battery Electric Vehicles in Europe surged from 1% to around 25%. Our point being, while passenger FCEV figures currently remain low, consumer sentiment can undergo significant shifts. Given the establishment of a hydrogen refuelling network, there could be upside potential for passenger FCEVs. However, this potential is likely to be confined to larger, premium passenger vehicles or in fuel cell pioneering countries with substantial domestic automotive industries:

- **First mover countries**: In regions where key players in fuel cell manufacturing are headquartered, notably South Korea and Japan, a persistent trajectory is anticipated in the adoption of passenger Fuel Cell Electric Vehicles (FCEVs). This is exemplified by the production of models like the Hyundai Nexo and Toyota Mirai in these pioneering nations. The impetus behind this momentum lies in the strategic imperative to showcase the viability of fuel cell technology, as well as government support. Despite these efforts, the prevalence of Battery Electric Vehicles (BEVs), which currently enjoy a cost advantage and benefit from a more extensive recharging infrastructure, will likely relegate the market penetration of light-duty FCEVs to a marginal status.
- **Premium/SUV**: Some premium automakers, such as BMW and Jaguar-Land Rover, have unveiled plans for the development of prototype or production lines catering to large, high-end Sports Utility Vehicles (SUVs). Battery Electric Vehicles (BEVs) exhibit a markedly higher reliance on energy transition metals compared to Fuel Cell Electric Vehicles (FCEVs), the latter aligning more closely with the traditional Internal Combustion Engine (ICE). In light of recent supply chain challenges, including diminished revenues and protracted lead times stemming from the silicon chip shortage, manufacturers are ardently focused on mitigating potential future production risks. A further example is potential disruption to BEV lines associated should a lithium supply deficit materialise. Consequently, there is a discernible shift toward the exploration of integrated production lines, enabling the concurrent availability of both BEV and FCEV model options.

Figure 30. Summary of advantages and disadvantages offered by FCEV's.

Application	Pros	Cons
FCEV	- Expanding model availability - Ideal for heavy loads - High payload capacity - Extended driving range - Shorter refuelling times - Zer emissions	- Highest CAPEX currently - High current cost of hydrogen. - Limited refuelling infrastructure
BEV	- Zero tailpipe emission - Highest energy efficiency - Lower operating costs - Mainstream technology. - Extensive model choice	- Higher CAPEX than ICE - High Depreciation. - Reliance on charging infrastructure availability. - Environmental impact of battery production and disposal
ICE	- Extensive refuelling infrastructure - Familiar technology - Long driving range - Short refuelling times - High power and performance	- Greenhouse gas emissions and air pollution - Higher operating costs compared to electric

Source: WPIC Research

What determines platinum use in fuel cells?

As with ICE, vehicle type is influential for platinum demand in FCEVs. Platinum content in a fuel cell vehicle is related to three underlying factors which impact loadings in LV, LCV and HDV respectively. Generally speaking, HDV can have 4 to 8 times more platinum than a passenger vehicle and LCV will vary depending on its application.

1. **Rated Power**: to produce more electrical potential to power a larger vehicle or mass a fuel cell will generally have a larger MEA surface area to conduct H+ ions. A large MEA will require more platinum to coat it. Therefore a 180 KW fuel cell will utilise more platinum than a 90 KW fuel cell.
2. **Rated Lifespan:** PEM fuel cells are corrosive and acidic environments; over time catalysts degrade resulting in reduced fuel cell performance. More demanding heavy-duty applications, have higher loadings of platinum per KW to compensate for catalyst deterioration, so that it will maintain its rated power for longer and through continual use.
3. **Application and drive train of vehicle:** Whilst essentially an extension of rated power it is important to clarify - larger vehicles generally require a higher rated power and therefore more platinum, although this is not always the case. Application and drive train impact the size of fuel cell utilised, particularly applicable to LCV. Some hydrogen vans and buses, whilst larger than a passenger car utilise a BEV drivetrain and then a small fuel cell as a range extender. Others, may have a disproportionately large fuel cell comparable to its size such as in cold storage vehicle applications where electrical draw is large.

