2022

INVESTMENT OPPORTUNITIES IN HYDROGEN INFRASTRUCTURE IN SELECTED COUNTRIES

SIPA Capstone Workshop

May 2022

Prepared for: Crédit Agricole CIB (CACIB)

Prepared by: Sho Aihara, Abdulaziz Alhumud, Sindhura Chakravarty, Xi Chen, Andres Moncada Lopez, Courtney Jacobs, Xiaoming Zhong

Faculty Advisor: James Guidera

TABLE OF CONTENTS

ACKNOWLEDGMENTS

This study is the product of a team of graduate students from the School of International and Public Affairs (SIPA) at Columbia University at request of Crédit Agricole Corporate Investment Bank's Structured Finance Group (SFI). The authors would like to thank Gabriel de Laval, Mathilda Rullier, Page Dillehunt, Evan Levy, Olivier Audemard and Eugene Kasozi for their valuable comments.

This study was undertaken with generous support of faculty advisor James Guidera.

EXECUTIVE SUMMARY

Climate change has spurred a global urgency for an energy transition toward a low carbon future. Visions for this energy transition include a vast potential for *clean hydrogen* produced with renewable energy or with fossil fuels sources coupled with carbon capture. Clean hydrogen could be a solution to displace fossil fuels in hard-to-decarbonize sectors: the production of steel, other metals, cement, fertilizer and other chemicals; as a transportation fuel for trucks, buses and marine vessels. Hydrogen would also fuel power generation and act as an energy storage medium to support a future electricity grid with increased levels of variable wind and solar generation.

Similar to the revolution of renewable generation sources in the last decade, hydrogen application is looking like the next disruptive technology in the energy sector for the next few years. This revolution cannot happen without coordination between public and private sectors. In general, investment cases in the energy sphere are only possible because of the conjunction of regulation and public policy with private capital endeavors. Hydrogen applications in terms of technology are still in very early stages but governments around the world are already identifying their strengths in capabilities to actively participate in this transformation.

The first part of this report identifies the high cost of manufactured hydrogen as the principal challenge to overcome for clean hydrogen to displace carbon-intensive fuels. The *levelized cost of hydrogen (LCOH)* model developed for the purpose of this study predicts the costs for producing green hydrogen under various scenarios of renewable energy sourcing and capital equipment cost-declines. The model estimates that the cost of *green hydrogen* production is $2.14-8.52/kg, currently higher than *blue hydrogen* ($1.5-2.5/kg) and grey hydrogen ($0.5-2.0/kg).[1] Further research concludes that opportunities for hydrogen investment will be paced by declining production costs over the next decade with early hydrogen applications likely to appear in selected markets as a fuel displacement of diesel and gasoline for buses and trucks as well as other chemicals.

The second part of this report analyzes six countries selected by the client as best positioned to present CACIB and its clients with near term investment opportunities based on factors such as local energy resources, government policies, and domestic energy consumption. The selected countries, *United States*, *Chile*, *Spain*, *Australia*, *Japan*, and *Saudi Arabia* are taking the lead in terms of public policy involvement in the development of the hydrogen industry. This analysis confirmed how investment in hydrogen production, import and export infrastructure is likely to appear in varying emphasis among the selected countries. The report also identified specific hydrogen-linked projects announced among these countries and featured particularly ripe projects as detailed case studies.

---

[1] Goldman Sachs. Carbonomics: The Clean Hydrogen Revolution. February 7, 2022. https://www.goldmansachs.com/insights/pages/carbonomics-the-clean-hydrogen-revolution.html

PART 1: BACKGROUND AND CONTEXT

1.1. BACKGROUND AND GLOBAL CONTEXT

Climate change is a global priority and an imminent threat to human life, leading, over the course of the last decade, to extreme and more frequent natural disasters.[2] Governments around the world have taken note of this by introducing carbon neutrality goals and decarbonization policies. These measures are poised to impact the global energy mix and consequently energy trade. Former fossil fuel importing nations are leading the energy transition by prioritizing renewable energy resources like solar and wind which has become more affordable owing to technological advancements.

While wind and solar have the potential to decarbonize most of the electricity sector, their intermittency would need to be firmed-up with other sources of carbon-free generation and energy storage. Moreover, there are other "hard to abate" sectors such as aviation, shipping and freight transportation remain dependent on fossil-fuel based energy: this is where low carbon hydrogen could play a key role.

Hydrogen can combust without carbon emissions, making it a viable fuel source of a zero-carbon future, provided decarbonized production processes are adopted. Fortunately, there are several routes to achieving this. Blue hydrogen producers can generate low carbon hydrogen from fossil fuel sources using carbon capture technologies. Green hydrogen, on the other hand, can be created from renewable energy sources.

Currently only 120 million tons of hydrogen are produced globally and are primarily used for industrial applications such as fertilizer manufacture and petroleum refining.[3] Yet, hydrogen has a range of potential applications that could enable decarbonization goals. It has the potential to act as an energy storage medium or generation fuel in the electricity sector; it could also be used as a fuel for space heating and in those hard-to-abate transportation sectors.

Current barriers to its uptake across these sectors stem from a lack of infrastructure required to support its application and the comparatively high cost of hydrogen.[4] Yet both the infrastructure and cost barriers may be overcome under evolving market contexts, with appropriate policy support. Market optimism has propelled a surge in the number of hydrogen projects in the last few years. In fact, according to Wood Mackenzie there has been a 50-fold increase in announced green hydrogen projects alone in the last 12 months.[5]

Countries around the world are also recognizing the benefits of instituting national hydrogen roadmaps and strategies to encourage greater investment into the sector. Large nations that represent centers of

---

[2] Intergovernmental Panel on Climate Change. Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. June 2012. https://www.ipcc.ch/report/managing-the-risks-of-extreme-events-and-disasters-to-advance-climate-change-adaptation/

[3] International Energy Agency. Global Hydrogen Review 2021. November 2021. https://iea.blob.core.windows.net/assets/5bd46d7b-906a-4429-abda-e9c507a62341/GlobalHydrogenReview2021.pdf

[4] Commonwealth Scientific and Industrial Research Organisation. National Hydrogen Roadmap (Australia). August 2018. https://www.csiro.au/-/media/Do-Business/Files/Futures/18-00314_EN_NationalHydrogenRoadmap_WEB_180823.pdf

[5] Wood Mackenzie, The Blue-green Planet: How Hydrogen can Transform the Global Energy Trade, October 2021. https://www.woodmac.com/horizons/the-blue-green-planet-how-hydrogen-can-transform-the-global-energy-trade/

energy demand, like Japan and Europe are expecting to import hydrogen to meet their electrification and other needs.

Over the last two months, Russia's invasion of Ukraine has severely impacted market appetite for natural gas from Russia. This avoidance of Russian supply by Western markets could mean that the elevated energy costs in 2021 are here to stay for longer than previously estimated. It also means that European markets may find it more urgent to develop policies that support the import and use of hydrogen in the electricity, heating, and other sectors.[6]

Equally on the supply side, countries like Chile, Australia and Saudi Arabia are viewing this nascent sector as a unique opportunity to export green energy to other markets. Nearly 60% of proposed export projects based in the Middle East and Australia, principally targeting markets in Europe and Northeast Asia.[7]

The objective of this capstone study is to advise Credit Agricole CIB's (CACIB) structured finance group on the likely investment opportunities in hydrogen-linked infrastructure to best position CACIB as a finance provider in the hydrogen transition. This report provides an overview of hydrogen, its technologies and value chain and analyzes the cost gaps that challenge its widescale adoption. It also goes on to highlight regional and policy drivers that could mitigate this cost gap and analyzes selected countries and markets identified with CACIB as likely to present early-stage or high-volume investment opportunities due to their regulatory policies, business environment, resources, and other factors.

1.2. TYPES OF HYDROGEN: BLUE VS. GREEN

There are multiple methods of extracting and producing hydrogen with different levels of carbon intensity. These methods differ based on their feedstock, which can be low-carbon renewable energy, natural gas, or other types of feedstocks. Color coding has been adopted in policy discussions to distinguish between different types of hydrogen production. For example, grey hydrogen uses natural gas or coal as a feedstock (and does not capture the carbon emissions from production) while pink hydrogen uses nuclear energy as a feedstock.[8] The investment opportunities highlighted in this study will be focused on blue and green hydrogen.

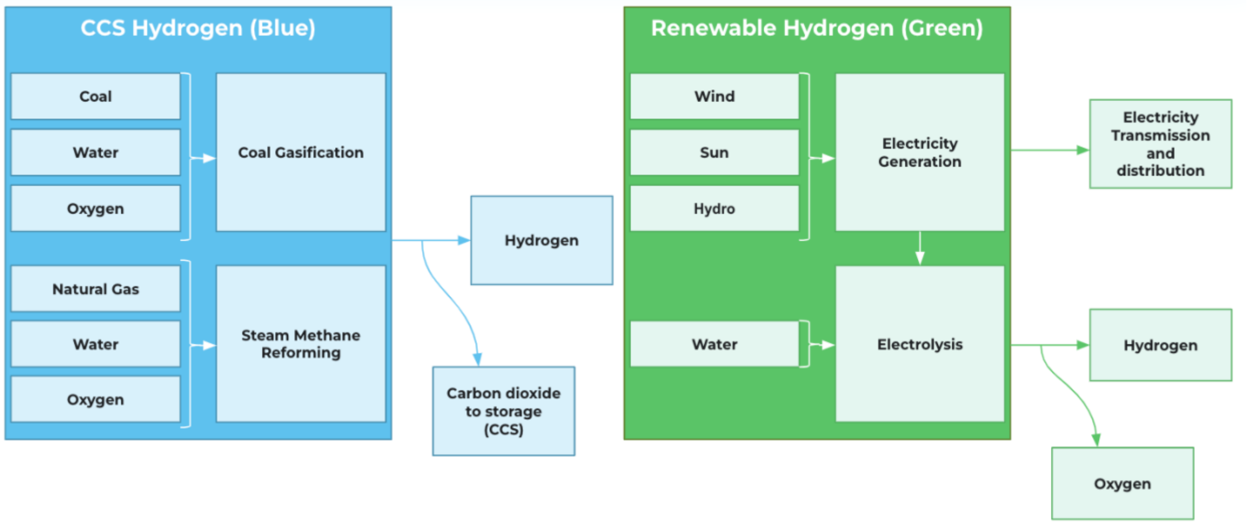
---

[6] European Commission. REPowerEU: Joint European Action for more Affordable, Secure, and Sustainable Energy. 8 March 2022. https://ec.europa.eu/commission/presscorner/detail/en/ip_22_1511

[7] Wood Mackenzie. The Blue-green Planet: How Hydrogen can Transform the Global Energy Trade. October 2021. https://www.woodmac.com/horizons/the-blue-green-planet-how-hydrogen-can-transform-the-global-energy-trade/

[8] Alverà, Marco, 2021, The Hydrogen Revolution: a blueprint for the future of clean energy. https://www.powells.com/book/hydrogen-revolution-a-blueprint-for-the-future-of-clean-energy-9781541620414#:~:text=We%20just%20need%20a%20new,global%20action%20on%20climate%20change.

Figure 1 Blue and Green Hydrogen Production Processes[9]



GREEN HYDROGEN

Green hydrogen is produced using *electrolysis*, a technology that has been successfully implemented and refined over the past several decades. The electrolysis production process involves the use of an *electrolyzer* that passes electrical current, generated by renewable sources, through water, splitting the water into hydrogen and oxygen molecules. Because pure water cannot conduct electricity, electrolytes are first added to the water to form a conductive substance. An electrolyzer consists of a series of electrochemical cells, with the main components of each cell being two electrodes and the electrolyte.

Today there are two main methods of water electrolysis in use, supplemented by emerging technologies being tested by continued research and development efforts:

Alkaline electrolytic cells (AEC) represent the most well-researched and mature form of electrolyzer technology deployed today. This method has been in commercial use in industrial applications since the 1920s, contributing to its credibility. AEC technology utilizes an electrolyte composed of an alkaline solution containing either sodium hydroxide (NaOH) or potassium hydroxide (KOH) and its electrodes are most often made of nickel-coated steel. AEC technology is well-suited for the storage of large quantities of energy and units have successfully been built at megawatt-scales. This electrolyzer approach also uses cheaper materials compared to other available forms of electrolyzer technology. AEC is limited, however, in its ability to respond to fluctuations in electrical inputs, a common occurrence when utilizing renewables such as wind and solar. The method also results in a lower gas purity than comparative technologies, requiring additional purification measures and added costs.

---

[9] Bank of America, Blue and Green Hydrogen Pathways, https://www.driehaus.com/perspectives/turning-hydrogen-green

Proton exchange membrane electrolyzer cells (PEMEC) represent the second most common method of electrolysis in use today. This technology has been commercially available for many years but has historically not been available at a large enough scale. This has been changing in recent years with a number of companies focusing on the development of such large-scale electrolyzers. PEMEC technology responds swiftly to fluctuations in electrical input which is an advantage if combined with variable renewable sources or if balancing excess generation from the grid. Moreover, it produces purer hydrogen and has the ability to produce hydrogen at a higher pressure than the oxygen output which is often preferable. However, PEMEC also currently has a higher capital cost relative to AEC technology due to its expensive membranes and electrode materials and is less reliable and scalable.

In addition to these two main methods, several electrolysis methods are currently in development, including high-temperature water electrolysis otherwise known as *solid oxide electrolytic cells (SOEC)*. High temperatures would allow water to be more easily split into hydrogen and oxygen, however, this electrolyzer technology is still nascent compared to PEMEC and AEC systems and is not commercially available yet.

Electrolyzer technologies are available and improving rapidly. The current learning curve expectations for electrolyzers range from 11 to 12% between 2020 and 2030 for PEMEC and AEC systems which are projected to lead to material cost declines. The greatest challenge to electrolysis adoption is its high capital costs, most cost reduction are expected to come from the scale effect (the more you produce the cheaper) discussed further in Section 1.4. [10]

BLUE HYDROGEN

Blue hydrogen is produced utilizing coal or natural gas feedstock through the processes of coal gasification or steam methane reformation (SMR), in each case accompanied by carbon capture and storage (CCS). Approximately 98% of current hydrogen production is from steam methane reformation or coal gasification. The production of blue hydrogen with CCS and green hydrogen from electrolysis requires similar amounts of water, however, blue hydrogen production requires significantly less electricity (55 kWh/kgH2 for electrolysis, 1.91 kWh/kgH2 for SMR with CCS, and 3.48 kWh/kgH2 for coal gasification plus CCS).[11]

Steam methane reforming (SMR) produces hydrogen, carbon monoxide, and carbon dioxide by reacting hydrocarbons with water in the form of steam. The most common source of hydrocarbons used in the process is natural gas.[12]

Coal gasification is the process by which carbon-rich materials such as coal or petroleum are converted into hydrogen and carbon monoxide. During the gasification process, coal or other solid fuels react with

---

[10] Fuel Cell Today, 2013, Water Electrolysis & Renewable Energy Systems. http://www.elygrid.com/wp-content/uploads/2021/07/down_water-electrolysis-renewable-energy-systems.pdf

[11] Global CCS Institute, 2021, Blue Hydrogen. https://www.globalccsinstitute.com/wp-content/uploads/2021/04/Circular-Carbon-Economy-series-Blue-Hydrogen.pdf

[12] Garcia, L, 2015, Hydrogen production by steam reforming of natural gas and other nonrenewable feedstocks. https://www.sciencedirect.com/science/article/pii/B9781782423614000042

air, oxygen, steam and carbon dioxide at extremely high temperatures exceeding 800°C. The heat and pressure subsequently break apart the bonds of the coal molecule and the resulting chemical reactions produce hydrogen and carbon monoxide.[13] The selection of gasification technology is typically dependent on the type of coal that is being processed. The production of hydrogen using coal gasification with CCS requires more capital than steam methane reforming which is reflected in its higher cost structure.[14]

Common methods for *Carbon Capture and Storage (CCS)* include sequestering carbon dioxide emissions deep underground in depleted oil and gas reservoirs, coalbeds, or saline aquifers. Fossil fuel-based hydrogen production facilities that utilize CCS technology have been operating at commercial scale for decades. To produce 1 kg of hydrogen from coal and natural gas, approximately 22 kg and 8 kg of carbon dioxide, respectively, need to be captured, transported, and stored. New CCS technology is constantly emerging through continued research and development efforts with a focus on reducing the cost of employing CCS technology. Emerging technologies on the horizon include chemical looping processes, new absorption processes, and the use of new membranes to separate carbon dioxide from other gases. Improvements in cost reduction are also being explored through the design of plants that integrate the hydrogen production process with the carbon capture and compression processes rather than operating these plants separately.[15]

HYDROGEN APPLICATIONS

The potential applications of green and blue hydrogen are overlapping but they display differences in production and transportation costs. The cost of electrolyzers, their capacities, and transportation play a significant role in limiting green hydrogen applications. Transforming green hydrogen to ammonia or methanol, the most common methods, allows for the use of green hydrogen in the chemical industry and transportation sectors as an alternative fuel.[16]Before the recent increases in natural gas, blue hydrogen was cheaper to produce than green hydrogen, and was more suitable for countries that are not endowed with renewable energy sources..[17] The future applications for hydrogen, blue and green, are promising, including fuel for small cars, ships, airplanes, residential heat and power storage generation. Hydrogen applications described more fully in Section 1.3 of this report.

CRITICISM OF BLUE HYDROGEN

There are critiques among stakeholders in the policy debates of the benefits of blue hydrogen in reducing carbon emissions. Broad skepticism about the process exists among environmental advocates due to its utilization of fossil fuels as feedstock. A peer-reviewed paper published in August 2020 showed that burning blue hydrogen for heating produces 20% more greenhouse gas than conventional natural gas and

---

[13] Wagner, Nicola, 2008, Coal Gasification. https://www.sciencedirect.com/topics/earth-and-planetary-sciences/coal-gasification

[14] Global CCS Institute, 2021, Blue Hydrogen. https://www.globalccsinstitute.com/wp-content/uploads/2021/04/Circular-Carbon-Economy-series-Blue-Hydrogen.pdf

15 Global CCS Institute, 2021, Blue Hydrogen. https://www.globalccsinstitute.com/wp-content/uploads/2021/04/Circular-Carbon-Economy-series-Blue-Hydrogen.pdf

[16] IRENA (2021), Green hydrogen supply: A guide to policy making, International Renewable Energy Agency, Abu Dhabi. https://irena.org/publications/2021/May/Green-Hydrogen-Supply-A-Guide-To-Policy-Making

[17] Global CCS Institute, 2021, Blue Hydrogen. https://www.globalccsinstitute.com/wp-content/uploads/2021/04/Circular-Carbon-Economy-series-Blue-Hydrogen.pdf

60% more than burning diesel oil for heat.[18] Critics estimate that during the blue hydrogen production process, fugitive methane emissions are only 9% to 12% lower than those of grey hydrogen over a 20 year-period because fossil fuel is used in capturing the released carbon.[19]

Nevertheless, other reports, including one from the Climate Change Committee, indicate that a combination of blue and green hydrogen is consistent with reaching the net-zero emissions goal.[20] An environmental argument as to why countries may elect to pursue blue hydrogen production and related infrastructure is that producing green hydrogen requires greater land resources. A study from The Nature Conservancy found that green hydrogen production impacts 40 times more land per unit of energy than conventional natural gas. Blue hydrogen is seen as a suitable alternative to conserve land.[21]

A conclusion about the decarbonizing merits of blue hydrogen is outside the scope of this paper. Advantaged over green hydrogen by firm lower-cost production, blue hydrogen appears on track to be in the mix of decarbonizing solutions for some countries, especially those with low priced gas feedstock and carbon-storing resources. At the same time, the criticism of its decarbonizing impact may limit its broad adoption.

1.3. HYDROGEN TECHNOLOGY AND VALUE CHAIN

Hydrogen can be produced using different technologies and primary energy sources. As stated in Section 1.2, global hydrogen production today is grey dominated by the use of fossil fuels without CCS. Hydrogen from electrolysis plays only a minor role. However, the declining costs for renewable power, especially solar PV and wind, is expected to enable the use of green hydrogen across several industries. Policy makers, energy related companies and investors are working on green (and blue) hydrogen applications in power, transportation and industry to boost the long-awaited energy transition.

Similar to the oil and gas sector, the hydrogen value chain can be subdivided into *upstream*, *midstream* and *downstream* segments. The upstream segment relates to the production of hydrogen. This section will be focused on green and blue hydrogen production. The midstream segment comprises the storage and transportation of hydrogen from the production site and the consumption centers. Finally, the downstream segment relates to the uses of hydrogen in the power, transportation and industrial sectors.