Fuel cell electric vehicles (FCEVs) should represent 55% (505koz) of total hydrogen related platinum demand by 2030. HD-FCEV vehicles have the highest platinum loadings and the greater the fleet on the road has a relatively larger effect towards increasing platinum demand compared to the manufacture of passenger and light commercial segments. We estimate that HD-FCEV will represent 75% of FCEV demand.

Off-Road FCEV Applications (Rail, Marine & Heavy Machinery)

In line with the rationale driving heavy-duty transport toward FCEV adoption, the challenges faced by BEVs in managing high payloads and enduring extreme duty cycles become apparent in industrial application. Many industrial applications operate in such demanding conditions, making FCEVs a promising solution. As a result, we anticipate the emergence of FCEV applications in sectors like Rail, Marine, and off-road operations. Ballard, a prominent player in fuel cell manufacturing, has already deployed numerous MW systems in these sectors, underpinning the growing traction of FCEVs in rugged environments.

Figure 31. FCEVs can be scaled to provide high power output suitable for applications such as freight and earthworks.

Source: Canadian Pacific, Anglo American

Rail: Hydrogen-powered rail presents a sustainable alternative to diesel-powered locomotives, significantly reducing greenhouse gas emissions and local air pollutants. Hydrogen-powered trains offer extended ranges to battery powered trains, making them well-suited for non-electrified passenger rail lines or where electrification may be challenging or costly such as in long distance freight. They also provide quick refuelling times akin to traditional diesel trains. Areas of particular use include remote commodity fright in locations such as Canada and Australia. WPIC expects hydrogen-powered rail to support incremental platinum demand of 5 koz by 2030.

Marine: Hydrogen holds significant promise as an alternative fuel for marine vessels, especially in providing auxiliary power or serving as the main propulsion system. As auxiliary power, hydrogen fuel cells can support various onboard operations, including lighting, heating, and powering auxiliary machinery, reducing the reliance on conventional diesel generators and thus lowering emissions in ports and during idle times. Additionally, hydrogen can be used in fuel cell-based propulsion systems for ships, either as a primary source or in combination with other power sources like batteries, offering zero-emission operation. WPIC expects hydrogen-powered marine to support incremental platinum demand of 24 koz by 2030.

Off-road: Fuel cells can be scaled sufficiently for off-road settings, such as construction, mining, and agricultural machinery. The torque and power delivery of hydrogen fuel cells suit the demanding requirements of off-road machinery, providing ample power for heavy lifting, excavation, or agricultural tasks while reducing greenhouse gas emissions and enhancing sustainability in these critical sectors. Anglo American and Fortesque have been trailing a fleet of hydrogen haul trucks (fig 31) as the extractive industries look to decarbonise. WPIC expects hydrogen-powered off-road to support incremental platinum demand of 30 koz by 2030.

Stationary FCEV Applications

Stationary fuel cells present a scalable, low-emission solutions for decentralised power generation, back-up power generation and grid stability while reducing reliance on fossil fuels (detailed below):

Microgrids and Backup Power: Providing reliable power in grid-tied or off-grid scenarios, ensuring uninterrupted electricity supply in critical infrastructure.

Residential and Commercial Use: Powering homes, offices, and commercial buildings, either as standalone power systems or combined with grid electricity in combined heat and power (CHP) setups.

Remote and Off-Grid Areas: Where access to centralised grids is limited, addressing power requirements presents a significant challenge. The concept of "hydrogen islands" emerges as an integrated solution offering sustainability and reliability. This framework entails the generation of hydrogen from off-peak renewable power through an electrolyser, subsequently storing it for future deployment or as a backup power source. By providing remote locations with a dependable and sustainable energy reservoir, hydrogen islands contribute to bolstering energy resilience and autonomy.

Industrial Applications: Supplying process heat and power for various industrial operations, contributing to enhanced efficiency and reduced emissions in manufacturing processes.

Direct Reduced Iron (DRI) – "Green Steel"

Steel making is a significant emitter of CO_2, with many commentators attributing around 10% of global CO_2 production to the sector. Traditionally iron ore is heated with coke in a blast furnace. Iron ore is an iron oxide, primarily hematite (Fe_2O_3) and magnetite (Fe_3O_4), which needs to be reduced to obtain elemental iron (Fe) for steelmaking. Carbon in coal acts as a reducing agent to from elemental iron but also combines with the oxygen to produce and emit CO_2.