---

[18] Ambrose, Jillian, 2021, UK plan to replace fossil gas with blue hydrogen 'may backfire'. https://www.theguardian.com/environment/2021/aug/12/uk-replace-fossil-gas-blue-hydrogen-backfire-emissions

[19] Burgess, James, 2021, Blue hydrogen 20% worse for GHG emissions than natural gas in heating: study. https://www.spglobal.com/commodity-insights/en/market-insights/latest-news/natural-gas/081221-blue-hydrogen-20-worse-for-ghg-emissions-than-natural-gas-in-heating-study

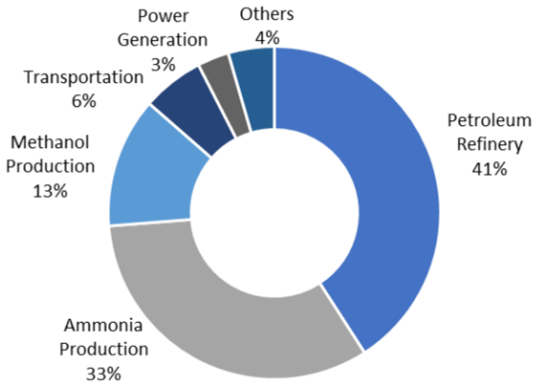
[20] Ambrose, Jillian, 2021, UK plan to replace fossil gas with blue hydrogen 'may backfire'. https://www.theguardian.com/environment/2021/aug/12/uk-replace-fossil-gas-blue-hydrogen-backfire-emissions

[21] Fowler, Mike, 2021, We need "blue" hydrogen. And we need to get it right. https://www.catf.us/2021/09/we-need-blue-hydrogen-and-we-need-to-get-it-right/#:~:text=Hydrogen%20is%20essential%20to%20decarbonizing,policy%2Dmakers%20reward%20appropriate%20performance.

UPSTREAM: PRODUCTION OF GREEN AND BLUE HYDROGEN

Currently approximately 120 million tons of hydrogen is produced annually; around 75 million tons of pure hydrogen with the remainder being mixed with other gases, predominantly carbon monoxide (CO) in syngas (synthesis gas). Pure hydrogen is used mostly in refining (39 million tons) and ammonia production (33 million tons). Less than 0.01 million tons of pure hydrogen is used in fuel cell electric vehicles. The syngas containing the remaining 45 million tons is used mostly in methanol production, direct reduction iron making and other industrial processes, including as a source of high heat.[22]

Figure 2: Hydrogen Applications



The main factors influencing the production of green or blue hydrogen are the availability of feedstock resources and the consequent cost of producing hydrogen which varies across countries. Cost reductions and policy incentives are key to developing a strong hydrogen production industry. According to the IEA, the impact of renewable electricity and gas costs on hydrogen production costs becomes clearer when evaluating selected countries. For countries that are endowed with strong renewable resources but are still dependent on natural gas and LNG imports, producing green hydrogen from renewables may be more economic. Production of blue hydrogen from natural gas or coal with CCS may be the lower-cost option in regions with domestic gas or coal resources and CO2 storage availability. Generally, the energy input costs are the single largest component of hydrogen production costs. Future hydrogen costs will therefore largely be influenced by changes in electricity and gas costs, or parameters influencing these costs such as conversion efficiencies. Electrolysis production costs can also be sensitive to CAPEX requirements and plant utilization rates which can greatly vary where the electricity comes from wind and solar. These factors contributing to green hydrogen costs are discussed in greater detail with sample calculation tables in Section 1.4.

The main players in the blue hydrogen industry will likely be the companies currently involved in the oil and gas sector. Therefore, NOCs and the big majors can be expected to mimic their current market share in the natural gas production to the blue hydrogen production. On green hydrogen, technology is evolving,

---

[22] Global CCS Institute, 2021, Blue Hydrogen. https://www.globalccsinstitute.com/wp-content/uploads/2021/04/Circular-Carbon-Economy-series-Blue-Hydrogen.pdf

and the market still has several players. The following list summarize the most advanced players in R&D and commercial strategy for green hydrogen:

Table 1 Leading Market Players in Green Hydrogen Production

Company	Country	Website
Hydrogen Producers		
Air Products and Chemicals Inc.	USA	https://www.airproducts.com/
Air Liquide	France	https://www.airliquide.com/
Linde	USA / Germany	https://www.linde.com/
Electrolyzer Manufacturers		
Green Hydrogen	Denmark	https://greenhydrogensystems.com/
Hydrogenics	Canada	https://www.cummins.com/new-power
Nel ASA	Norway	https://nelhydrogen.com/
Toshiba Energy Systems	Japan	https://www.global.toshiba/ww/company/energy.html
Siemens	Germany	https://www.siemens-energy.com/global/en.html
TK Nucera	Germany	https://www.thyssenkrupp-nucera.com/
ITM Power	UK	https://itm-power.com/
John Cockerill	Belgium	https://johncockerill.com/en/
McPhy	France	https://mcphy.com/en/

MIDSTREAM: STORAGE AND TRANSPORTATION

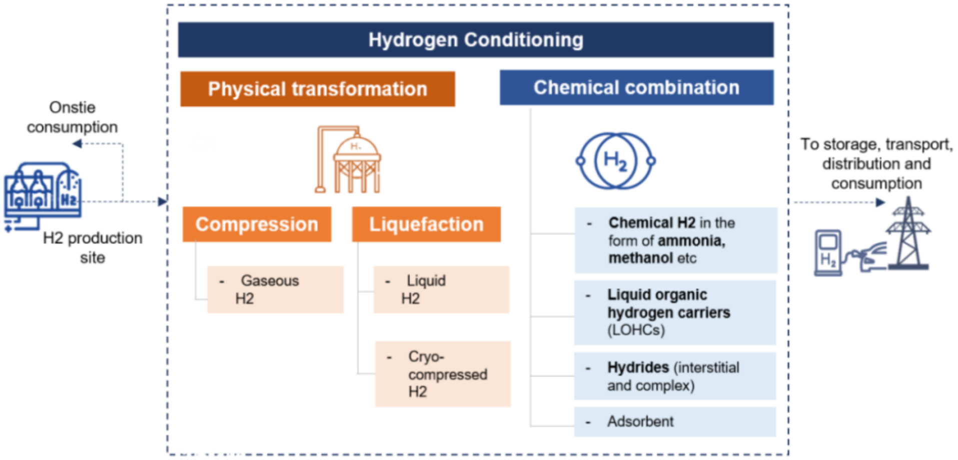
Transport and storage costs will play a significant role in the competitiveness of hydrogen. If hydrogen can be used close to where it is produced these costs could be kept to a minimum. For this reason, many market participants are collaborating on the development of “hydrogen hubs” sometimes with the help of government subsidies (examined further with the *Spain Catalina Case Study* in Section 1.5). However, many market players are structuring strategies to move hydrogen from advantageous production points to more distant markets (see *HESC Case Study* in Section 1.5).

TRANSPORTATION

The smooth operation of large-scale and intercontinental hydrogen value chains will depend on available methods of transportation and adequate storage capacity and functionality. There are certain constraints that future technology developments need to address. Long-distance transmission and local distribution of hydrogen is difficult given its low energy density. Compression, liquefaction or incorporation of hydrogen into larger molecules are possible options to overcome this hurdle but hydrogen conditioning is a prerequisite.

Hydrogen conditioning is broadly classified into two categories, physical and chemical conditioning; physical conditioning encompasses all processes which change the physical conditions of hydrogen but do not interfere with its chemical properties. These include the change of pressure (pressurized hydrogen) as well as changes in the physical state, such as liquefaction or cryo-compression. Chemical conditioning on the other hand entails the transformation of hydrogen into a different chemical compound for which hydrogen is a constituent element, a hydrogen carrier such as ammonia, methanol, liquid organic hydrogen carriers (LOHCs), and metal hydrides.

Figure 3 Hydrogen Conditioning Overview



LOCAL DISTRIBUTION

For distances below 1500 km, transporting hydrogen as a gas by pipeline is likely to be the cheapest delivery option. The exact cost depends on the availability of existing networks and suitable retrofitting. Typically, gas pipelines made of steel would need a polymer retrofit to avoid hydrogen leakage and, given the higher leakage and ignition range (which is about seven times that of methane) an upgrade to leak detection and flow control systems may be required. Newly built hydrogen pipelines will require higher upfront capital expenditure than retrofitting, including the necessary network planning permits. Analysis by the European Hydrogen Backbone study and the Hydrogen Council suggests conversion costs are typically 10%-40% of the cost of a new hydrogen pipeline making retrofitting a more economically attractive solution. Overall, according to the IEA, depending on the pressure of hydrogen transported and the amount, the capital cost associated with hydrogen pipelines can be in the range of US$0.3-1.0 million per km for local distribution (c.>10% higher than natural gas equivalent pipelines). Demand expectations for high volumes of hydrogen and high utilization would be required to support these costs.

LONG DISTANCE TRANSMISSION

For long distance transmission, pipelines (onshore and subsea) as well as shipping by marine vessels (with H2 converted to various forms such as ammonia, methanol, LOHCs and LH2) both appear to be feasible solutions. This approach can be compared to the manner in which natural gas moves worldwide through pipelines or as LNG in ships.

Onshore pipelines, depending on the terrain and distance, could be the most economical solution for distances up to 2,000-3,000 km, particularly retrofitted onshore pipelines. Subsea pipelines can cost 1.3-2.3x the cost of onshore ones, according to the Hydrogen Council. As the transmission distance increases, the cost of transporting gaseous hydrogen through pipelines increases at a faster pace than shipping in a liquid form (LH2, ammonia, LOHC) since a greater number of compressor stations are required.

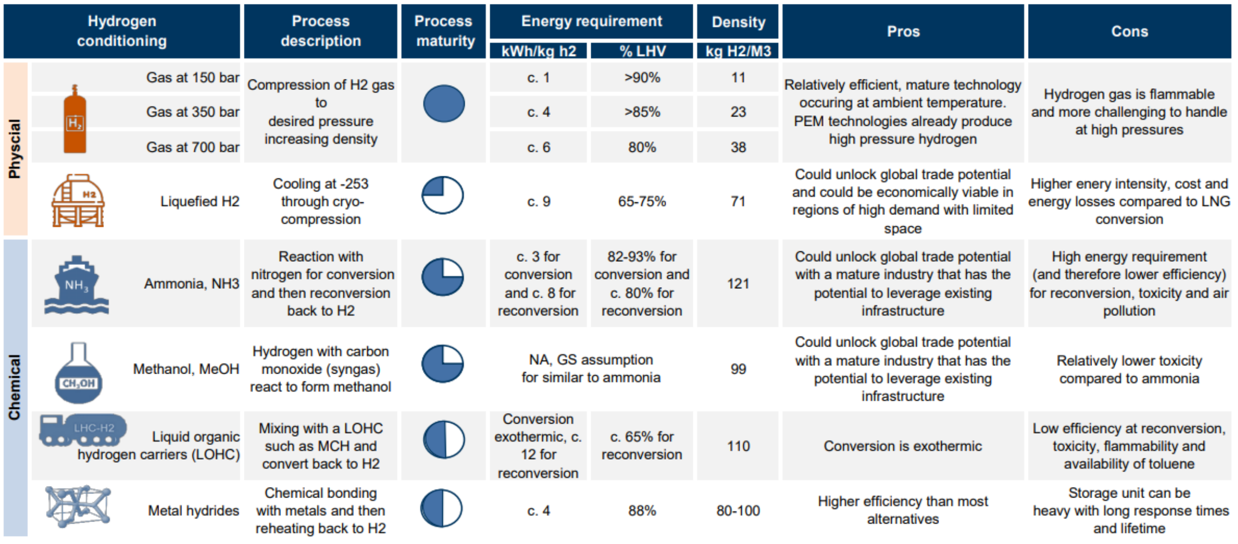
Ammonia is increasingly gaining traction as a promising hydrogen carrier in consideration of its high energy efficiency at the current technology levels, the advantage of leveraging reliable existing infrastructure of its global supply chain, and the potential of direct ammonia uses, which would further improve environmental and economic efficiency by eliminating dehydrogenation process at receiving sites. A seaborne trade in ammonia is an existing market at scale. The current annual ammonia production is about 178 million tons, and around 10% of them are traded through seaborne. There are currently 65 active ammonia carriers worldwide with an average size of 25,000 DWT. There are also existing ports for importing and exporting ammonia with more than 100+ global ammonia terminal locations[23]. Ammonia can be produced in regions with abundant renewable resources and shipped at a relatively low cost to importing areas. For most hydrogen producers, it might be much more convenient and feasible to use the existing supply chains to ship hydrogen in the form of ammonia around the world.

Similar to the transport of liquified natural gas (LNG), shipping liquefied hydrogen could be a potential longer-term solution for hydrogen transport., The relatively low liquefaction point of hydrogen (-253°C), make further technological innovation necessary to enhance the feasibility and economics. Currently, hydrogen liquefaction is a very energy intensive process and has relatively low efficiency, consuming about 1/3 of the energy of hydrogen. In the Japan-focused section in part 2 of this report, the goal of market participants in developing specialized shipping and infrastructure for liquified hydrogen is described.

---

[23] Oliver Hatfield. 2021. Country traded ammonia logistics and storage, present and future. https://www.ammoniaenergy.org/wp-content/uploads/2021/11/AEA-presentation-Oliver-Hatfield.pdf

Table 2 Hydrogen Conditioning Comparison

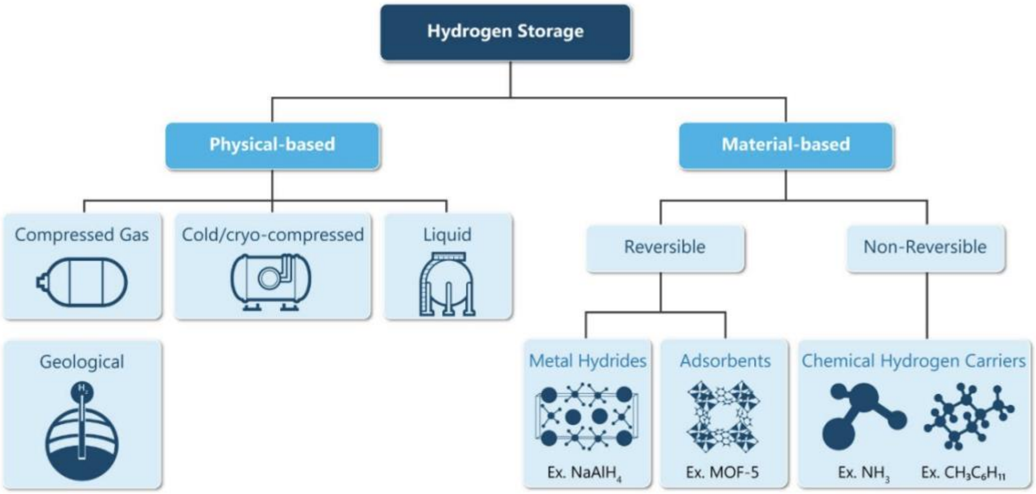


	Hydrogen conditioning	Process description	Process maturity	Energy requirement		Density	Pros	Cons
				kWh/kg h2	% LHV	kg H2/M3		
Physcial	Gas at 150 bar	Compression of H2 gas to desired pressure increasing density	●	c. 1	>90%	11	Relatively efficient, mature technology occuring at ambient temperature. PEM technologies already produce high pressure hydrogen	Hydrogen gas is flammable and more challenging to handle at high pressures
	Gas at 350 bar			c. 4	>85%	23		
	Gas at 700 bar			c. 6	80%	38		
	Liquefied H2	Cooling at -253 through cryo-compression	◔	c. 9	65-75%	71	Could unlock global trade potential and could be economically viable in regions of high demand with limited space	Higher enery intensity, cost and energy losses compared to LNG conversion
Chemical	Ammonia, NH3	Reaction with nitrogen for conversion and then reconversion back to H2	◕	c. 3 for conversion and c. 8 for reconversion	82-93% for conversion and c. 80% for reconversion	121	Could unlock global trade potential with a mature industry that has the potential to leverage existing infrastructure	High energy requirement (and therefore lower efficiency) for reconversion, toxicity and air pollution
	Methanol, MeOH	Hydrogen with carbon monoxide (syngas) react to form methanol	◕	NA, GS assumption for similar to ammonia		99	Could unlock global trade potential with a mature industry that has the potential to leverage existing infrastructure	Relatively lower toxicity compared to ammonia
	Liquid organic hydrogen carriers (LOHC)	Mixing with a LOHC such as MCH and convert back to H2	◐	Conversion exothermic, c. 12 for reconversion	c. 65% for reconversion	110	Conversion is exothermic	Low efficiency at reconversion, toxicity, flammability and availability of toluene
	Metal hydrides	Chemical bonding with metals and then reheating back to H2	◐	c. 4	88%	80-100	Higher efficiency than most alternatives	Storage unit can be heavy with long response times and lifetime

Source: Kearney Energy Transition Institute, IEA, Company data, Goldman Sachs Global Investment Research

STORAGE

Figure 4 Hydrogen Storage Options[24]



Hydrogen can be stored in two forms: as a gas or a cryogenic liquid using *physical processes* or in chemically formed compounds using *material-based processes*. Hydrogen is commonly stored using physical processes, which includes the storage of liquid or gaseous hydrogen in tanks or in large-scale geological formations.

---

[24] U.S. Department of Energy, 2020, Department of Energy Hydrogen Program Plan. https://www.hydrogen.energy.gov/pdfs/hydrogen-program-plan-2020.pdf

Gaseous hydrogen storage utilizing pressurized tanks are common storage applications for fuel cell electric vehicles, commercial equipment, hydrogen refueling stations, and stationary power applications. These tanks are commonly constructed entirely from metal or a carbon fiber composite-overwrap. Current research and development efforts are aimed at reducing costs associated with tank materials such as carbon fiber.

Hydrogen can also be stored in a liquid form at extremely low cryogenic temperatures in insulated tanks. The technology used in the design and construction of these tanks has already been commercially adopted for industrial-scale transport and storage applications. Storage at lower temperatures increases the density of hydrogen which lends itself well to usage in applications for medium to heavy-duty vehicles, ships, and trains. Continued research development efforts are needed to improve these systems and address challenges such as boiling off when hydrogen is stored for extended durations.[25]

Beyond tank storage, hydrogen can also be stored on a larger scale in geological formations. Hydrogen gas can be compressed and then injected underground into a geological cavity and released when needed. Salt caverns provide strong options for storage, with tight walls that can hold in hydrogen gas under high pressure. The Chevron Phillips Clemens Terminal in Texas has utilized salt caverns to store hydrogen for its refineries since the 1980s and the United Kingdom currently utilizes three salt caverns for hydrogen storage. In addition to salt caverns, saline aquifers and depleted natural gas or oil fields present other alternatives for long-term and large-scale storage.[26]

SAFETY

Like all fuels, the handling of hydrogen must account for important safety considerations and technology should be designed with safety in mind. In particular, hydrogen gas is flammable and relatively easy to ignite relative to gasoline or natural gas. Consequently, technologies utilizing hydrogen must provide adequate ventilation and leak detection systems. Hydrogen is also nearly invisible when it burns, requiring the inclusion of specialized flame detectors.

Despite these characteristics, hydrogen also has properties that can also make it easier to handle safely and responsibly. Hydrogen is non-toxic and lightweight, allowing it to dissipate quickly when released into the air if there is a leak.[27]

INVESTMENT IN GREENFIELD INFRASTRUCTURE VS. RETROFITTING

A key consideration in the expansion of hydrogen infrastructure will be around whether investments should be made into greenfield infrastructure development or retrofitting existing infrastructure, which depends heavily on assessing the capacity of the technology already in existence. Investment is needed particularly in the pipeline infrastructure used to transport and deliver hydrogen. Key concerns with using

---

[25] U.S. Department of Energy, 2020, Department of Energy Hydrogen Program Plan.https://www.hydrogen.energy.gov/pdfs/hydrogen-program-plan-2020.pdf

[26] Alverà, Marco, 2021, The Hydrogen Revolution

[27] U.S. Office of Energy Efficiency & Renewable Energy, 2022, Safe Use of Hydrogen. https://www.energy.gov/eere/fuelcells/safe-use-hydrogen

existing pipelines include the ability of hydrogen to potentially embrittle the steel and welds used in the pipelines, the need to control for hydrogen leaks, and the need for lower cost, more durable and more reliable hydrogen compression technology.[28]

When retrofitting existing pipeline infrastructure is feasible, this alternative presents a low-cost method of transportation and can save 60-90% of the cost of greenfield pipeline investment. Newly built hydrogen pipelines will require higher upfront capital expenditure than retrofitting, including the necessary network planning permits. The feasibility of retrofitting an existing pipeline depends on a variety of factors including: the quality of the steel used in the pipeline, the diameter and pressure of the pipeline, the pipeline's overall condition, and the existence of cracks.[29] The quality of the pipeline's steel is particularly important as it determines how much damage hydrogen could do to the pipeline. Pipelines composed of softer steel are less vulnerable and better suited to accommodate hydrogen.[30] Many of these factors vary regionally, meaning that some countries have an advantage in their ability to retrofit their infrastructure. For example, the Netherlands has parallel natural gas grid infrastructure that allows for retrofitting pipelines to carry hydrogen while phasing out natural gas gradually.[31] Improvements that can be made to existing pipelines include the use of fiber reinforced polymer (FRP) pipelines. FRP pipeline installation can cost approximately 20% less than steel pipeline installation because FRP can be obtained in longer segments requiring less welding.[32] Other components of the transmission network may also require changes including the need for new compressor stations.[33]

DOWNSTREAM

Today, hydrogen is used mostly in three very specific sectors: oil, refining, and chemicals. The production of hydrogen for use in these sectors exists at large commercial scale but is derived almost entirely from natural gas, coal and oil feedstocks, with the associated environmental impacts. The following table summarizes hydrogen use in industrial applications and its future potential.