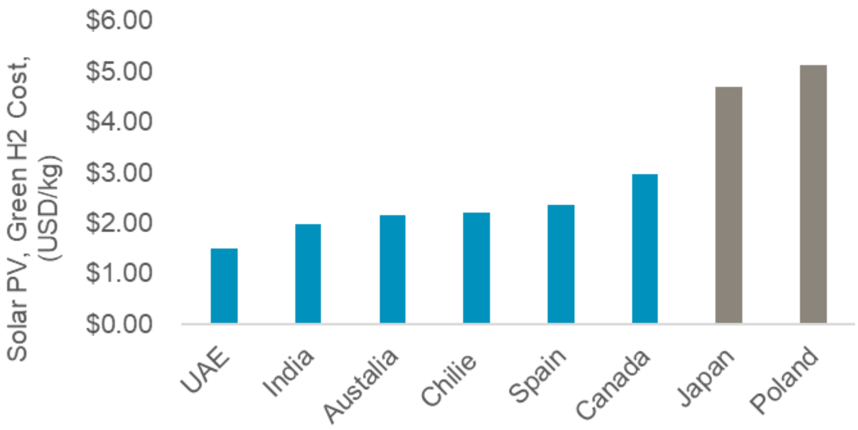
Direct Reduced Iron (DRI) is a process that utilises electrification and green hydrogen as a reducing agent that removes oxygen from the iron ore without melting the ore in a blast furnace. The ore is reduced utilising low carbon hydrogen in a shaft furnace producing only elemental iron and water. The iron is then processed in an electric arc furnace (which can be powered by renewable energy sources) to produce steel with a reduced carbon footprint compared to traditional methods.

By integrating renewable energy to power the plant and green hydrogen produced through an electrolyser, steel manufacturers can in fact become carbon neutral businesses. LKAB, Sweden's largest steel producer, has mandated that it will become carbon neutral by 2050.

Cost competitiveness of green steel

Green steel is currently less cost competitive than blast furnace steel. However, a combination of carbon taxing and reduction in hydrogen prices will shift the dynamic. According to McKinsey and Company green steel becomes economic under a range of scenarios. At a carbon price of €60/ tonne hydrogen would be required to cost €1.2/kg, conversely at a higher price of €90/ tonne the hydrogen price could be as high as €2.0/kg to be cost competitive (carbon in Europe is currently trading at €61/t with an all-time high of €82/t). Currently, 'at the gate' hydrogen can be produced under USD$2.0/kg (~€1.85/kg) in cost competitive regions (fig 32). Although this ignores midstream costs (compression, liquification and transport) and return of investment requirements for the providers of capital. WPIC estimates domestic midstream costs of around US$3.00 per kg in 2022. By 2030, through subsidies and lower hydrogen costs green steel will be available. Sweden's HYBRIT green steel plant is planned to produce commercial fossil-free steel for the market by 2026.

Figure 32. Levelised cost of hydrogen 'at the gate' production costs of hydrogen via solar PV in select countries.