---

[28] U.S. Office of Energy Efficiency & Renewable Energy, 2022, Safe Use of Hydrogen. https://www.energy.gov/eere/fuelcells/safe-use-hydrogen
[29] McKinsey & Company, 2021, Hydrogen Insights. https://hydrogencouncil.com/en/hydrogen-insights-2021/
[30] Alverà, Marco, 2021, The Hydrogen Revolution
[31] McKinsey & Company, 2021, Hydrogen Insights.https://hydrogencouncil.com/en/hydrogen-insights-2021/
[32] U.S. Office of Energy Efficiency & Renewable Energy, 2022, Hydrogen Pipelines. https://www.energy.gov/eere/fuelcells/hydrogen-pipelines
[33] Alverà, Marco, 2021, The Hydrogen Revolution

Table 3 Hydrogen Use and Potential in Industrial Applications[34]

Sector	Current Hydrogen Role	2030 Hydrogen Demand	Long-term demand	Low-carbon hydrogen supply	
				Opportunities	Challenges
Oil refining	Used primarily to remove impurities (e.g. sulphur) from crude oil and upgrade heavier crude. Used in smaller volumes for oil sands and biofuels.	7% increase under existing policies. Boosted by tighter pollutant regulations, but moderated by lower oil demand growth.	Highly dependent on future oil demand but likely to remain a large source of demand in 2050, even in a Pariscompatible pathway.	Retrofit natural gas or coalbased hydrogen with CCUS. Replace merchant hydrogen purchases with hydrogen from low-carbon electricity.	Hydrogen production and use is closely integrated within refining operations, making a tough business case for replacing existing capacity. Hydrogen costs strongly influence refining margins.
Chemical Production	Central to ammonia and methanol production, and used in several other smaller-scale chemical processes.	31% increase under existing policies for ammonia and methanol due to economic and population growth.	Hydrogen demand for existing uses set to grow despite materials efficiency (including recycling); new ammonia and methanol demand could arise for clean uses as hydrogen-based fuels.	Retrofit or newbuild hydrogen with CCUS. Use low-carbon hydrogen for ammonia and methanol production (urea and methanol will still require a source of carbon).	Competitiveness of low-carbon hydrogen supplies depends on gas and electricity prices. CCUS retrofitting is not a universal option.
Iron and Steel Production	7% of primary steel production takes place via the direct reduction of iron (DRI) route, which requires hydrogen. The blast furnace route produces byproduct hydrogen as a mixture of gases, which are often used on site.	A doubling under existing policies as the DRI route is used more, relative to the currently dominant blast furnace route.	Steel demand keeps rising, even after accounting for increased materials efficiency. 100% hydrogen-based production could dramatically increase demand for low-carbon hydrogen in the long term.	Retrofit DRI facilities with CCUS. Around 30% of natural gas can be substituted for electrolytic hydrogen in the current DRI route. Fully convert steel plants to utilise hydrogen as the key reducing agent.	All options require higher production costs and/or changes to processes. Direct applications of CCUS are usually projected to have lower costs, although these are highly uncertain. Longterm competition from direct electrification.
High-temperature heat	Virtually no dedicated hydrogen production for generating heat. Some limited use of hydrogencontaining offgases from the iron and steel and chemical sectors.	9% increase in hightemperature heat demand under existing policies. No additional hydrogen use without significant policy support.	Heat demand likely to rise further, providing an opportunity for hydrogen if it can compete on cost in the prevailing policy environment.	Hydrogen from any source could replace natural gas, e.g. in industrial clusters or near hydrogen pipelines. Blends with natural gas are more straightforward but less environmentally beneficial.	Hydrogen expected to compete poorly with biomass and direct CCUS in general, but may prove competitive with direct electrification. Full fuel switches, or CCUS, tend to entail significant investment.

In the energy transition, hydrogen has the long-term potential for many applications beyond existing industrial ones. Transportation, buildings, space heating and power sectors have the potential to use hydrogen if the costs of production and utilization develop favorably relative to other options.

ROAD TRANSPORTATION

The theoretical potential for future use of hydrogen in road transport is very high. Any road transport mode can technically be powered using hydrogen directly via fuel cells (FCEVs). While FCEVs became

---

[34] IEA, 2019, The Future of Hydrogen. https://www.iea.org/reports/the-future-of-hydrogen

commercially available in 2014, registrations remain three orders of magnitude lower than electric vehicles (EVs) as hydrogen refueling stations are not widely available and unlike EVs cannot be charged at home.[35] High hydrogen fuel costs and FCEV purchase prices, mean that these vehicles are less economically viable than EVs in today's markets. However, as costs reduce in the future these may pose viable alternatives especially in the heavy-duty vehicle segment.

In addition to the use of fuel cells, hydrogen can be combined with carbon dioxide to produce synthetic transportation fuels that can in turn be applied to various transportation applications. The use of synthetic fuels allows vehicles to continue using traditional internal combustion engines and existing fueling infrastructure. Hydrogen-formed ammonia can also be utilized in various applications.[36]

As an indication of the size of this market, if all the 1 billion cars, 190 million trucks and 25 million buses currently on the road globally were replaced by FCEVs, hydrogen demand would be as high as 300 million tons H_2 per year, more than four times current global demand for pure hydrogen. The theoretical potential future demand is even larger. Over the next 10 years to 2030, oil demand from road transport is set to grow by 10% without strong action to meet the goals of the Paris Agreement. In particular, this would be driven by demand for trucks in emerging economies, but also rising car ownership. Car ownership in countries like India and even China is well below that of industrialized countries such as the European Union and the United States. For example, US per-capita car ownership is 25 times higher than India's.[37]

FCEVs have better fuel efficiency than internal combustion engine cars with most of the fuel's energy lost primarily as heat in the combustion process. According to the table below, FCEVs are approximately four times as efficient as gasoline cars, which means, given the same amount of input energy, FCEVs end up going four times the distance compared to gasoline cars. This information is particularly valuable when comparing the cost of hydrogen for transportation purposes with other energy sources. By assessing these relative costs to include the outstanding system-wide efficiency of the targeted hydrogen technology like a fuel cell stack, hydrogen is found to be in a more advantageous position compared to other energy sources than if the cost of hydrogen was simply calculated based on input price of energy considered.

Table 4 Comparison of tank-to-wheel efficiencies[38]

Gasoline Cars	16%
Hybrid Cars	40%
Fuel Cell Electric Vehicles (FCEVs)	60%

Notwithstanding the higher efficiencies of FCEVs, the current market demand for emission-free passenger vehicles demonstrably favors EV's with lithium-ion batteries. In the near term, the sub-market for heavy

---

[35] IEA. 2021. Global EV Outlook 2021. https://iea.blob.core.windows.net/assets/ed5f4484-f556-4110-8c5c-4ede8bcba637/GlobalEVOutlook2021.pdf

[36] U.S. Department of Energy, 2020, Department of Energy Hydrogen Program Plan. https://www.hydrogen.energy.gov/pdfs/hydrogen-program-plan-2020.pdf

[37] IEA. 2019. The Future of Hydrogen. https://www.iea.org/reports/the-future-of-hydrogen

[38] H. Yakabe, 2015, Operation of a palladium membrane reformer system for hydrogen production: the case of Tokyo Gas. https://reader.elsevier.com/reader/sd/pii/B9781782422341500140?token=CA199729A46DCB44AF841DD4C1BDA7531E2A2BF04A41989BC7AE6DA20A98CAC3981915C2CF2D516E7CE32BA964531DCD&originRegion=us-east-1&originCreation=20220414001751

haul trucks and buses is a target for hydrogen-linked fuels. Hydrogen has the potential to achieve higher penetration with this submarket in future phases of the energy transition owing to the energy efficiency advantage of fuel cell technology.[39]

AVIATION

Aviation is identified as one of the hardest-to-decarbonize sectors today. According to the IEA, this sector accounted for 2.8% of CO2 emissions in 2019 (pre-pandemic levels). It is also a sector with a high dependence on fossil fuels because jet-fuel is a key component in the cost structure of the aviation industry. There have been some studies during the last years on the feasibility of using hydrogen as the primary fuel for airplanes but these are still in early stages and require more investment in R&D. Hydrogen's low energy density and the need for cryogenic storage would require changes in aircraft design, as well as new infrastructure in the airports. On the other hand, similar to biofuels, the use of hydrogen-based fuels in aviation could be promoted through targets for blend shares.

POWER GENERATION

Hydrogen and hydrogen-based fuels such as ammonia and synthetic natural gas can be fuels for firm power generation. Ammonia can be co-fired in coal-fired power plants to reduce coal usage and reduce the carbon footprint of these plants; if low carbon, it would also reduce overall emissions. Hydrogen and ammonia can also be used as fuels in gas turbines, CCGTs or fuel cells, thus providing a flexible and potentially low-carbon generation option.

Fuel cells produce electricity by combining hydrogen and oxygen atoms. The hydrogen and oxygen react together through an electrochemical process to produce electricity, water, and heat.[40] Fuel cells generate electricity through a chemical reaction rather than combustion and can therefore be more efficient than traditional energy production methods such as steam turbines and internal combustion engines. Fuel cell efficiency can reach 60%, and even exceed 80% when coupled with combined heat and power systems. Fuel cells are very similar to batteries, which both composed of positive and negative electrodes separated by an electrolyte membrane. However, unlike batteries which need to be recharged, fuel cells can run for longer durations as long as fuel and air remain available.[41]

Combustion turbines can combust hydrogen in a similar process to other common fuels such as natural gas and diesel. A major exception, however, is that hydrogen combustion turbines produce water and not carbon dioxide as a major byproduct. However, it can also produce other harmful gases such as nitrous oxide (NOx). Increased focus on the development and improvement of hydrogen combustion turbines is aimed at increasing the amount of hydrogen that can be combusted.[42] The level of hydrogen that can run in a gas turbine depends on the turbine model, combustion model, combustion system, and the overall

---

[39] Ewing, Jack, 2022, Truck Makers Face a Tech Dilemma: Batteries or Hydrogen? https://www.nytimes.com/2022/04/11/business/electric-hydrogen-trucks.html

[40] U.S. Energy Information Administration, 2022, Hydrogen Explained. https://www.eia.gov/energyexplained/hydrogen/use-of-hydrogen.php

[41] U.S. Department of Energy, 2020, Department of Energy Hydrogen Program Plan. https://www.hydrogen.energy.gov/pdfs/hydrogen-program-plan-2020.pdf

[42] U.S. Department of Energy, 2020, Department of Energy Hydrogen Program Plan. https://www.hydrogen.energy.gov/pdfs/hydrogen-program-plan-2020.pdf

amount of fuel consumption.[43] Today, large frame turbines able to fire blends of up to 30% hydrogen with natural gas and aeroderivative turbines able to fire over 90% hydrogen are commercially available. Additional research and development are still needed to address concerns with hydrogen combustion turbines. Notably, when hydrogen concentration in turbines exceeds 75%, there is a significant change in combustion behavior which requires new combustor designs, different sensor locations, and revised control schemes.[44]

ELECTRICITY STORAGE

Hydrogen could play a key role as a storage option in the power generation sector. In the form of compressed gas, ammonia or synthetic methane, hydrogen could become a long-term option to balance seasonal variations in electricity demand and variable generation from renewables. Energy storage is key so that excess renewable generation can be stored for later use when wind and solar production is insufficient to serve power loads, thus providing reliability for the electric grid.

BLENDING

In addition to being used for electricity production on its own, hydrogen can also be blended into existing gas networks to reduce the amount of carbon related to the displaced natural gas. This technology was historically employed worldwide during the Industrial Revolution to accommodate "town gas", a mixture of hydrogen, carbon, and methane, before infrastructure was later converted to accommodate natural gas.[45]

As discussed previously, existing pipeline infrastructure can be sensitive to carrying hydrogen concentrations exceeding a certain level. The degree to which natural gas pipelines can accommodate hydrogen must be assessed on a case-by-case basis and is dependent largely on the quality of steel. The durability of natural gas pipelines under these circumstances poses a constraint on the amount of hydrogen that can be blended into gas networks. However, a report from the National Renewable Energy Laboratory estimates that a less than 15-25% blend of hydrogen would not pose significant risk to end users and could maintain the general safety of existing infrastructure. [46]

Another important consideration with regards to blending is that natural gas transmission pipelines and distribution systems may require very different standards and practices. Depending on the proximity of distribution systems to highly populated areas with frequent hazards such as fires or explosions, these systems may require additional leak detection systems and management practices. The level of hydrogen

---

[43] General Electric, 2022, Hydrogen fueled gas turbines. https://www.ge.com/gas-power/future-of-energy/hydrogen-fueled-gas-turbines

[44] U.S. Department of Energy, 2020, Department of Energy Hydrogen Program Plan. https://www.hydrogen.energy.gov/pdfs/hydrogen-program-plan-2020.pdf

[45] Columbia Center on Global Energy Policy, 2021, Green Hydrogen in a Circular Economy: Opportunities and Limits. https://www.energypolicy.columbia.edu/research/report/green-hydrogen-circular-carbon-economy-opportunities-and-limits

[46] Columbia Center on Global Energy Policy, 2021, Green Hydrogen in a Circular Economy: Opportunities and Limits. https://www.energypolicy.columbia.edu/research/report/green-hydrogen-circular-carbon-economy-opportunities-and-limits

that is acceptable for natural gas transmission pipelines may also need to be adjusted to account for varying risks and conditions specific to distribution systems.[47]

1.4. COST GAP ISSUE

As noted already, the biggest obstacle to the adoption of hydrogen in hard-to-decarbonize sectors would be its high-cost relative to the traditional fossil fuels and the chemical feedstocks derived from fossil fuels. The unit cost of producing blue hydrogen (estimated at $1.5-2.5/kg) is marginally higher than the unit cost of grey hydrogen (estimated at $0.5-2.0/kg) since carbon capture, and storage costs are incremental over the common grey hydrogen equipment and feedstock costs. The estimates of producing green hydrogen presently range to much higher levels: $2.14 -8.52/kg (see figure 5 below), according to a model developed by the Capstone team to forecast the LCOH of green hydrogen. This model (described further below and in the Appendix) captures the key green hydrogen cost drivers: renewable electricity prices, electrolyzer equipment Capex and utilization rates. These cost drivers seem likely to evolve favorably to make green hydrogen more competitive with alternative fuels over time, especially in the near term when intended to displace higher-priced transportation fuels such as diesel fuel and gasoline.

Figure 5 below converts the price ranges for blue and green hydrogen to an energy cost metric equivalent to market costs for natural gas and diesel fuel in the target markets of Europe and Japan in February 2022. Hydrogen (normally priced at $/kg), natural gas (normally priced at $/MMBtu), and diesel fuel (normally priced at $/liter) are all compared according to a common energy unit: gigajoules ($/GJ). At a low heat value of 120 MJ per kg, our model estimates green hydrogen at LCOH prices ranging from $2.14/kg increasing up to $8.52/kg and higher (from table 1 depending on various electricity costs and utilization) has an equivalent energy value range of $17/GJ to $71/GJ. The blue hydrogen with a price of $1.5/kg to $2.5/kg[48] is also converted into their equivalent GJ value.

The lowest production costs for green hydrogen would be in countries with the most favorable wind and solar like Saudi Arabia and Chile while lower cost blue hydrogen would come from countries with cheap gas or coal feedstock like the US or Australia. The cost estimates of importing clean hydrogen to target markets like Japan and Europe vary widely from $0.6/kg to $3.5/kg[49], so for the comparison in Figure 5, a $2/kg average has been added to arrive at a cost-range after transportation to the target markets (the darker-shaded end of the hydrogen cost bars).

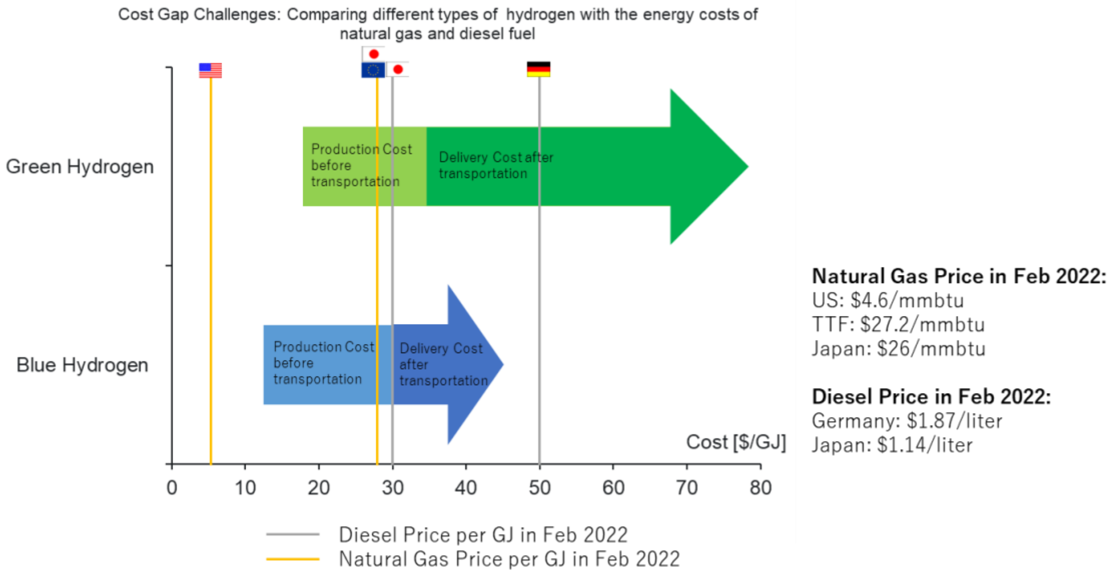
---

[47] National Renewable Energy Laboratory, 2013, Blending Hydrogen into Natural Gas Pipeline Networks: A Review of Key Issues. https://www.nrel.gov/docs/fy13osti/51995.pdf

[48] Goldman Sachs. Carbonomics: The Clean Hydrogen Revolution. February 7, 2022. https://www.goldmansachs.com/insights/pages/carbonomics-the-clean-hydrogen-revolution.html

[49] McKinsey & Company. Hydrogen Insights: A perspective on hydrogen investment, market development and cost competitiveness. https://hydrogencouncil.com/wp-content/uploads/2021/02/Hydrogen-Insights-2021-Report.pdf

Figure 5 Comparison of Hydrogen Costs with Fuel Alternatives[50] [51]



Natural Gas Price in Feb 2022:
US: $4.6/mmbtu
TTF: $27.2/mmbtu
Japan: $26/mmbtu

Diesel Price in Feb 2022:
Germany: $1.87/liter
Japan: $1.14/liter

These price ranges are compared with the average market costs for natural gas and diesel fuel converted to GJs in Japan, Europe and Germany in February 20212. Figure 5 shows how a theoretical estimate for the delivered green hydrogen priced at the lower end of the cost-range ($4.14/kg; $34/GJ) could compete with the price of diesel in Germany as it prevailed in February 2022 ($ 1.87/litre; $49GJ). This estimate for delivered green hydrogen would be only slightly above the February 2022 diesel price in Japan and the natural gas prices in Europe and Japan.

Energy prices in February 2022 were relatively high compared with pre-2020 winters, reflecting the tight energy supplies in 2021-22 and the lead-up to war in Ukraine. While prevailing global security concerns make it hard to label what would be "normalized" prices for competing fossil fuels, the Figure 5 still implies the possibility for green hydrogen to close the cost gap with fossil fuels in targeted markets. Moreover, because the hydrogen industry is in a fast-growing stage with rapid improvements in technologies and the potential for cost reductions, with the help of government policies and incentives, these cost gaps could be reduced or even eliminated in the coming years.

KEY FACTORS TO REDUCE THE COST OF HYDROGEN

The major cost drivers for green hydrogen manufacture are the cost of electricity feedstock from renewable energy and the CAPEX of the electrolyzers – which can, in turn, represent a high embedded capital cost if the electrolyzers are operating at low utilization rates. Since solar and wind generation sources operate when the sun is up and the wind is blowing at capacity factors in the range of 20-30% and 40-60% for the better solar and wind resources respectively, the utilization rate of a manufacturing

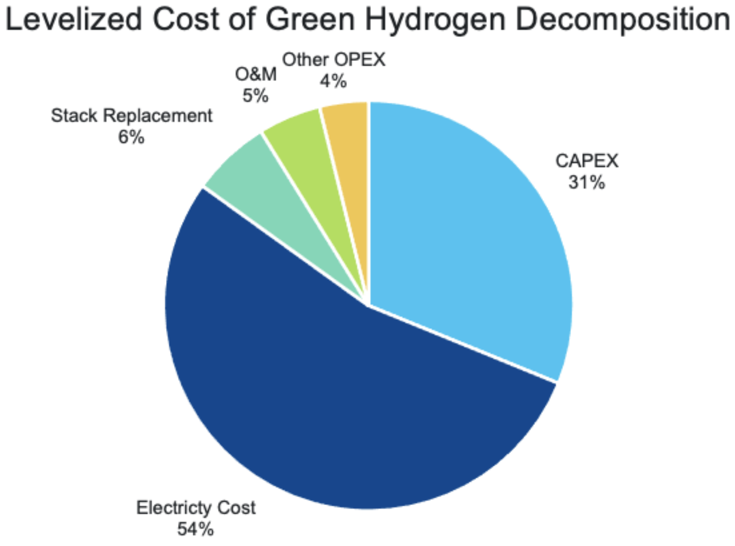
---

[50] Developed by the Columbia SIPA Capstone team based on the data from Goldman Sachs. Carbonomics: The Clean Hydrogen Revolution. February 7, 2022. https://www.goldmansachs.com/insights/pages/carbonomics-the-clean-hydrogen-revolution.html

[51] Natural gas prices here reflect 2022 levels which are abnormally high given the energy crisis in Europe. Natural price is converted at 1 MMBtu=1.05GJ, diesel price is converted at 1 liter=38MJ, hydrogen price is converted at low heat value of 120 MJ per kg

process fed by solar or wind will be limited. Without being powered by a fully decarbonized grid, a green hydrogen manufacturing process powered by solar or wind could be expected to operate at a utilization rate that matched the capacity factor of the renewable energy source: in the range of 30% for the best solar or 60% for the best wind sources; a combined wind and solar electricity source might allow the green hydrogen manufacturing process to achieve a utilization rate above 60%.

Figure 6 Levelized Cost of Green Hydrogen Decomposition[52]



As shown above, the cost of electricity from renewable energy can represent more than 50% of the levelized cost of green hydrogen. The CAPEX of electrolyzers is the second largest cost component at 31% in this example which assumes a 40% utilization rate. Therefore, these key cost drivers will be the primary factors in closing the cost gaps between green hydrogen and other traditional energy sources.

ELECTROLYZER CAPEX

As discussed in Section 1.2, PEM and Alkaline are the two dominant technologies in the electrolyzer market. The left graph below shows that PEM and Alkaline technologies accounted for 92% of the total global installed electrolysis capacity in 2020. Although there are other ongoing technology innovations, PEM and Alkaline will still be the dominant technologies in green hydrogen production.

---

[52] Note: Assumed 20MW capacity Alkaline electrolyzer efficiency at 67% efficiency and 40% utilization rate with project life of 20 years, US$860/kW electrolyzer cost, 10-year stack replacement, $40/MWh electricity cost, with an WACC of 6.37%, developed by Columbia SIPA Capstone Team

Figure 7 Global Electrolysis Capacity (2015-2020)[53]

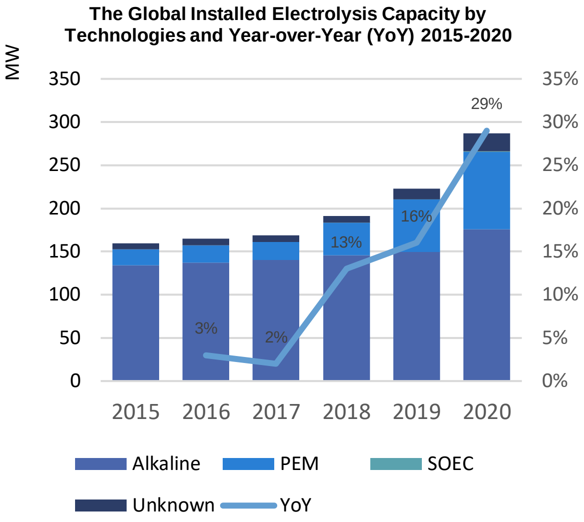
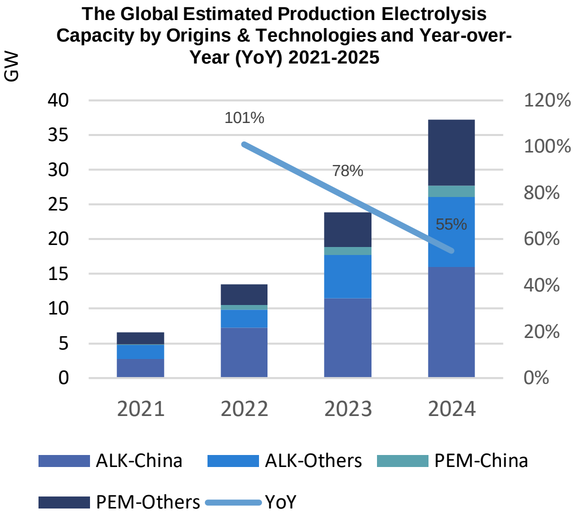


Figure 8 Global Estimated Electrolysis Capacity (2021-2025)



Alkaline is the more mature and lower-cost technology with a cost range of $600 - $1,100/kW.[54] PEM is more expensive, with a cost range of $800- $1270.[55] According to industry experts and other reports, Electrolyzer cost reduction of 50%–70% is achievable throughout the acceleration of deployment and technological innovation for the electrolyzer systems.

As shown in the above graphs, the global installation of electrolysis capacity has been trending upwards over the past five years. Many countries have set incremental installed electrolyzer targets for 2030 with a total of 73GW.[56] This global demand for electrolyzers in the coming years will increase. Major manufacturers of electrolyzers also intend to expand their production capacity, with an average growth rate of 78% in the next three years. Market participants interviewed for this report expect that the rapid price reductions observed for Solar PV during the 2010s might recur with China's electrolyzer manufacturers likely to be able to cut the costs at a faster rate with lower labor costs and larger-sized giga-factories.[57]

Technological innovation could be another critical trigger for cost reduction. For both PEM and Alkaline systems, the cost could be broken into electrolyzer stack components and the remainder of the plant. Balance of plant consists of 55% of the total cost for a 1 MW PEM electrolyzer, but the cost could be quickly reduced by scaling up in plant capacity. On the other hand, the electrolyzer stack consists of 45% of the total cost. Research shows that this component is still overdesigned with great opportunities for cost reduction through technological innovations.[58]

---

[53] Bloomberg NEF Conference and IEA

[54] Goldman Sachs. Carbonomics: The Clean Hydrogen Revolution. February 7, 2022. https://www.goldmansachs.com/insights/pages/carbonomics-the-clean-hydrogen-revolution.html

[55] Goldman Sachs. Carbonomics: The Clean Hydrogen Revolution. February 7, 2022. https://www.goldmansachs.com/insights/pages/carbonomics-the-clean-hydrogen-revolution.html; IEA. Global Hydrogen Review 2021. https://www.iea.org/reports/global-hydrogen-review-2021

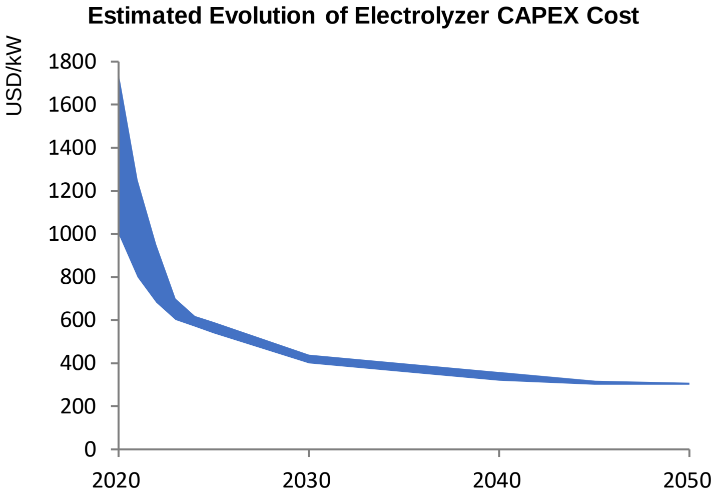
[56] Bloomberg NEF Conference

[57] Bloomberg NEF Conference

[58] IRENA. Green Hydrogen Cost: Scaling up Electrolyzers to meet the 1.5°C Climate Goal. 2020. https://irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Green_hydrogen_cost_2020.pdf

Overall, with the industry's scale-up in deployment and potential for technological innovations, it is expected that the cost of electrolyzers can be decreased by more than 50% by 2030.[59]

Figure 9 Estimated Evolution of Electrolyzer CAPEX Costs[60]



COST OF ELECTRICITY FROM RENEWABLE POWER

As mentioned earlier, the cost of electricity from renewable energy can represent more than 50% of the LCOH of green hydrogen. Over the past decade, the renewable power sectors have experienced a remarkable cost reduction for both wind and solar electricity. As shown in the exhibit below, the global average levelized cost of energy (LCOE) for solar PV has the most noteworthy decrease of 85%, from $0.381/kWh in 2010 to $0.057 in 2020, with a more than 93% reduction in installation costs. The global average LCOE for onshore wind also experienced a 56% reduction in electricity cost from $0.089/kWh to $0.039 in 2020, increasing capacity factors and a 31% reduction in installation costs. The offshore wind experienced a 48% reduction in LCOE from $0.162/kWh to $0.084 in 2020, with also a 40% reduction in installation costs.[61]

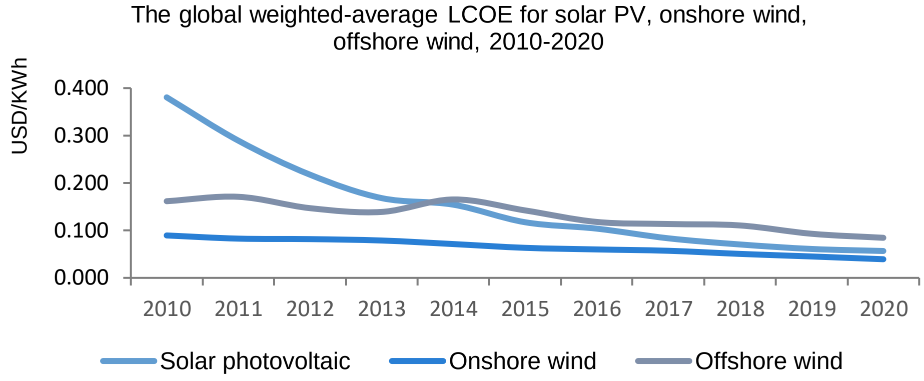
---

[59] Goldman Sachs. Carbonomics: The Clean Hydrogen Revolution. February 7, 2022. https://www.goldmansachs.com/insights/pages/carbonomics-the-clean-hydrogen-revolution.html

[60] IEA Global Hydrogen Review 2021, based on data from announced Pledges and Net Zero Emissions Scenarios

[61] IRENA. Green Hydrogen Cost: Scaling up Electrolyzers to meet the 1.5°C Climate Goal. 2020. https://irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Green_hydrogen_cost_2020.pdf

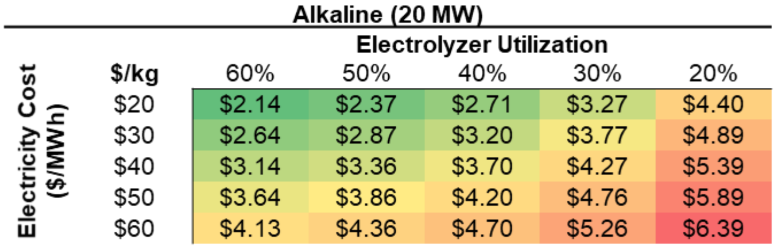
Figure 10 Global weighted average LCOE for solar & wind (2010-2020)[62]



Moreover, the cost of renewable power also varies in different regions, which largely depends on the availability of renewable natural resources and local development in the renewable energy market. Countries such as Spain, Chile, and Saudi Arabia have the best solar resources in terms of irradiance, capacity factors, installation and transmission costs which lead to the lowest renewable power prices. These resources provide a cost advantage in producing green hydrogen, which is highlighted in the country-specific analyses in Part 2 of this report. For example, in April 2021, Saudi Arabia announced the 600 MW PV project at $0.0104/kWh[63], which demonstrates the country's potential to produce green hydrogen at a very competitive price. According to the table generated by the SIPA Capstone team's model for forecasting LCOH values for green hydrogen, an electricity price of $0.0104/kWh combined with the lower cost range of $600 for Alkaline means hydrogen could potentially be produced for as little as $1.75 in Saudi Arabia today.

The table below was generated from the Capstone team’s model for calculating the LCOH of green hydrogen under various combinations of renewable energy input costs and electrolyzer utilization rates. As noted above, a manufacturing process run by wind and solar would likely have limited utilization rates. Lower utilization would increase the allocation of capital costs per unit of production, with higher LCOH values resulting.

Table 5 LCOH Cost Comparison with Alkaline Electrolyzer[64]



Alkaline (20 MW)

		Electrolyzer Utilization				
Electricity Cost ($/MWh)	$/kg	60%	50%	40%	30%	20%
	$20	$2.14	$2.37	$2.71	$3.27	$4.40
	$30	$2.64	$2.87	$3.20	$3.77	$4.89
	$40	$3.14	$3.36	$3.70	$4.27	$5.39
	$50	$3.64	$3.86	$4.20	$4.76	$5.89
	$60	$4.13	$4.36	$4.70	$5.26	$6.39

---

[62] IRENA, 2020

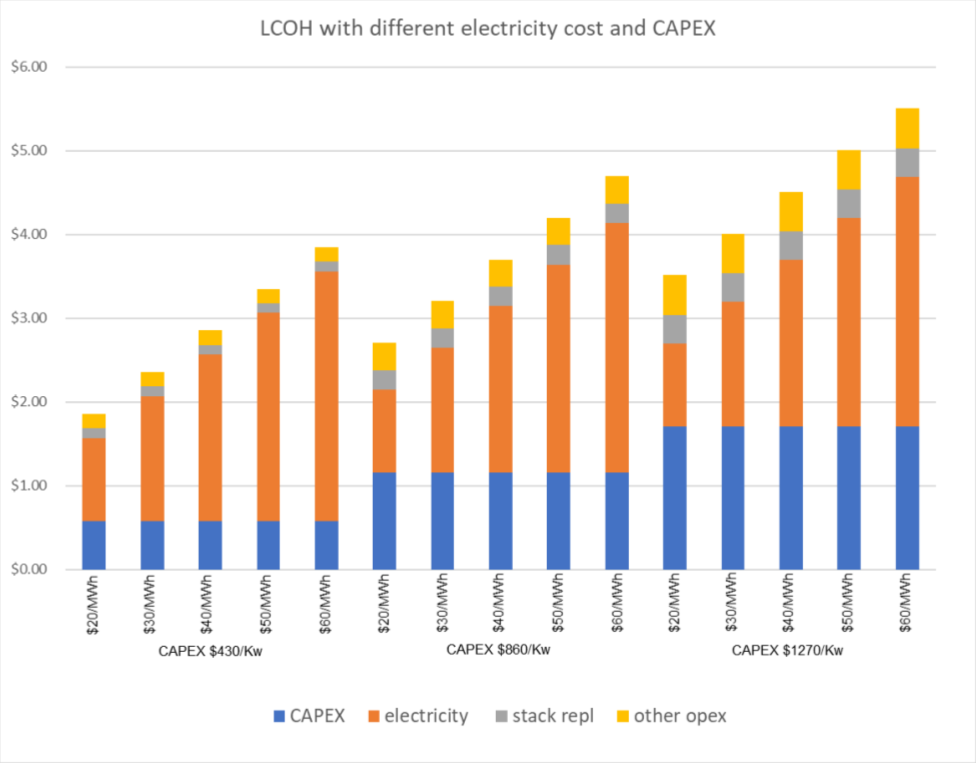
[63] IRENA, 2020

[64] Table based on 20MW alkaline at a CAPEX of $860/kW with 67,500 stack lifetime, assuming 67% efficiency rate, developed by Capstone Team.

The methodology and assumptions driving the model's forecast of LCOH values in the table above, along with forecasted LCOH values under alternative scenarios, are described in greater detail in the Appendix. The table above assumes electrolyzer capital cost of $860/kW.

The below graphs show the impact of various electricity prices and electrolyzer costs on the LOCH modeling alternative scenarios. The cost of electricity plays a crucial role in the final cost of green hydrogen, and together with lower ranges of electrolyzer capex costs, the resulting levelized cost of green hydrogen could vary from $1.85/kg to $5.50/kg in the bar chart below. With the combination of policy and regulatory support and industry drive, the renewable industry achieved a remarkable price reduction over the past decade. The cost of these renewable power might experience a further decrease with economies of scale, improvement in technologies, a reduction in the cost of capital for developments, and a more mature supply chain market.

Figure 11 Impact of Electricity Cost and CAPEX on LCOH[65]



INVESTMENT OPPORTUNITIES TO BE PACED BY EVOLVING HYDROGEN COST

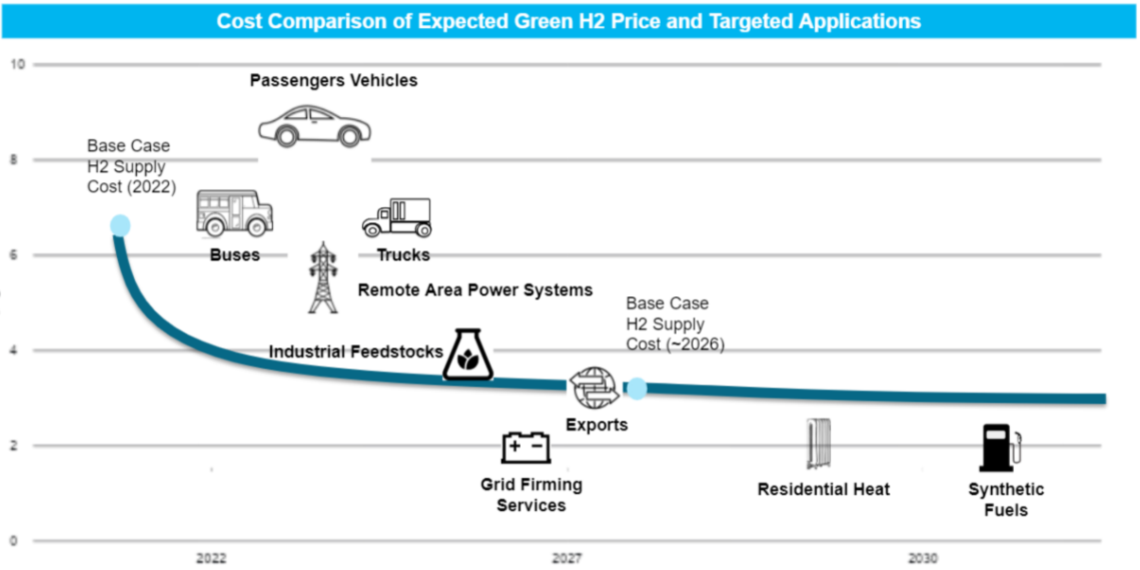
The near-term investment opportunities for hydrogen-linked infrastructure are most likely to be paced by the evolving trend of the cost of hydrogen. With green hydrogen production costs ranging from $6/kg down to the $2kg range with the best solar and wind resources, hydrogen is in a better position to

---

[65] Developed by Columbia SIPA Capstone Team

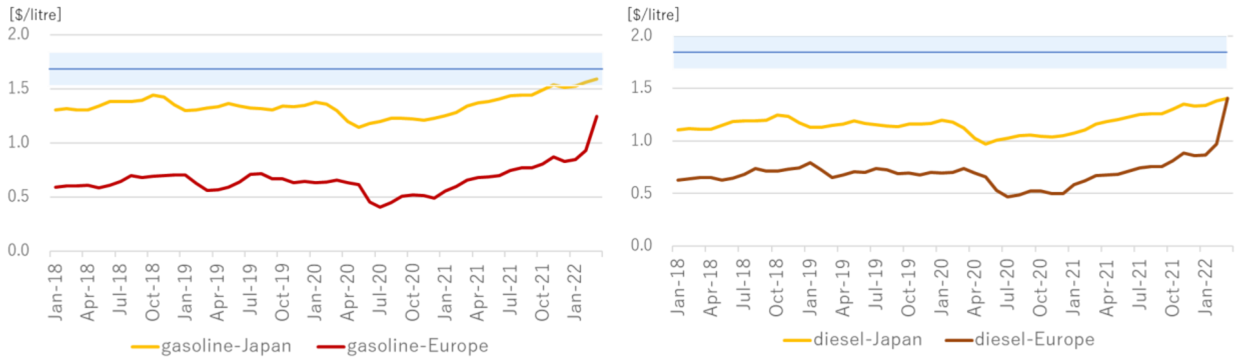
compete with and displace expensive fuels like gasoline and diesel for buses and heavy-haul vehicles. Remote power markets running on diesel fuels may now also be economic for hydrogen-linked power generation. Blue and green hydrogen costs would need to decline toward $2.50-$3/kg delivered-to-market to be competitive for use as an industrial feedstock or to provide grid-firming generation during high demand periods, and perhaps this may happen by 2025-30. Hydrogen pricing needs to drop further into the years beyond 2030 to displace natural gas for home heating and gasoline for vehicles in broad retail markets. The figure below illustrates a possible path for hydrogen applications becoming economic among the different sectors over the long term.