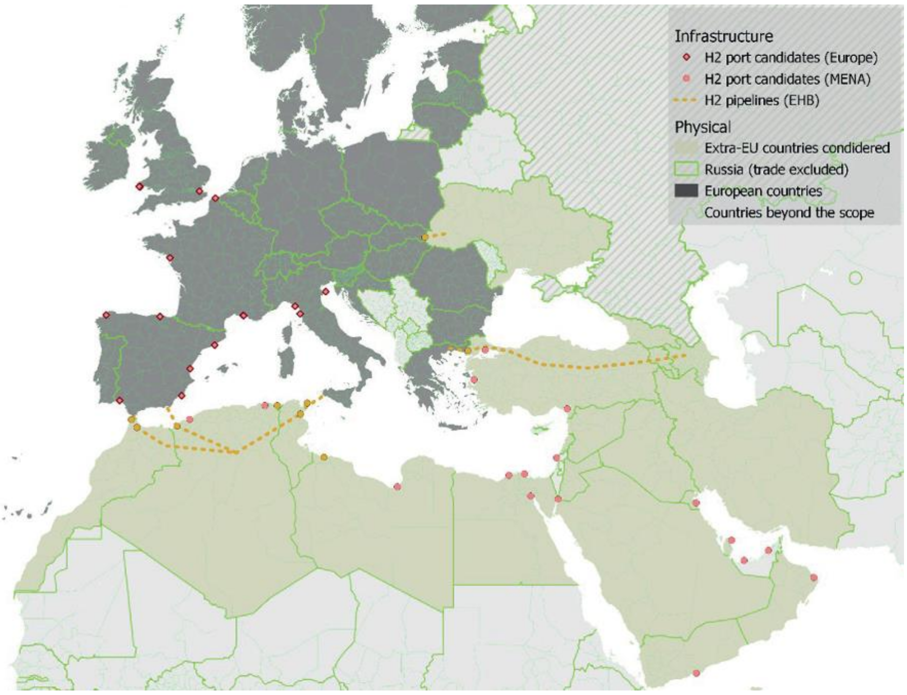
Source: IRENA, WPIC Research

Hydrogen transport and support infrastructure

Today, most hydrogen never leaves the chemical plant it is produced on. Instead, it is produced and utilised in chemical and petrochemical process. However, utilising hydrogen as an energy carrier requires transportation across various sections of the hydrogen economy. Today, hydrogen is only transported in small quantities and small distances. This is done via cooling or compressing hydrogen into trucks. However, as the industry scales, more efficient methods of transport will be required.

Energy is the largest cost component of renewable hydrogen production. Renewable electricity is generally cheaper in regions with abundant and high intensity renewables. Upstream hydrogen will require transport across land and sea to downstream markets. The likely options are pipelines, shipping or a combination of the two. Figure 33, provided by Hydrogen4EU gives example as to how this system can form a hydrogen backbone. The hydrogen 'backbone' is a proposed network of ports and pipelines that can be built to enable international trade of hydrogen. The purpose is to leverage cheap renewable energy in North Africa and the Middle East to produce hydrogen for export to end markets in Europe.

Figure 33. The hydrogen 'backbone' is a proposed network of ports and pipelines that can be built to enable international trade of hydrogen. The purpose is to leverage cheap renewable energy in North Africa and the Middle east to produce hydrogen for export to Europe.



Source: Hydorgen4EU

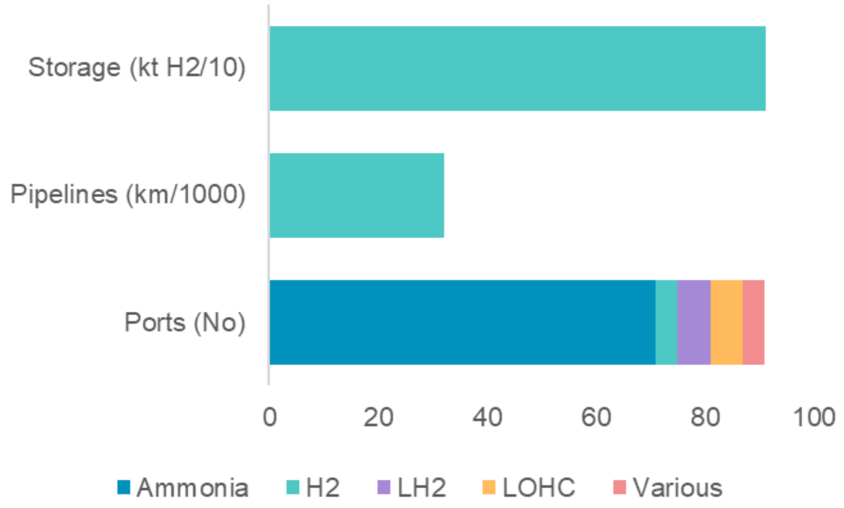
Hydrogen is produced as a gas from electrolysis. Whilst it has an extremely high energy by mass, it has an extremely low density. What this means is that it's energy per volume occupied is low. Since ships are volume constrained, this inevitably means more trips and higher costs. Fortunately, hydrogen can be converted and combined into different forms or compounds which improve the economics.