Figure 12 Hydrogen Application and Cost Trends



The case studies in this report demonstrate how the uses for hydrogen in the near term would be as an industrial feedstock for fertilizer and as motor fuels in target importing markets of Europe, Japan and Korea. The price of hydrogen imported from potential exporting countries such as Saudi Arabia or Australia may prevail in the $6/kg range at refueling stations in these target markets. On an energy equivalent basis, the hydrogen priced at $6/kg could equate to $1.67/liter and $1.91/liter, respectively for gasoline and diesel. The figure below shows how this hydrogen-based fuel could be competitive with the recent price evolution of diesel and gasoline in these markets. The above corresponding hydrogen prices are represented by the blue horizontal lines with bands that indicate a hydrogen price range from $5.5/kg to $6.5/kg.

Figure 13 Comparison of hydrogen price with comparable retail gasoline (left) and diesel prices (right)[66]

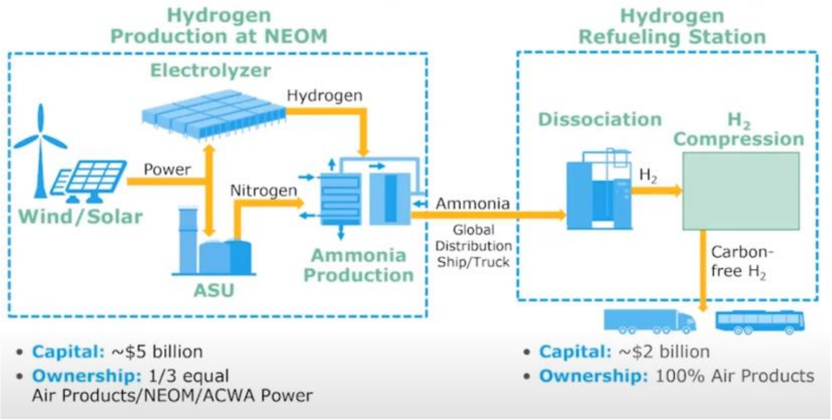


These comparisons of the hydrogen, diesel and gasoline on an energy cost equivalent basis assume the hydrogen may displace fossil-based transportation fuels in vehicles with combustion engines in the near term. As discussed in Section 1.3, vehicles operating on fuel cells would convert the energy from hydrogen fuel into motion at much higher efficiencies. In time the broader adoption of fuel cells over combustion engines in transport vehicles would materially strengthen the economics of hydrogen as a transportation fuel.

1.5. SELECTED CASE STUDIES DEMONSTRATING ECONOMICS OF HYDROGEN PROJECTS

CASE STUDY 1 – PROJECT HELIOS: GREEN HYDROGEN PROJECT IN NEOM, SAUDI ARABIA

Figure 14 Helios Production and Shipment



PROJECT INFORMATION

The Helios project, to be located at the ambitious Neom city development in northwest of Saudi Arabia, is the largest green hydrogen project globally for which investment commitments have been announced. The Helios project was announced in 2020, and the construction will start in May 2022, after clearing the

---

[66] Based on data from the Petroleum Association of Japan and EU Weekly Oil Bulletin.

site.[67] The Helios project is being developed by Air Products, ACWA Power, and NEOM with one-third ownership for each developer. The project will have a dedicated generating capacity of 4 GW from solar PV and wind power and 2000 MW of water electrolysis capacity. It is expected to produce 240,000 million tons of hydrogen per year and the hydrogen will be converted to green ammonia for shipping and exporting to other countries. The possible importing countries from Helios's production are Japan, Korea, and Europe. The hydrogen production capital is approximately $5 billion, and the hydrogen refueling station capital is approximately $2 billion. The earliest announced production date of this project is 2025.[68]

Market sources report that international project finance banks are being asked to commit to finance the project for 25 years. The project's revenue risk is backed by a long-term off-take contract from Air Products, which has A2 credit rating. As reported by industry research, Air Products would remarket the ammonia globally and settle periodically with the project for the difference between market ammonia sales and a contracted "strike price." Lenders are evaluating how Air Products may bear this risk as the market price for ammonia has varied between $225 a ton to $1,000.[69]

Table 6 Summary of Project Helios

Project Name	Project Helios (green hydrogen)
Location	Neom, Saudi Arabia
Equity stakeholders	Air Products, ACWA Power, and NEOM
Power source	Wind and solar PV 4 GW
Hydrogen output	240,000 million tons of hydrogen
Use of hydrogen	Transportation sector; short term (City buses and trucks); long term (operating ships, planes, and trains)
Cost	$5b in hydrogen production; $2b in refueling stations

WHY THE PROJECT ATTRACTS PRIVATE INVESTMENTS

The project serves as one of the initiatives that Saudi Arabia is pursuing to diversify its economy. It has a goal to be the world's biggest exporter of hydrogen, building on its expertise in energy production globally. Therefore, the state supports this project through the Neom company, which is funded by the Public Investment Fund "PIF". The project is financed by 80% debt and 20% equity, with 50% international debt and 50% local debt.[70]

Air Products has multiple roles in the project: the hydrogen and ammonia production, operating refueling stations in target markets, and as an exclusive off-taker of the project output, green ammonia, which it

---

[67] Nereim, Vivian. Saudi Arabia to Start Building Green Hydrogen Plant in Neom. https://www.bloombergquint.com/business/saudi-arabia-to-start-building-green-hydrogen-plant-in-neom

[68] Air Products. Investors Pitch: Carbon-Free Hydrogen: The energy source of the future. https://investors.airproducts.com/static-files/5b14c454-b1d8-44ff-8a21-e65af8d23e2e

[69] PFI. Neom green ammonia PF officially launched. 2022

[70] Nereim, Vivian. Saudi Arabia to Start Building Green Hydrogen Plant in Neom. https://www.bloombergquint.com/business/saudi-arabia-to-start-building-green-hydrogen-plant-in-neom

would distribute globally. For now, the green ammonia will be used in operating trucks and city buses in the short term, and it will be used in operating ships, planes, and trains in the long term.[71] Air Products wants to have a first-mover advantage in a country rich in renewable energy resources.

In addition, Air Products has a strategic goal to eliminate three million tons of carbon dioxide per year, and this project will help in achieving that goal.

ACWA Power is one of the largest power project developers in Saudi Arabia, and it is investing in this project because the company has experience in reducing the cost of renewable energy used in the project. Furthermore, it will benefit from selling power for the project on a long-term basis. Lastly, it has a track record in developing such complex projects.[72]

LIKELY ECONOMICS FOR THE TARGET MARKETS

Until now, there are no publicly disclosed details about the project economics, and there are no end-use customers for the project's output disclosed. A confidential market study for the project may exist, but it is not available to the Capstone team. However, the Capstone team has calculated a rough estimation for the project economics. LCOH in Saudi Arabia estimated by the team's model is at the low-end of the cost spectrum, which is approximately $2.40/kg, assuming 20MW alkaline, 50% electrolyzer utilization, and $20/MWh electricity cost. Based on an interview with Ralph De Hann, Director Business Development Hydrogen and Green Fuels in Neom, the estimated transportation cost is around $40 - $50 per ton ($0.04/kg - $0.06/kg).[73] Apart from the cost of converting hydrogen to green ammonia and back to hydrogen at the refueling stations, the delivered cost will be approximately $2.5/kg. This would have an equivalent cost of in liters $1.55/liter.[74] This is comparable with the prices for diesel which have been elevating over the past two years as figure 13 above demonstrates. In the first quarter of this year, prices of diesel in the announced importing countries vary in the range of $1.4/liter in Japan to $1.6/liter in South Korea.[75]

CASE STUDY 2 – PROJECT CATALINA: CAPTIVE GREEN HYDROGEN IN ARAGON, SPAIN

PROJECT INFORMATION

The second case study presents a green hydrogen captive project, Project Catalina, planned in Aragon of Spain. As hydrogen is an important chemical commodity for producing refined products, ammonia, methanol, and fertilizers, a captive project produces feedstock hydrogen at scale near the production sites for local industrial producers as a key part of their supply chain.

---

[71] Valley, Lehigh. Air Products, ACWA Power and NEOM Sign Agreement for $5 Billion Production Facility in NEOM. https://www.airproducts.com/news-center/2020/07/0707-air-products-agreement-for-green-ammonia-production-facility-for-export-to-hydrogen-market

[72] Almasoudi, Shatha. ACWA Power won't start other hydrogen projects before NEOM venture advanced: CEO. https://www.arabnews.com/node/1926881/business-economy

[73] Mission Hydrogen Conference. Neom: World's Next Hydrogen Supplier. 2022. https://www.youtube.com/watch?v=Jxa3aCiu-Sw&t=55s

[74] 1 kg = 1.613 liter

[75] Global Petrol Prices.

Copenhagen Infrastructure Partners (Denmark), fertilizer producer Fertiberia (Spain), and wind turbines producer Vestas (Denmark) will partner with Spain's national gas grid owner Enagás and gas and electricity utility company Naturgy to develop a green hydrogen and ammonia mega project utilizing renewable energy from the excellent solar and wind resources in the Aragon region, Spain.

Phase 1 of Project Catalina is planned to produce 40,000 tons of green hydrogen per year, utilizing 1.7GW wind and solar PV capacity and 500MW of electrolyzer capacity. Hydrogen from the project will be transported from Aragón to Valencia through a pipeline to produce 200,000 tons of green ammonia per year in a newly built green ammonia plant in Valencia. The green ammonia will be upgraded to fertilizers at the equity investor Fertiberia's existing plant at Sagunto of Valencia. The hydrogen produced can also be used for other local industrial consumption and is planned to be blended into the natural gas grid for industrial use. Catalina Phase I is applying for grid connection in Andorra of Teruel Province at the Mudejar auction.[76]

The phased project is ultimately expected to build-out to 5 GW of combined wind & solar generating capacity with 2 GW of electrolyzers. It will produce around 160,000 tons of green hydrogen per year if fully realized, which will take up 30% of Spain's current hydrogen demand. Phase I is currently in an advanced development stage and is expected to be fully developed and permitted in less than two years from 2022. Construction is planned to start at the end of 2023. Once under operation, the project will make a large contribution to decarbonizing Spain's fertilizer production and agriculture industry. The table below summarizes the project information.

Table 7 Summary of Project Catalina

Project Name	Project Catalina
Location	Aragon, Spain
Equity stakeholders	Copenhagen Infrastructure Partners (CIP), Fertiberia, Vestas, Enagás, Naturgy,
Power source	Phase I: Wind and solar PV with an installed capacity of 1.7GW Planned capacity full-size: Wind and solar PV with an installed capacity of 5GW
Hydrogen output	Phase I: 500MW electrolyzer, 40,000 tons of green hydrogen per year Planned capacity full-size: 2GW electrolyzer, 160,000 tons of green hydrogen per year
Use of hydrogen	The project will connect the hydrogen production site in Aragón with Valencia through a pipeline to produce 200,000 tons of green ammonia per year and then upgrade ammonia to fertilizers at Fertiberia's existing fertilizer plant in Valencia.
Cost	Not publicly disclosed, as of April 14, 2022

---

[76] Copenhagen Infrastructure Partners. Copenhagen Infrastructure Partners announces partnership with Enagás, Naturgy, Fertiberia and Vestas to build a project for the large-scale production of green hydrogen and ammonia in Spain. February 1, 2022. https://cipartners.dk/2022/02/01/copenhagen-infrastructure-partners-announces-partnership-with-enagas-naturgy-fertiberia-and-vestas-to-build-a-project-for-the-large-scale-production-of-green-hydrogen-and-ammonia-in-spain-creating/

WHY THE PROJECT ATTRACTS PRIVATE INVESTMENTS

In general, using green hydrogen as feedstock to produce ammonia and fertilizers would currently be more expensive than using alternative sources such as grey hydrogen from coal and blue hydrogen from natural gas in many markets. Project Catalina has nevertheless been able to attract investors who expect to make profits from the investment for several reasons.

First, Project Catalina will have immediate access to domestic demand. The market for ammonia already exists. The project is very close to the midstream and downstream ammonia and fertilizer industrial production cluster that demands a large quantity of hydrogen. Fertiberia will be the off-taker of green hydrogen as a feedstock of low-carbon fertilizers. The short distance between the hydrogen production project site and the green ammonia demand center also enables the project's use of pipelines for hydrogen transportation, resulting in low cost-estimates for delivering hydrogen: only $0.6-0.8/kg in the case of delivering one million tons of hydrogen per year in a distance of 2500 km, versus cost-estimates of more than $1/kg for marine-transportation of pure hydrogen.[77]

In addition, the quality of solar resources in Spain can drive down the cost of green hydrogen production. According to Reuters, the average award for solar power in Spain's 2021 auction was at €25.31/MWh, with the lowest at €14.89/MWh.[78] The award indicated that LCOE for solar in Spain could be lower than $20/MWh, due to its abundant high-irradiance solar resources. The LCOH estimated using our model of Section 1.4 is at the low end of the cost spectrum, which is $2.37/kg ($17.5/MMBtu) assuming 20MW alkaline, 50% electrolyzer utilization, and $20/MWh electricity cost.

The recent trends for rising natural gas and EU carbon prices increase the competitiveness of ammonia made from green hydrogen. According to the sensitivity analysis by IEA, assuming low electrolyzer costs, the tipping point where green ammonia is cost-competitive could be reached at about $400/t when the natural gas price is higher than $4/MMBtu, the electricity cost is lower than $40/MWh, and when the carbon price is higher than $30/t.[79] Based on the IEA analysis, the price of ammonia produced from green hydrogen by Project Catalina has an optimistic outlook to be competitive, given low renewable energy costs in Spain and the trend of high natural gas and carbon prices in Europe.

LIKELY ECONOMICS FOR THE TARGET MARKETS

Hydrogen is an important chemical commodity for generating ammonia which is a key ingredient for fertilizer production. Project Catalina will mainly function as a captive green hydrogen production project to produce green ammonia as feedstock for Fertiberia's existing fertilizer plants, which is one of the equity investors of the project and a leading company in the fertilizer sector. In such a captive hydrogen project, the economics will be targeted at cost-saving: to lower the cost of feedstock hydrogen and the cost

---

[77] EU Joint Research Center. Assessment of Hydrogen Delivery Options. 2021. https://joint-research-centre.ec.europa.eu/system/files/2021-06/jrc124206_assessment_of_hydrogen_delivery_options.pdf; Also see Goldman Sachs. Carbonomics: The Clean Hydrogen Revolution. February 7, 2022. https://www.goldmansachs.com/insights/pages/carbonomics-the-clean-hydrogen-revolution.html; also see Edison. https://www.edisongroup.com/investment-themes/finding-the-sea-of-green-the-opportunity-and-options-for-shipping-green-h2/

[78] Reuters. Spain's record wind prices fail to curb the rise of solar. March 3, 2021. https://www.reutersevents.com/renewables/wind/spains-record-wind-prices-fail-curb-rise-solar

[79] International Energy Agency (IEA). Ammonia Technology Roadmap. 2021. https://www.iea.org/reports/ammonia-technology-roadmap

transportation of from the hydrogen production site. Up to April 2022, there is no publicly disclosed information about the costs and project economics from the developers. As estimated by the Capstone Team's model in Section 1.4, in Project Catalina, the large amount of hydrogen feedstock demanded can be produced at a low LCOH at \$2.37/kg and transported through pipelines in a distance of 300km at \$0.6-0.8/kg from the hydrogen production site in Aragon to fertilizer plants in Valencia.

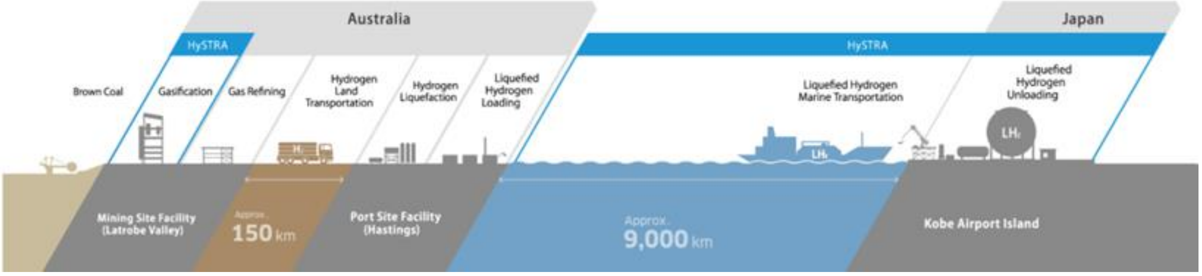
CASE STUDY 3 – HYDROGEN ENERGY SUPPLY CHAIN PROJECT (HESC): BLUE HYDROGEN IN VICTORIA STATE, AUSTRALIA

PROJECT INFORMATION

The third case study is a blue hydrogen project called "Hydrogen Energy Supply Chain (HESC)". The project is located in Victoria State, Australia, and mainly developed by Japanese companies that have the key technologies. This would be the world's first project using a liquid blue hydrogen supply chain across countries via marine transportation. Hydrogen would be produced from coal gasification, combined with a local CCS plan and exported to Japan.

With its energy system heavily dependent on imported fossil fuels, Japan keenly views low-carbon hydrogen as an important driver to decarbonization. While Japan is assumed to become a typical hydrogen importer in the future given its production constraints, Australia benefits from the natural resources for both green and blue hydrogen production and aims to become a major exporter (see *Australia* country analysis in Section 2.2). These two countries have already been economically tied with the export of Australian coal and iron ore and are now trying to determine how their relationship should fit into a carbon-neutral context with hydrogen emerging as a primary focus.

Figure 15 Diagram of HESC Project[80]



The figure above shows an overview of HESC. Coal gasification and hydrogen purification facilities are constructed at Latrobe Valley, an area in Victoria State with abundant brown coal. The produced hydrogen is to be transported to the port of Hastings, where hydrogen liquefaction, storage, and loading facilities are built. Specially built Liquefied hydrogen carrier vessels would be used to transport about 1,000km to Japan, where hydrogen can be directly used as fuel for cars and eventually power generation.

---

[80] HySTRA is the name of the special aggregation entity established by Japanese developers to take responsibility for the demonstration phase.

HESC project is divided into the pilot phase and the commercial phase. While the hydrogen production is without carbon-capture in the current pilot phase, equivalent amount of carbon offsets is purchased by the developer. For the full-fledged commercial phase which is expected to start in the 2030s, HESC plans to collaborate with a CCS plan called "CarbonNet" project, which is now being developed by the federal and local governments. The projected amount of hydrogen production is about 238,500 tons per year.

The developer of HESC is a consortium of Japanese and Australian companies. Notably, the following Japanese companies have key roles:

Kawasaki Heavy Industries, Ltd (KHI): Constructed a liquefied hydrogen carrier and built a liquefied hydrogen cargo handling and mass storage facility, utilizing its cryogenic technology cultivated through the development of LNG carriers and liquified hydrogen tanks for rocket fuel

Electric Power Development Co., Ltd. (J-POWER): Producing hydrogen gas from brown coal using gasification technology cultivated in the coal gasification project in Japan

Iwatani Corporation (Iwatani): Execution of a demonstration project based on expertise in the production, storage, and distribution of liquefied hydrogen

Marubeni Corporation (Marubeni): As a trading house, demand survey and plan for commercialization of liquefied hydrogen supply chain

Sumitomo Corporation (Sumitomo): As a trading house, promotion of CCS commercialization, negotiation with the Australian government, and compilation of local permits and licenses

AGL Energy (AGL), an Australian energy company, also participates in the consortium. Some companies like *Royal Dutch Shell (Shell)* are only involved in the Japanese domestic areas regarding this project. Both Australian and Japanese governments are in support.

The pilot phase of HESC started the operation in 2022 and is expected to take about one year to see if this project can become commercially viable.

The demonstration requires about $375 million investment. Both the Australian and Victorian state governments have provided $50 million, respectively. The Japanese government also assists through the subsidies of the New Energy and Industrial Technology Development Organization (NEDO), a national research and development agency.

The world's first liquid hydrogen carrier called "Suiso Frontier", which was built by KHI, arrived at the port of Hastings on January 21st, 2022, and returned to Kobe port in Japan with its first cargo of hydrogen on February 25th, 2022.

(Left) Liquid Hydrogen carrier "Suiso Frontier", (Right) Ceremony Celebrating the Successful Transportation of Liquefied Hydrogen from Australia to Kobe on April 9, 2022, in which Japan's Prime Minister Kishida gave a speech.[81]

The FID to proceed to a full-fledged commercial phase will be made in the 2020s with the targeted start of operation in the 2030s. Table 8 serves as a summary of the project information.

Table 8 Summary of HESC

Project Name	Hydrogen Energy Supply Chain (blue hydrogen)
Location	Victoria State, Australia
Equity stakeholders	KHI, J-Power, Iwatani, Marubeni, Sumitomo, AGL, and others
Power source	Brown coal at Latrobe Valley
Hydrogen output	238,500 tons per year in a commercial phase in the 2030s (commercial phase)
Use of hydrogen	Mainly exported to Japan in liquified form and used as fuel for cars, heavy transport, power generation, and industry
Cost	$375 million investment (demonstration phase) Not publicly disclosed for the commercial phase
LCOH	Currently around $24/kg, aimed at $3.0/kg in commercial phase (CIF price)

WHY THE PROJECT ATTRACTS PRIVATE INVESTMENTS

This project leverages an abundant cheap fossil fuel, which would otherwise be of limited use, combined with a CCS solution. Brown coal contains very high levels of water and impurities. It is heavy and bulky and has a low calorific value. Besides, it is unsuitable for transportation and storage due to the risk of spontaneous combustion when exposed to air. Yet, this low-grade category accounts for about half of the world's coal reserves, and Australia has brown coal equivalent to several hundred years of Japan's total energy needs.

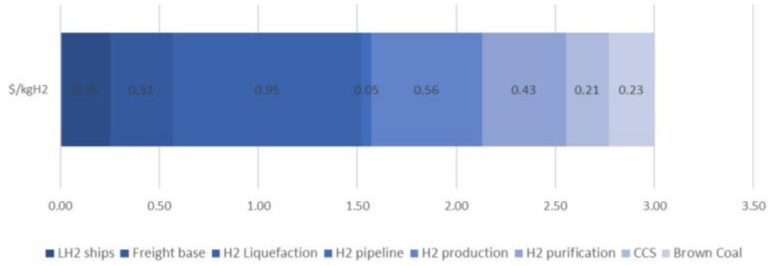
While the cost in the demonstration phase is very high, the hydrogen cost as CIF price at Japan's port in the commercial phase is expected to be down to $3.0/kg. The figure below shows the breakdown of the cost, which includes the estimated CCS cost. The cost of liquefaction at the Australian site accounts for

---

[81] KHI, Prime Minister's Office of Japan

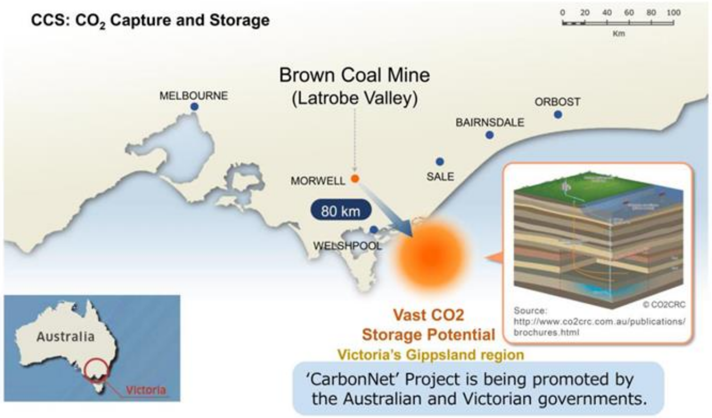
the largest share of the total cost, followed by the cost of hydrogen production through coal gasification. Raw material cost is not so critical.

Figure 16 Breakdown of the Projected Cost of Imported Hydrogen[82]



The project site is proximate to what is expected to be a vast CO2 storage capacity under the seafloor called Gippsland region. Victoria state has developed "CarbonNet" CCS plan together with Australian federal government in that area, and HESC aims to collaborate with this CCS solution in the coming commercial phase. The HESC developers have also made it clear that they won't proceed to a full operation without this CCS option realized.

Figure 17 Overview of CarbonNet Project, a CCS Plan Currently in Development[83]



LIKELY ECONOMICS FOR THE TARGET MARKETS

While some portion of the produced hydrogen may be assigned to domestic use in Australia in the future, the project put a heavy emphasis on exporting to and penetrating Japan's energy market.

Given that the imported hydrogen is to be used mainly as motor fuels, the hydrogen price at refueling stations across Japan is calculated by adding the domestic distribution cost of \$3.0/kg, which is estimated to be almost the same as the CIF price mentioned above. Finally, the price at stations is estimated to be

---

[82] New Energy and Industrial Technology Development Organization of Japan (NEDO)

[83] ERIA. Review of Hydrogen Transport Cost and Its Perspective. 2020. https://www.eria.org/uploads/media/Research-Project-Report/RPR_2020_16/11_Chapter-4-Review-of-Hydrogen-Transport-Cost-_(Liquefied-Hydrogen)_0801.pdf

$6.0/kg, which would have an energy equivalence of $1.67/litre for gasoline and $1.91/litre for diesel respectively and is expected to be highly competitive given the high energy cost in Japan.

Consequently, because HESC is leveraging an efficient use of the abundant unused cheap fossil fuel and high comparable energy costs like gasoline and diesel at the destination, this project is successfully attracting both public and private stakeholders' interests.

HESC is also noteworthy because it is betting on the liquid form of hydrogen as an internationally traded carrier rather than ammonia. The analysis on this point is revisited in the Japan country analysis later in Section 2.2 of this report.

1.6. CONDITIONS TO MITIGATE COST GAPS

As low carbon hydrogen technologies evolve, efforts to accelerate its market adoption need to bridge the cost gap between clean hydrogen and its carbon intensive alternatives. Some universal factors that can contribute towards reducing the cost of hydrogen include economies of scale and optimization of electrolyzer capacity.[84] However, the case studies from Saudi Arabia, Spain and Australia/Japan also demonstrate that regional and policy factors play a key role in making large-scale hydrogen projects commercially viable.

For example, access to affordable solar energy, government support for the hydrogen sector as well as global interest in green hydrogen exports helped make the Helios project in Neom, Saudi Arabia commercially viable. Similarly, the availability of solar energy in Spain, as well as rising carbon prices and high gas prices in the EU help explain the economics of the Catalina project. On the other hand, the HESC project was prompted by high gasoline prices in Japan (an energy demand center) coupled with Japan and Australia's commitment towards exploring hydrogen technologies.

The following Part 2 of this report further highlights regional and policy factors that are driving growth within the hydrogen sector globally and among the hydrogen markets in countries selected through discussions with CACIB. The countries analyzed could present viable opportunities for hydrogen-linked investments based on their particulars regarding regulatory and business priorities and the availability of low-cost renewables and other resources. These include nations with ambitions to become hydrogen producers and exporters as well as those that may require to import large volumes of hydrogen in the near future.

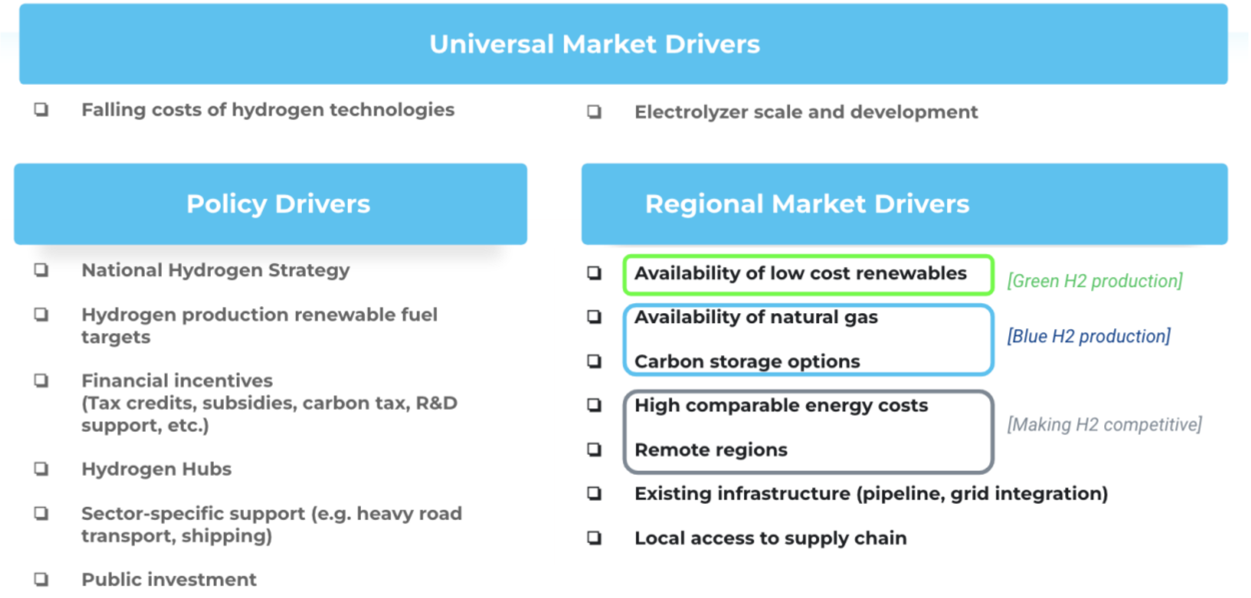
---

[84] IRENA. Green Hydrogen Cost: Scaling up Electrolyzers to meet the 1.5°C Climate Goal. 2020. https://irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Green_hydrogen_cost_2020.pdf

PART 2: COUNTRY-LEVEL ANALYSIS

2.1. CONDITIONS FOR COST-GAP MITIGATION

As discussed previously in this report in Section 1.4, there are several cost barriers to hydrogen adoption in hard-to-decarbonize sectors that must be overcome for the technology to grow globally at scale. Part 2 of this report will identify a matrix of the conditions that will help enable green and blue hydrogen costs to decline and will further assess how these factors are evolving in selected countries that have been identified as markets with strong hydrogen potential. As shown in the figure below, these conditions for cost gap mitigation have been divided between conditions applicable on a global scale: Universal Market Drivers, and conditions that are analyzed on a country-by-country basis: Policy Drivers and Regional Market Drivers.



Universal Market Drivers

☐ Falling costs of hydrogen technologies
☐ Electrolyzer scale and development

Policy Drivers

☐ National Hydrogen Strategy
☐ Hydrogen production renewable fuel targets
☐ Financial incentives (Tax credits, subsidies, carbon tax, R&D support, etc.)
☐ Hydrogen Hubs
☐ Sector-specific support (e.g. heavy road transport, shipping)
☐ Public investment

Regional Market Drivers

☐ Availability of low cost renewables *[Green H2 production]*
☐ Availability of natural gas
☐ Carbon storage options *[Blue H2 production]*
☐ High comparable energy costs
☐ Remote regions *[Making H2 competitive]*
☐ Existing infrastructure (pipeline, grid integration)
☐ Local access to supply chain

UNIVERSAL MARKET DRIVERS

As previously identified in Section 1.4, two important drivers of declining green hydrogen costs are the falling costs of energy from wind and solar and the growth and development of new more cost-effective forms of electrolyzers, an important bottleneck now in green hydrogen production costs. For example, the European Union has announced a 40-gigawatt (GW) electrolyzer capacity target for 2030, a significant increase from less than 0.1 GW today.[85] These conditions are applicable on a global scale and will be vital in making hydrogen more cost-competitive on a large scale.

REGIONAL MARKET DRIVERS

Regional conditions and geographical considerations and priorities would represent critical drivers of the hydrogen industry. These drivers could play a role in determining whether the production and application of hydrogen (across different industries) is economically viable. Such factors would also be key to policymakers establishing hydrogen

---

[85] McKinsey & Company. Hydrogen Insights: A perspective on hydrogen investment, market development and cost competitiveness. https://hydrogencouncil.com/wp-content/uploads/2021/02/Hydrogen-Insights-2021-Report.pdf

centric policies and provisions. This section introduces some of these factors that could impact both the supply side and demand side of the hydrogen sector. These will be discussed in detail in the country analyses.

SUPPLY SIDE:

- *Renewable Resources:* Regions with access to best renewable energy resources are more likely to be able to produce affordable green hydrogen. This is because a large component of the cost of producing hydrogen is driven by the prices of underlying energy inputs.[86] This would also explain how Chile could potentially produce some of the world's cheapest green hydrogen. Since its deserts experience high solar radiation and its wind prone regions have wind projects with the highest capacity factors, Chile's LCOH could drop significantly (as discussed in the coming sections).[87]

- *Availability of natural gas***:** In regions where conventional fuels such as natural gas are abundant and low cost, investments in blue hydrogen are likely to be more commercially viable. However, since carbon capture and storage for blue hydrogen production has its associated costs, government policies are also needed to incentivize early investors in such regions to select blue hydrogen production over gray hydrogen.

- *Access to Carbon capture Storage (CCS):* For power and industry applications where CCS is feasible and CO2 storage is accessible, competitive blue hydrogen costs could fall below USD 1.5 per kg.[88] This would clearly provide a cost advantage to countries with accessible underground geological structures that can be used as carbon storage sites. Captured carbon can be injected into former oil and gas reservoirs, deep saline formations and coal beds. Accordingly, blue hydrogen production is likely to be more viable in countries like Australia and USA with readily accessible geological storage.

- *Existing infrastructure:* Wide-scale adoption of hydrogen would require its transportation through pipelines. At least at the early stages of hydrogen deployment, the presence of gas pipelines that can be used for the transportation of blended hydrogen represents an added advantage to countries that are exploring opportunities to decarbonize the use of natural gas. In the long run however, natural gas pipelines are likely to need retrofits/upgrades.

DEMAND SIDE:

- *Cost of energy:* Regions with high energy costs are more likely to be the earlier markets for hydrogen to displace fossil fuels, especially for applications like transport at first and later for power generation. In such contexts, green or blue hydrogen may present as an economically rational choice. For example, countries like Japan with high transport fuel costs are willing to use hydrogen as a fuel alternative. That being said, policy incentives would remain important to enable a transition. Taking the example of mobility, acquiring a hydrogen FCEV remains more expensive than diesel cars, regardless of fuel prices, and therefore policy support will be critical.

---

[86] Amena Saiyed (IHS Market). 2021. Renewables key to lowering US green hydrogen costs: Hydrogen Council CEO. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Sep/IRENA_Hydrogen_2019.pdf

[87] McKinsey & Company. Hydrogen Insights: A perspective on hydrogen investment, market development and cost competitiveness. https://hydrogencouncil.com/wp-content/uploads/2021/02/Hydrogen-Insights-2021-Report.pdf

[88] Hydrogen Council. 2020. Path to hydrogen competitiveness: A cost perspective. https://hydrogencouncil.com/wp-content/uploads/2020/01/Path-to-Hydrogen-Competitiveness_Full-Study-1.pdf

- Similarly, for island nations like the French Guiana that rely on diesel for power generation, renewables with hydrogen storage to balance intermittency may be a commercially viable alternative (as demonstrated by the CEOG project).[89]

- *Large Industrial Base:* Countries with large hard-to-decarbonize sectors such as steel, other metals, cement, chemicals and fertilizer production, plus transportation and power generation could eventually support large domestic clean hydrogen markets (e.g., United States, UK, China, Germany) or become centers for hydrogen imports (e.g. Japan, South Korea.

POLICY DRIVERS

One important driver for countries in making hydrogen more cost competitive is the presence of a *National Hydrogen Strategy*. These plans are important in outlining a strategy for the country in reaching their hydrogen targets and mobilizing the necessary resources and funding toward meeting these objectives.

In a similar vein, *renewable fuel targets* that include the use of hydrogen are instrumental in encouraging the adoption of hydrogen, particularly in the transportation sector. For example, the European Union has suggested that Member States incorporate low-carbon hydrogen production among their renewable fuel targets. In addition, four European countries – France, Germany, Portugal and Spain – have recently announced industry-specific clean hydrogen consumption targets in their national strategies.[90]

Government support that can help encourage hydrogen adoption can also take the form of *financial incentives*, including the implementation of a carbon tax, hydrogen tax credit, or subsidies for hydrogen technologies.

European Union countries have proposed a carbon dioxide tariff on imports into European Union member countries which is intended to tax aluminum, cement, electricity, fertilizer and steel. The proposal will be discussed and voted on for likely implementation in 2023-2024.[91] While it has not been approved, in the United States the Biden Administration has proposed a hydrogen production tax credit in its recent "Build Back Better" bill which would have granted clean hydrogen producers a choice of production tax credits of up to $3/kg for 10 years or an investment tax credit of up to 30% of the cost of electrolyzers and other hydrogen production equipment.[92] Another important policy driver is the creation of *Hydrogen Hubs*, which are projects to collocate the green or blue hydrogen production with consumption for various end-uses of hydrogen including heat, power, and transportation. The hub projects are valuable in creating clusters of industries that benefit from economies of scale and lower per unit costs through the sharing of infrastructure and avoidance of long-haul transportation costs. Hydrogen Hubs are emerging in Europe, and the United Kingdom in particular has developed a strong network of hydrogen hub projects. In addition to Europe, countries such as the United States have recently passed legislation that provides funding for the development of new regional hydrogen hubs, discussed further in the Section 2.2.

Policy can also play a large role in directing *public investment* into furthering research and development efforts to advance clean hydrogen technologies and drive down costs. Though technologies for hydrogen production,

---

[89] CEOG. 2018. Renewables: a very competitive but intermittent energy. https://www.ceog.fr/operatingprinciples

[90] McKinsey & Company. Hydrogen Insights: A perspective on hydrogen investment, market development and cost competitiveness. https://hydrogencouncil.com/wp-content/uploads/2021/02/Hydrogen-Insights-2021-Report.pdf

[91] DW, 2022, EU backs plan to impose carbon emissions tariff on imports, https://www.dw.com/en/eu-backs-plan-to-impose-carbon-emissions-tariff-on-imports/a-61139117#:~:text=EU%20countries%20voted%20to%20back,EU%20to%20offsett%20carbon%20emissions.