Hydrogen Pipelines: Retaining hydrogen in its gas form and utilising pipelines presents the most cost-effective way of transport. Just under 30,000km of hydrogen pipelines have been announced to be constructed (figure 34). Due to the substantial capital investment requirements of gas-carrying pipelines, hydrogen pipeline development will primarily focus on repurposing existing gas infrastructure, supplemented by new connections. Transport routes are expected to be predominantly regional, with limited intercontinental transportation (e.g., Africa to Europe) as cost become intuitively prohibitive at longer distances.

Hydrogen Shipping: Hydrogen shipping overcomes pipeline limitations by linking existing seaports. Given hydrogen gas's low density, it requires transformation into another form for efficient transport. Options include compression, liquefaction, or conversion into derivative products. Ammonia, Liquid Organic Hydrogen Carriers, Methanol, and Synthetic fuels stand out, offering superior technical and economic advantages over elemental hydrogen. With higher energy densities per unit of volume, these derivatives enhance transport efficiency by concentrating the energy payload. Moreover, their longstanding presence in the market means that there is already significant established technical know-how and infrastructure for safe handling and transportation. The IEA indicates that by 2030 Ammonia will be the most commonly ocean freighted form of hydrogen, with liquid hydrogen transport only constituting a minor share (fig 34).

Ammonia can be stored and transported in liquid form at ambient temperature and moderate pressure, whereas hydrogen typically requires cryogenic temperatures or high-pressure storage to remain in a liquid state. This makes the storage and handling of ammonia more practical and less energy-intensive compared to hydrogen. Finally, derivative products such as ammonia have established infrastructure for production, storage, and distribution, particularly in the agricultural and chemical industries. This existing infrastructure could potentially be repurposed or leveraged for other applications, such as energy storage or transportation, without the need for significant additional investment.

Figure 34. Support for planned infrastructure suggests pipeline and ammonia shipping will be the preferred methods of transport.



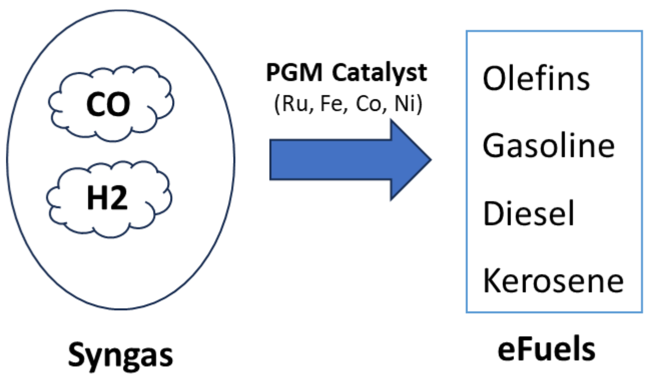
Source: IEA

Synthetic fuels are low-carbon or carbon neutral fuels produced via combing sustainable carbon dioxide and hydrogen produced by electrolysis. The Fischer-Tropsch process' is utilised to combined carbon and hydrogen in the presence of a PGM catalyst to produce synthetic fuels.

These synthetic hydrocarbons - such as syn-kerosene and syn-diesel - can be utilised in existing internal combustion engines in the automotive and aviation sectors. Due to the mass of batteries and fuel cells e-fuels are seen as the primary method to decarbonise the aviation industry alongside SAF (sustainable aviation fuel). Where SAF differs to e-fuels in that it is produced through biomass, waste oils, or agricultural residues.

According to the ICCT, e-kerosene is approximately ~3x the production cost of jet fuel in the EU. However, this reduces to ~1.5x by 2050. The introduction of a carbon tax onto aviation operations utilising carbon intensive fuels would likely bring cost parity.

Figure 35. PGM Catalysts are utilised in the process of creating e-fuels.



Source: WPIC Research

Conclusion

The need to decarbonise the world is acute meaning that all options to reduce emissions are going to be needed and are for the most part complimentary to each other, rather than competitors.