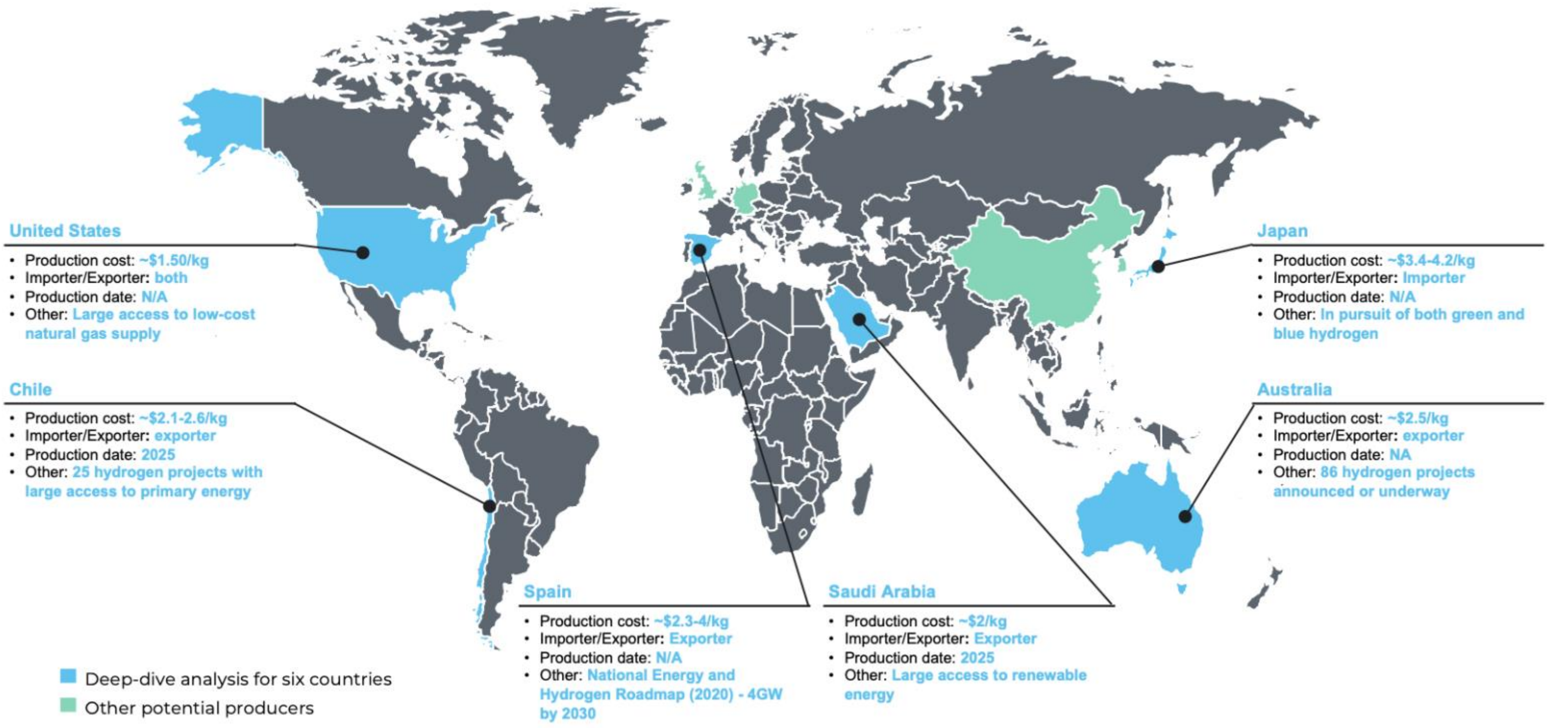
[92] S&P Global, 2021, Hydrogen tax credit would support both blue, green hydrogen, https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/hydrogen-tax-credit-would-support-both-green-blue-production-67404374

transportation, and storage already exist, there is still plenty of opportunity for innovation to improve upon the efficiency of design of these technologies. Areas of R&D research could include[93]:

- Electrolyzers: efficiency; lifetime; manufacturing and installation costs; recyclability; oxygen production.
- Fuel cells: precious metals content; efficiency; recyclability; manufacturing costs; storage tank costs.
- Safety of hydrogen: understanding of implications of new uses; management techniques.
- CCUS and methane pyrolysis: Capture rates > 90%; integrated demonstrations of pre-commercial approaches.
- Storage: solid-state; lightweight tanks; porous media.

GLOBAL OVERVIEW OF HYDROGEN-PRODUCING COUNTRIES HIGHLIGHTED IN THE REPORT

Figure 18 Global Overview of Hydrogen-Producing Countries



United States
- Production cost: ~$1.50/kg
- Importer/Exporter: both
- Production date: N/A
- Other: Large access to low-cost natural gas supply

Chile
- Production cost: ~$2.1-2.6/kg
- Importer/Exporter: exporter
- Production date: 2025
- Other: 25 hydrogen projects with large access to primary energy

Spain
- Production cost: ~$2.3-4/kg
- Importer/Exporter: Exporter
- Production date: N/A
- Other: National Energy and Hydrogen Roadmap (2020) - 4GW by 2030

Saudi Arabia
- Production cost: ~$2/kg
- Importer/Exporter: Exporter
- Production date: 2025
- Other: Large access to renewable energy

Japan
- Production cost: ~$3.4-4.2/kg
- Importer/Exporter: Importer
- Production date: N/A
- Other: In pursuit of both green and blue hydrogen

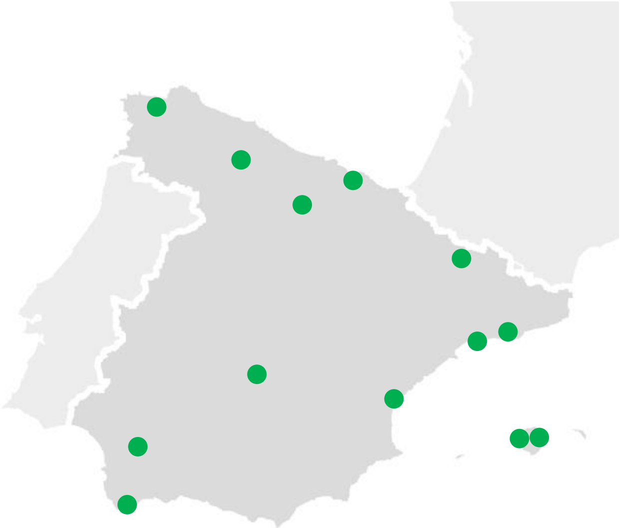
Australia
- Production cost: ~$2.5/kg
- Importer/Exporter: exporter
- Production date: NA
- Other: 86 hydrogen projects announced or underway

🟦 Deep-dive analysis for six countries
🟩 Other potential producers

---

[93] IEA, 2019, The Future of Hydrogen, https://iea.blob.core.windows.net/assets/9e3a3493-b9a6-4b7d-b499-7ca48e357561/The_Future_of_Hydrogen.pdf

SPAIN



Country Statistics

LCOH (Green)	~$2.3 - 4/kg
Solar LCOE	~$15 - 30/MWh
Wind LCOE	~$20 - 60/MWh
LCOH (Blue)	~$2.8 - 3.7/kg
EU LNG IM Price	~$42/MMBtu (March 2022)

National Hydrogen Target

Spain National Energy and Hydrogen

Regional Market Drivers	
Availability of low-cost renewables	✓
Availability of natural gas	X
Carbon storage options	X
High comparable energy cost	✓
Existing infrastructure	✓
Access to market	✓

Policy Drivers	
National hydrogen strategy	✓
Hydrogen fuel targets	✓
Financial incentives	✓
Hydrogen hubs	✓
Public investment	✓
Carbon pricing	✓

COUNTRY-SPECIFIC MARKET DRIVERS

Spain has the potential to lead the green hydrogen economy and value chain among EU member states. The country has a great abundance of renewable energy sources from solar irradiance and wind. According to the study by EU Fuel Cells and Hydrogen Joint Undertaking (FCH JU), Spain's technical variable renewable electricity production potential is ten times more than the expected power demand in 2030.[94] A great advantage exists for Spain's expanding the use of dedicated renewable electricity sources for green hydrogen production.

Spain receives 3.0-3.5 kWh per square meter of solar energy per day, which is about three times the irradiance in Germany and comparable to the levels in southern Italy, Greece, California, and Texas.[95] The estimation of LCOE for solar in Spain is in the range of $15 to 30/MWh.[96] The LCOE of large-scale solar PV has dropped by around 80% globally since 2010 the number is predicted to further decline in the future owing to decreasing costs of equipment and operation expenditures. Spain also has plentiful renewable sources of wind and the world's top manufacturers of wind farm equipment. In 2021, wind power has become the largest source (23%) of electricity production in the country, higher than nuclear (21%) and gas (17%).[97]

Spain's latest power auction revealed that solar was allocated at an average price of $30.5/MWh (€25.31/MWh) with the lowest at $17.87/MWh (€14.89/MWh). The price for power from wind was also secured at an average of $30.5/MWh (€25.31/MWh) with the lowest price at $24/MWh (€20/MWh).[98] Based on the assumption of low LCOE from solar and wind, our model estimates the LCOH in Spain to be competitive at $2.37/kg, assuming $20/MWh electricity cost and 50% electrolyzer utilization of alkaline (20 MW).

In the context of the pandemic and the Ukraine crisis, natural gas prices in Europe are likely to stay high for longer than previously expected. This is further closing the cost gap between green and blue hydrogen and boosting EU countries' demand for alternative sources of energy such as hydrogen. With low LCOE from renewables and competitive LCOH, Spain is in a favored position to become a green hydrogen exporting country. In addition to trading hydrogen in the EU and global markets, Spain will consume hydrogen it produces for captive use. With a well-established domestic industrial base using hydrogen as feedstock, Spain uses 500,000 tons of hydrogen per year in industrial applications, primarily 70% in refineries and 25% in chemicals production.[99] Taking advantage of the access to both external and internal markets, Spain is well-positioned to adapt to a new green economy for export, ammonia, fertilizers, refinery, and transport sectors with renewable hydrogen.

---

[94] The Fuel Cells and Hydrogen Joint Undertaking (FCH JU). Opportunities for Hydrogen Energy Technologies Considering the National Energy & Climate Plans. 2020. https://www.fch.europa.eu/publications/opportunities-hydrogen-energy-technologies-considering-national-energy-climate-plans

[95] Reuters. Key facts about solar power in Spain. March 29, 2011. https://www.reuters.com/article/us-solar-spain-factbox-idUSTRE72S10X20110329

[96] Goldman Sachs. Solar to transform Europe's energy mix. May 2, 2018. https://www.goldmansachs.com/insights/pages/gs-research/nextgen-power/report.pdf

[97] Agence France-Presse. Favourable breezes boost Spain's wind power sector. April 10, 2022.

[98] Reuters. Spain's record wind prices fail to curb the rise of solar. March 3, 2021. https://www.reutersevents.com/renewables/wind/spains-record-wind-prices-fail-curb-rise-solar

[99] National Hydrogen Roadmap of Spain. October 6, 2020. https://energia.gob.es/es-es/Novedades/Documents/hoja_de_ruta_del_hidrogeno.pdf

COUNTRY-SPECIFIC POLICY DRIVERS

Spain announced its *National Hydrogen Roadmap* in October 2020. The roadmap sets the goal to achieve installed capacity of electrolyzers of at least 4 GW by 2030, with a short-term milestone of installing 300-600 MW capacity by 2024. To achieve the goal, the country plans to attract €8.9 billion of private-sector investment and public investment from the EU, national and provincial levels by 2030. The strategy has been echoed by ambitious plans and projects from the regional governments and large companies in the energy industry such as Iberdrola, Endesa, Repsol, Naturgy, and Enagás.

In May 2021, the Spanish government announced to spend €1.5 billion from the European Union recovery fund to develop green hydrogen production by 2024. In December 2021, the government further approved the *Strategic Project for Economic Recovery and Transformation (PETRE)* instrument, a renewable and hydrogen public-private partnership financing tool. Under the instrument, €6.9 billion public funds will be allocated via a competitive tendering process to green energy projects such as heavy-duty transport decarbonization, electrolysis plants, and green hydrogen hubs, of which €1.56 billion is budgeted for renewable hydrogen projects. Most of the funding will be awarded by the end of 2023, aimed at bringing €9.5 billion private investments by 2030.[100]

Up to April 2022, the government has not discussed the exercise of the Contracts for Difference (CfD) schemes for hydrogen in its hydrogen roadmap or other public announcements. In comparison, Germany has launched a CfD scheme under the H2 Global initiative for green hydrogen imports in 2021. UK and Norway also highlight the intent to use CfD schemes to scale up hydrogen production in their national hydrogen strategies. Policy support by the Spanish government through CfD schemes would mitigate the risk and reassure investors of their financial returns while moving from pilot green hydrogen projects towards scale-up in commercial size.

In addition to the policy support from Spain's national hydrogen strategy and public investment, the EU-level policy has been promoting the large-scale deployment of green hydrogen as a key climate mitigation solution. EU sets the goal to reduce greenhouse gas emissions by a minimum of 55% by 2030 and achieve net-zero emissions by 2050. As EU's important instrument for achieving net-zero, the current EU *Emissions Trading System (ETS)* includes power plants, carbon-intensive industries, and intra-EU aviation. In July 2021, the European Commission proposed to add the road transport and construction sectors to the ETS. In February 2022, the EU carbon price hits the €97.50/t milestone and remains above €75/t as of early April 2022. Spain faces substantial internal demand for clean alternatives from power, heating, and emission-intensive industries due to EU's regulatory pressure to decarbonize. On the hydrogen supply side, the high carbon price can mitigate the cost gap between green and blue hydrogen production. On the demand side, it provides incentives for the transport, iron and steel, and refinery industries to adopt green hydrogen as low-carbon feedstock. According to FCH JU, 45% of Spain's industry energy consumption is for generating heat for high-temperature processes. Green hydrogen can serve as a good alternative to the carbon-intensive energy carriers for meeting the EU's industrial decarbonization goals.

---

[100] RenewablesNow. Spanish govt approves public-private funding tool for green energy transition. December 15, 2021. https://renewablesnow.com/news/spanish-govt-approves-public-private-funding-tool-for-green-energy-transition-765784/

While the EU has initiated both technical and financial efforts for its member states in developing green hydrogen for fighting against climate change and assuring energy security, a clear hydrogen terminology has not been established at the EU level. The certification and verification policy for clean hydrogen and its derivatives is absent at the current stage. It also lacks a regulatory framework for using hydrogen as a combustion gas in the end-use application of the supply chain such as steel production. Establishing a comprehensive and clear hydrogen terminology and regulatory framework would be beneficial for the full development of hydrogen and its applications in the member states.

INFRASTRUCTURE DEVELOPMENT

Spain's existing pipeline infrastructure could be utilized for the country's inland hydrogen domestic transportation. 84% of Spain's distribution grid is made of polyethylene pipelines.[101] Since Spain's existing pipeline infrastructure can be used for hydrogen transport and distribution - by blending hydrogen into the public grid without physical adjustments to the transport and end-use infrastructure - it is technically and economically more feasibility. In the long-term, transforming this transportation network partially to hydrogen could be at a relatively low cost, due to the high proportion of polyethylene pipelines in the distribution grid. Spain also has the advantage of retrofitting or developing hydrogen storage infrastructure. It has two operating underground gas storage facilities for natural gas and abundant natural underground salt layers that could be developed for gas storage.

EMERGING BUSINESS OPPORTUNITIES FOR FINANCIAL PLAYERS

According to IEA's hydrogen project database, the recent projects announced in Spain are mostly green hydrogen production projects from solar and wind sources (*Table 9*).[102] The hydrogen produced by these projects is planned for the end-use in ammonia, mobility, grid injection, synfuels, and iron and steel production. Among these, Phase II of the two large-scale projects by Fertiberia and Iberdrola will each build over 200MW electrolyzer capacity to produce green ammonia.

Summarizing for the near future of 2030, Spain's hydrogen investment opportunities can emerge from renewable hydrogen production projects, hydrogen carriers' production and dissociation facilities (e.g., ammonia), hydrogen-in-end-use production (e.g., refineries, fertilizers, iron and steel), and integrated hydrogen hubs covering the full hydrogen value chain from production, transportation, and end-use.

In the long term beyond 2040, with a vision that the drop in green hydrogen production costs would allow it to be deployed at scale for power generation, heating, and mobility, investment opportunities could arise in retrofitting existing infrastructure or developing greenfield infrastructure for hydrogen distribution, storage, and refueling at a large scale.

---

[101] FCH JU, Opportunities for Hydrogen Energy Technologies, 2020.

[102] International Energy Agency (IEA). Hydrogen Projects Database. October 4, 2021. https://www.iea.org/data-and-statistics/data-product/hydrogen-projects-database

Table 9 List of recent hydrogen projects announced in Spain[103]

Project name	Expected date online	Status	Energy source	Product	End-use	Announced Size	Normalized capacity (kt H2/year)
Power to Green H2 Mallorca (GREEN HYSLAND) - Phase 2	2022	FID	Renewable-Solar PV	H2	Mobility, grid injection	7.5 MW	1.3
SoHyCal	2022	Under construction	Renewable-Solar PV	H2	Mobility	7.5MW	1
BP Castellon refinery	2023	Feasibility study	Renewable-Solar PV	H2	Not announced	20MW	3
Compostilla - Endesa	2023	Feasibility study	Renewable-Solar PV	H2	Not announced	4MW	1
Fertiberia/Iberdrola - Palos de la Frontera I	2023	Feasibility study	Renewable-Solar PV	Ammonia	Ammonia	Phase I-230MW	40
Hidrogeno El Cierzo	2023	Feasibility study	Renewable-Onshore wind	H2	Not announced	7.2MW	1
Hysencia, Phase I	2023	Feasibility study	Renewable-Solar PV	H2	Mobility	40MW	7
Repsol advanced biofuels plant Cartagena	2023	FID	Renewable-photoelectrocatalysis	H2	Biofuels	Not announced in public sources	Not announced in public sources
Alcudia - Endesa	2024	Feasibility study	Renewable-Solar PV	H2	Not announced	8MW	1
Almeria - Endesa	2024	Feasibility study	Renewable-Solar PV	H2	Not announced	20MW	3
Huelva - Endesa	2024	Feasibility study	Renewable-Solar PV	H2	Not announced	100MW	17
ORANGE.BAT Castellon	2024	Feasibility study	Renewable-Not announced in public sources	H2	Not announced	100MW	17
Repsol Bilbao port synfuels project	2024	FID	Renewable-Not announced in public sources	Synfuels	Synfuels	10MW	2
Seseña - Endesa	2024	Feasibility study	Renewable-Solar PV	H2	Not announced	4MW	1
Tarragona - Endesa	2024	Feasibility study	Renewable-Solar PV	H2	Not announced	20MW	3
Teruel - Endesa	2024	Feasibility study	Renewable-Not announced in public sources	H2	Not announced	60MW	10
ArcelorMittal DRI Gijon	2025	Feasibility study	Renewable-Solar PV	H2	Iron & Steel	2.3 million tons green hydrogen direct reduced iron (DRI)	Not announced in public sources
As Pontes power plant	2025	Feasibility study	Renewable-Onshore wind	H2	Not announced	100MW	17
Barranco de Tirajana - Endesa	2025	Feasibility study	Renewable-Solar PV	H2	Not announced	7MW	1
Fertiberia/Iberdrola - Puertollano II	2025	Feasibility study	Renewable-Solar PV	Ammonia	Ammonia	Phase I-20MW, Phase II-210MW	36
Granadilla - Endesa	2025	Feasibility study	Renewable-Not announced in public sources	H2	Not announced	10MW	2
Fertiberia/Iberdrola - Palos de la Frontera II	2027	Feasibility study	Renewable-Solar PV	Ammonia	Ammonia	Phase II-370MW	64

---

[103] Source: International Energy Agency (IEA). Hydrogen Projects Database. https://www.iea.org/data-and-statistics/data-product/hydrogen-projects-database

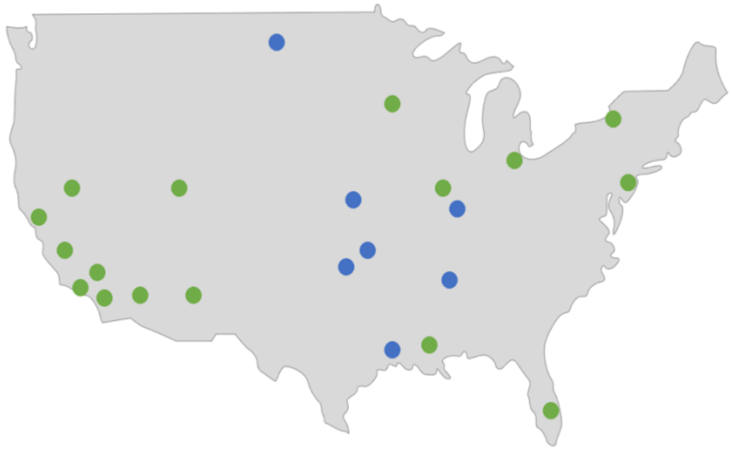
SHYNE (Spanish Hydrogen Network)

SHYNE (Spanish Hydrogen Network) is the largest consortium planned in Spain that incorporates the full hydrogen value chain from production, transport and end-use. The integrated multi-sectoral hydrogen hub is led by Repsol, Spanish petroleum company, and six other companies including Alsa, Bosch, Celsa, Enagas, Scania, and Talgo, along with 26 partners from public and private sectors. The consortium will construct projects in ten locations. It is aimed to reach an installed capacity of 500 MW in 2025 and 2 GW in 2030, meeting half of the 2030 target set in the National Hydrogen Roadmap by the Spanish Government. SHYNE projects will involve a total investment of €3.23 billion. The SHYNE project has an ambition to connect large regional hydrogen hubs already under planning in Basque, Catalonia, and Murcia. The initiative will also invest in developing and experimenting photo-electrocatalysis and solid oxide electrolysis technologies for low-carbon hydrogen production.