With more than $300 billion of subsidies currently available for hydrogen projects globally, it is now a question of when rather than if the hydrogen economy takes off, or more accurately, the pace at which it grows and the feedthrough impact in terms of demand for platinum that arises from hydrogen applications.

There are a number of existing technologies available that can realise the hydrogen economy today, but innovation, new technologies and economies of scale are needed to bring costs down. Competitive cost reduction, whether on a standalone basis or in coordination with carbon taxes will be needed for the rapid adoption of hydrogen, and for platinum containing electrolysers and fuel cells.

Our regular publications addressing hydrogen-related demand for platinum will present our estimates as the landscape evolves, but as things stand now, we expect electrolysers and heavy-duty fuel cell electric vehicles to be the major drivers of early demand, with wider fuel cell applications becoming the biggest driver of demand later this decade and into the 2030’s.

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Glossary

Battery Electric Vehicle (BEV) - A plug-in vehicle with a large battery that is plugged in to an electric power source to charge.

Alkaline Electrolysis (AEL) - An electrolyser that uses an alkaline electrolyte solution to split water into hydrogen and oxygen gases.

Ammonia - A compound composed of nitrogen and hydrogen, often used as a fertilizer and in various industrial processes.

Carbon Capture and Storage (CCS) - A technology that captures carbon dioxide emissions from industrial processes and stores them underground to mitigate climate change.

Contract for Difference (CfD) - A financial instrument used to manage the risk of electricity price fluctuations in renewable energy projects.

Direct Reduced Iron (DRI) - A process used to produce iron from iron ore using natural gas or hydrogen as a reducing agent.

Electrolysis - A chemical process that uses electricity to split a compound into its constituent elements.

Fuel Cell Electric Vehicle (FCEV) - An electric vehicle that uses a fuel cell to produce electricity (by passing hydrogen and oxygen over a platinum catalyst). Thus, they drive an electric motor/s consuming hydrogen fuel.

Greenhouse Gas (GHG) - Gases (such as carbon dioxide) that trap heat in the Earth's atmosphere, contributing to the greenhouse effect and climate change.

Hybrid Electric Vehicle (HEV) – A vehicle with a small battery combined with small combustion engine. The vehicle has negligible electric only range as the engine cuts in and out routinely. The battery is charge by the engine.

Levelised Cost of Energy (LCOE) – Methodology to assess and compare the costs of alternative methods of energy production.

Levelised Cost of Hydrogen (LCOH) – Standardised methodology which accounts for operating and capital costs to produce hydrogen allowing comparability across production pathways.

Liquid Organic Hydrogen Carrier (LOHC) - A substance used to store and transport hydrogen in liquid form.

Net Present Value (NVP) – The sum of the present value of future cashflows. The calculation allows future cash flows to be reflected in today's real value terms thereby allowing comparable of different investment opportunities.

Platinum Group Metals (PGMs) - A group of metals commonly present with platinum in platinum bearing ore. Can refer to some or all of platinum, palladium, rhodium, iridium, ruthenium, and osmium.

Plug-in Hybrid Electric Vehicle (PHEV) - A vehicle that combines an internal combustion engine with a mid-sized battery that can be plugged in to charge to run as a BEV for a limited distance as well as run on petrol or diesel alone.

Proton Exchange Membrane Water Electrolysis (PEM) - An electrolyser splits water molecules (H_2O) into its constituent oxygen and hydrogen elements by breaking the bonds. PEM technology uses a gas-tight solid polymer-based membrane as an electrolyte. PEM employs platinum and iridium as coated catalysts as part of the membrane.

Power Purchase Agreement (PPA) - A contract between an electricity generator and a buyer, stipulating terms for the sale of electricity over a specified period.

Steam Methane Reforming (SMR) - A process used to produce hydrogen from natural gas by reacting it with steam.

Synthetic Fuel (Synfuel) - Fuel produced from renewable resources or through processes like Fischer-Tropsch synthesis, often used as an alternative to fossil fuels.

Total Cost of Ownership (TCO) – Calculation of an assets life cycle costs which incorporates both the purchase price and operating costs. Used to compare returns forecasts of different assets.

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