SHYNE
Spanish Hydrogen Network

Source: Repsol. SHYNE, the largest consortium to promote renewable hydrogen in Spain, is born. January 19, 2022. https://www.repsol.com/en/press-room/press-releases/2022/shyne-largest-consortium-to-promote-renewable-hydrogen-in-spain-is-born/index.cshtml

United States



Country Statistics

LCOH (Green)	~$5.20/kg
Solar LCOE	~$34.59/MWh
Wind LCOE	~$35.19/MWh
LCOH (Blue)	~$1.5/kg
Gas Price (HH)	~$2.57/MMBtu

Regional Market Drivers	
Availability of low-cost renewables	✓
Availability of natural gas	✓
Carbon storage options	✓
High comparable energy cost	X
Existing infrastructure	X
Access to market	✓

Policy Drivers	
National hydrogen strategy	X
Hydrogen fuel targets	✓
Financial incentives	✓
Hydrogen hubs	X
Public investment	~ $9.9 bn
Carbon pricing	X

COUNTRY-SPECIFIC MARKET DRIVERS

The hydrogen market in the United States, while in its early stages, is growing and promising. According to the National Renewable Energy Laboratory (NREL), demand for hydrogen in the United States could rise to 41 million tons per year by 2050, a four-fold increase compared with current demand.[104] 95% of current hydrogen demand in the U.S. is to be used as a feedstock or reactant in industrial processes for applications in refining, ammonia, and methanol.[105] Gas companies in the U.S. have been constructing grey hydrogen production facilities at or near refineries to meet hydrogen demand for these plants.[106]

---

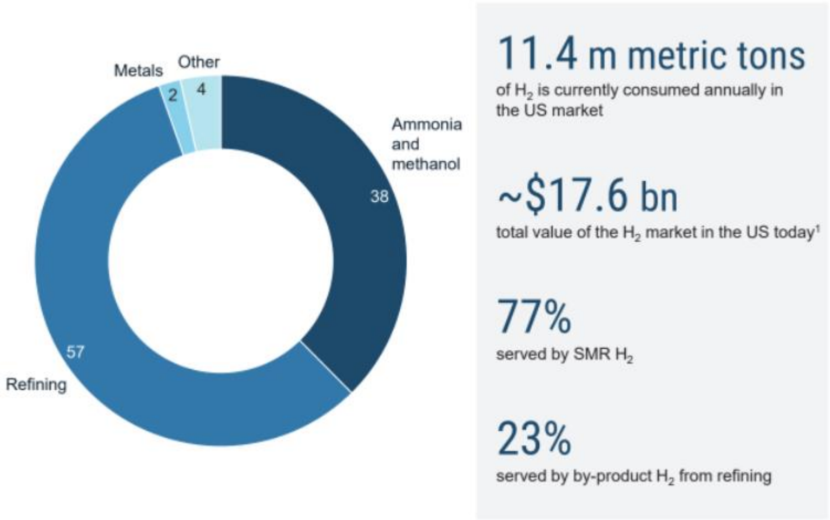
[104] IHS Markit, 2020, US demand for hydrogen may quadruple by 2050: NREL, https://cleanenergynews.ihsmarkit.com/research-analysis/us-demand-for-hydrogen-may-quadruple-by-2050-nrel.html

[105] CMS, 2021, Facing the Future of Hydrogen: An International Guide, https://cms.law/en/media/expert-guides/files-for-expert-guides/the-promise-of-hydrogen-an-international-guide-nov-2021

[106] Department of Energy, 2019, DOE Hydrogen and Fuel Cells Program Record, https://www.hydrogen.energy.gov/program_records.html

Increasingly, hydrogen is also being used for transportation.[107] Approximately 11.4 million tons per year of hydrogen is currently consumed in the U.S. It is expected that the demand for hydrogen in these sectors will continue to grow with the need for heavier crude oils and increasing fertilizer demand among other applications.

Figure 19 Current U.S. Hydrogen Market[108]



The market for hydrogen in the United States is characterized in particular by the country's access to a strong domestic supply of low-cost natural gas, owed to the hydraulic fracturing fracking boom of the recent decade. While this resource has thus far been the feedstock for grey hydrogen it also positions the United States to become a domestic producer and consumer of blue hydrogen using steam methane formation coupled with carbon capture and storage. According to an interview conducted for this report, there is significant appetite from the oil and gas sector in the United States to develop blue and green hydrogen opportunities to align their business models with the energy transition. Currently, only about 0.25 mtpa worth of complete blue hydrogen capacity exists in the U.S., with an additional >0.1 mtpa in the feasibility study stage. Several green hydrogen projects have also been announced due to the presence of relatively low-cost renewable resources in the United States. However, green hydrogen production is even less developed with approximately 0.2 mtpa of production capacity in the feasibility stage.[109]

The cost gap between hydrogen and traditional energy sources is still a challenge in the United States. A 2020 study conducted by the Massachusetts Institute of Technology (MIT), found that green hydrogen production from electrolysis generated by solar power could reach a price of $2.50/kg by 2030 in certain

---

[107] Fuel Cell & Hydrogen Energy Association, 2019, Road Map to a US Hydrogen Economy, https://cafcp.org/sites/default/files/Road+Map+to+a+US+Hydrogen+Economy+Full+Report.pdf

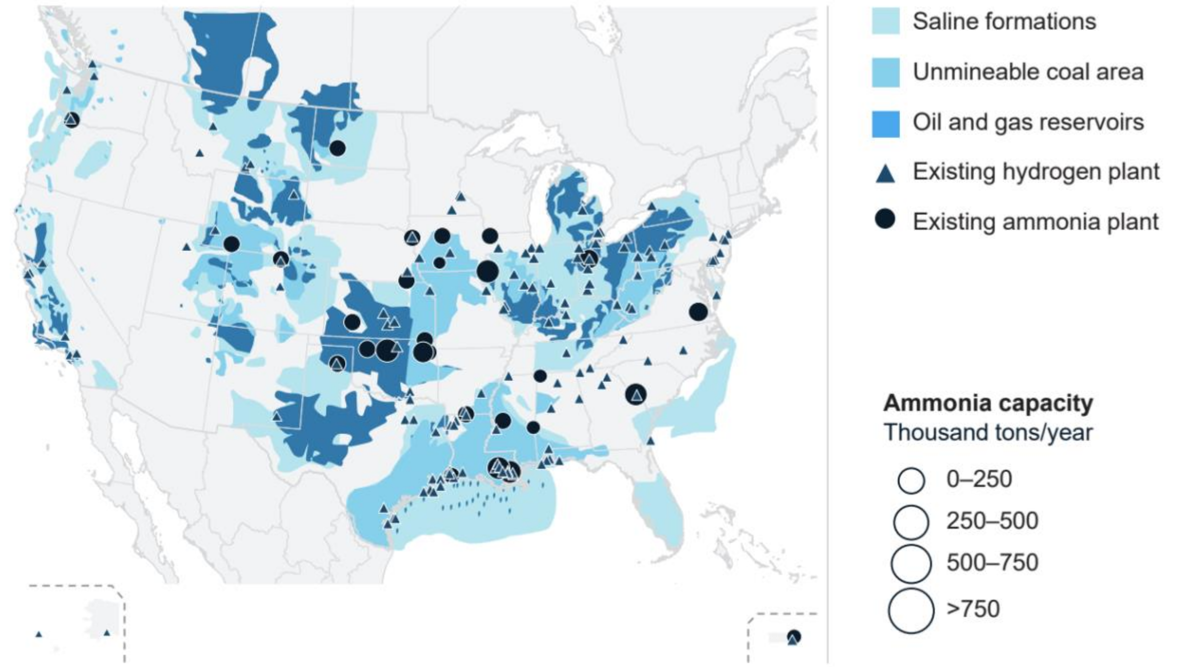
[108] Fuel Cell & Hydrogen Energy Association, 2019, Road Map to a US Hydrogen Economy, https://cafcp.org/sites/default/files/Road+Map+to+a+US+Hydrogen+Economy+Full+Report.pdf

[109] Hydrogen Central, 2021, GlobalData – Low-Carbon Hydrogen Production in North America to Nearly Triple by 2030, Reaching 1.4 Million tpa https://hydrogen-central.com/globaldata-hydrogen-production-america-triple-2030-1-4-million-tpa/

states with very strong solar resources.[110] This would be a significant decrease from the current LCOH of green hydrogen of approximately $5.20/kg in the U.S. The study also predicts a price of blue hydrogen generated from natural gas using CCS to be approximately $1/kg[111], declining from its current estimate of $1.5/kg.

Blue hydrogen production would also be aided by the United States' underground geological storage capacity for the carbon capture and storage required in the blue hydrogen production process. The storage capacity in United States is estimated to be around 3,000 mGt of greenhouse gas emissions, which is equivalent to approximately 600 years' worth of the current level of the country's total emissions.[112] This storage capacity can be found in the form of salt caverns, coal areas and oil and gas reservoirs, shown geographically in the map below. The Gulf Coast region in the U.S. in particular has strong storage potential.

Figure 20 CCS Locations in the United States



Source: Gary F. Teletzke, *Evaluation of Practicable Subsurface CO_2 Storage Capacity and Potential CO_2 Transportation Networks, Onshore North America*, 14th Greenhouse Gas Control Technologies Conference, Melbourne, October 21–26, 2018 (GHGT-14).

The United States currently hosts more than 2,575 kilometers (1,600 miles) of dedicated hydrogen transmission pipelines, the majority of which are on the Gulf Coast and used to service hydrogen

---

[110] Mallaprangada, Dharik Sanchan, 2020, Can Industrial-Scale Solar Hydrogen Supplied from Commodity Technologies Be Cost Competitive by 2030?, https://www.cell.com/cell-reports-physical-science/pdf/S2666-3864(20)30185-5.pdf https://www.cell.com/cell-reports-physical-science/pdf/S2666-3864(20)30185-5.pdf

[111] Mallaprangada, Dharik Sanchan, 2020, Can Industrial-Scale Solar Hydrogen Supplied from Commodity Technologies Be Cost Competitive by 2030?, https://www.cell.com/cell-reports-physical-science/pdf/S2666-3864(20)30185-5.pdf

[112] Fuel Cell & Hydrogen Energy Association, 2019, Road Map to a US Hydrogen Economy, https://cafcp.org/sites/default/files/Road+Map+to+a+US+Hydrogen+Economy+Full+Report.pdf

demand from refineries. Hydrogen expansion in the U.S. will require significant modifications to additional pipeline infrastructure to accommodate hydrogen.

COUNTRY-SPECIFIC POLICY DRIVERS

The Biden Administration has made growing the hydrogen market in the U.S. a priority in its energy transition agenda. While it's notable that the United States does not currently have a National Hydrogen Strategy, the recent Infrastructure Bill passed in November 2021 outlines several near and long-term steps that country is taking toward investing in the domestic hydrogen market and provides $9.5 billion in funding toward hydrogen development. Of this funding, $8 billion has been allocated toward the development of at least four Regional Clean Hydrogen Hubs that will co-locate areas with strong hydrogen production potential with end-user demand. The expectation is that these hubs will create commercial entities in the long-term that will in turn create more co-located projects.[113] In addition, the law has allocated $1.5 billion toward hydrogen R&D efforts with the goal of driving down costs associated with hydrogen technology, this includes $1 billion for a Clean Hydrogen Electrolysis Program to reduce production costs associated with electrolyzer technology and $500 million for Clean Hydrogen Manufacturing and Recycling Initiatives to support equipment manufacturing. The law also calls on the federal government to draft a national hydrogen roadmap and strategy for the country.[114]

In addition to the new federal funding allocated in the *Infrastructure Law*, the Department of Energy has implemented a Hydrogen Program. In July 2021, the Department of Energy announced $52.5 million in funding for 31 projects to further the development of clean hydrogen technologies. This investment is also in support of the federal government's *Hydrogen Energy Earthshot* program which seeks to reduce the cost of clean hydrogen by 80% to $1/kg in 1 decade. The Department of Energy's allocation for hydrogen funding in the President's FY 2022 Budget Request for 2022 was $400 million, representing a significant increase from approximately $285 million in FY 2021. All these efforts signify an increasing push toward hydrogen investment in the policy landscape.

In addition to its recent public investment in hydrogen innovation and opportunities, the United States has implemented incentives such as the *Federal 45Q Tax Credit*. This incentive provides a tax credit for the geological sequestration of carbon dioxide emissions via oil recovery ($35 per metric ton of CO2) or storage ($50 per metric ton of CO2). This credit provides an added incentive to blue hydrogen production in the United States. However, it is expected that the current size of the incentive will only generate a relatively small number of CCS projects.[115]

Along with the federal programs and initiatives that have recently been enacted, some states have individually passed legislation that encourages the growth and uptake of hydrogen technologies.

---

[113] DOE Interview

[114] Department of Energy, 2022, DOE Establishes Bipartisan Infrastructure Law's $9.5 Billion Clean Hydrogen Initiatives, https://www.energy.gov/articles/doe-establishes-bipartisan-infrastructure-laws-95-billion-clean-hydrogen-initiatives#:~:text=The%20Bipartisan%20Infrastructure%20Law%20includes,and%20%24500%20million%20for%20Clean

[115] CMS, 2021, Facing the Future of Hydrogen: An International Guide, https://cms.law/en/media/expert-guides/files-for-expert-guides/the-promise-of-hydrogen-an-international-guide-nov-2021https://cms.law/en/media/expert-guides/files-for-expert-guides/the-promise-of-hydrogen-an-international-guide-nov-2021

California's *Low-Carbon Fuel Standard (LCFS)*, enacted in 2011, supports low carbon fuels including hydrogen by creating a market for tradeable credits. The U.S. is one of the leading countries in the FCEV adoption, with over 9,000 vehicles currently in use, accounting for approximately 25% of global FCEV adoption.[116] California is one of the states that are leading this charge, with the majority of U.S. FCEVs and hydrogen refueling stations in use within the state.[117]

INFRASTRUCTURE DEVELOPMENT

Currently the majority of production and activity is located on-site or close to its end-use.[118] One major shift needed in the United States if the country is going to rely more heavily on hydrogen use in the future is investment into the pipeline infrastructure to transport hydrogen longer distances. Based on the current gas infrastructure in the United States, blending levels should be safe within a range of 4% to 5% by volume.[119]

The pipes used in gas distribution systems in the United States are primarily made of relatively low strength steel, typically API 5L A, B, X42 and X46, which operate under lower pressures than transmission pipelines and are less susceptible to hydrogen embrittlement. Transmission pipelines operate under higher pressures and are more susceptible to higher stress and durability risks when carrying hydrogen. Approximately 95% of transmission pipelines are composed of steel, however, the steel used for transmission now is very different from what will be needed for 100% dedicated hydrogen use. Transitioning the current pipeline infrastructure in the U.S. to accommodate higher concentrations of hydrogen will require investment into retrofitting or greenfield infrastructure. The comparative costs of both will vary geographically and, on a case-by-case basis as discussed in Section 1.3.

Beyond investment, updating the pipeline infrastructure to accommodate hydrogen use will require heavy compliance and review from utilities and pipeline operators (i.e., engineering assessments) to assess pipeline integrity and comply with regulations. Calibrating and updating pipelines for a different blend will require changes in operating rules and procedures for each increase in the percentage of hydrogen that the pipeline will accommodate.[120]

EMERGING BUSINESS OPPORTUNITIES FOR FINANCIAL PLAYERS

Three of the states recognized by the Department of Energy as having some of the greatest potential for hydrogen production development in the U.S. are *California*, *Texas*, and *Louisiana*.[121] Texas, in particular is well situated for hydrogen expansion, with approximately 1,600 miles of dedicated hydrogen pipelines

---

[116] Samsun, Remzi, 2021, Deployment Status of Fuel Cells in Road Transport: 2021 Update, https://www.ieafuelcell.com/fileadmin/publications/2021-Deployment_status_of_fc_in_road_transport.pdf

[117] CMS, 2021, Facing the Future of Hydrogen: An International Guide, https://cms.law/en/media/expert-guides/files-for-expert-guides/the-promise-of-hydrogen-an-international-guide-nov-2021

[118] Department of Energy, Alternative Fuels Data Center, https://afdc.energy.gov/fuels/hydrogen_production.html

[119] Fuel Cell & Hydrogen Energy Association, 2019, Road Map to a US Hydrogen Economy, https://cafcp.org/sites/default/files/Road+Map+to+a+US+Hydrogen+Economy+Full+Report.pdf

[120] Interview with Gas Technology Institute

[121] CMS, 2021, Facing the Future of Hydrogen: An International Guide, https://cms.law/en/media/expert-guides/files-for-expert-guides/the-promise-of-hydrogen-an-international-guide-nov-2021

and three hydrogen-specific storage fields with a total capacity of approximately 6 billion cubic feet. Louisiana also has significant hydrogen storage potential, and the state already serves as provider of hydrogen supply and consumption from its chemical and refining sectors. [122]

As previously mentioned, the hydrogen market in the U.S. is in its early stages, with the majority of projects in the pilot phase. The table below summarizes some of the projects in the U.S. at various stages of development.

Table 10 List of hydrogen projects in the United States[123]

Project name	Expected date online	Status	Energy source	Product	End-use	Announced Size	Normalized capacity (kt H2/year)
SoCalGas - NREL	2019	Operational	Undisclosed	CH4	Synthetic methane grid injection	0.25 MW	0.04
SunLine Transit Agency	2018	Operational	Undisclosed (PEM)	H2	Mobility	1.5 MW	0.2
CF Industries – Donaldsonville Nitrogen Complex	2023	FID	Grid	Ammonia	Ammonia	20 MW	3.6
Coffeyville fertilizer plant	2013	Operational	Oil with CCUS	Ammonia	Ammonia	1000000 t CO2/y	
PCS Nitrogen	2013	Operational	NG with CCUS	H2	Ammonia	700000t CO2/y	
Port Arthur	2013	Operational	NG with CCUS	H2	Refining	1000000t CO2/y - 151000m3 H2/h	118
Air Liquide liquid hydrogen production plant	2022	Under Construction	Biomass	H2	Mobility	30t H2/d	4
Olive Creek	2021	Under Construction	NG with CCUS	H2	Not announced	14000t carbon black/y	5
LADWP – NREL Intermountain Power Project	2023	Feasibility study	Renewables	H2	Power; grid injection	1000 MW	173
Wabash CarbonSAFE	2022	Under Construction	Coal with CCUS	Ammonia	Ammonia	1650000t CO2/y	
Plug Power-Brookfield Renewable Susquehanna River (Pen) project	2022	FID	Renewables	H2	Mobility	30 MW	5
New York Science, Technology and Advanced Manufacturing Park	2025	FID	Hydropower	H2	Power	120 MW	18
Florida Power & Light utility pilot plant	2023	Feasibility study	Renewable-Solar PV	H2	Power	20 MW	3
Great Plains Synfuel Plant and Weyburn-Midale	2000	Operational	Coal with CCUS	CH4	Synthetic methane grid injection	3000000 t CO2/y	
New Jersey Resources Howell	2021	Under Construction	Renewables	H2	Grid injection	50 MW	9
BayoTech - Carbon Clean MoU	2022	Feasibility study	NG with CCUS	H2	Not announced	1t H2/d	0.4
Road Runner	2023	Feasibility study	Renewable-Solar PV	H2	Biofuels	20 MW	3
New Jersey Offshore Win plant		Feasibility study	Renewable-Offshore wind	H2	Not announced	5-10 MW	1

---

[122] CMS, 2021, Facing the Future of Hydrogen: An International Guide, https://cms.law/en/media/expert-guides/files-for-expert-guides/the-promise-of-hydrogen-an-international-guide-nov-2021

[123] International Energy Agency (IEA), Hydrogen Projects Database. https://www.iea.org/data-and-statistics/data-product/hydrogen-projects-database

Enid Fertilizer	1982	Operational	NG with CCUS	Ammonia	Ammonia	0.7 million tons CO2/y	
North Dakota Hydrogen Hub (former Great Plains Synfuel Plant)	2026	Feasibility study	NG with CCUS	H2	Not announced	310000t H2/y	310
NEL - Nikola Agreement H2 refueling stations in USA (1st phase)	2022	FID	Undisclosed	H2	Mobility	85 MW	15

PROJECT HIGHLIGHTS

Examples of private investment in hydrogen-linked projects are starting to emerge in USA. In October 2021, AirProducts announced plans in connection with the government of Louisiana for the construction of a $4.5 billion clean hydrogen complex with an expected COD of 2026 in Ascension Parish, Louisiana. The project, owned and operated by AirProducts, will produce over 750 million standard cubic feet per day of blue hydrogen. A portion of this hydrogen will be compressed and transmitted through Air Products' Gulf Coast hydrogen pipeline network, stretching more than 700-miles. Another portion of the hydrogen will be transformed into blue ammonia for export. Approximately 95% of the carbon dioxide emissions from the project will be captured and transported by pipeline to inland carbon storage sites.[124]

In addition to private investment, the Department of Energy's Loan Program Office funds hydrogen projects, often acting as a first-mover in the sector to encourage further investment and mainstream capital in the space. The Loan Program Office recently announced that they have conditionally granted a $1.04 billion 20-year loan to the clean hydrogen Monolith to further expand its hydrogen and carbon black production in Nebraska. The loan will be issued under the DOE's Title XVII innovation energy loan guarantee program and signifies the first use of funding from the program for large-scale hydrogen. The project will convert natural gas into hydrogen which will then be converted into ammonia for fertilizer and carbon black. Based on our interview with an officer of the DOE's Loan Guaranty Program, the DOE is keen to support hydrogen-linked projects like Olive Creek, and is especially sympathetic toward projects involving green hydrogen.

In addition, Calumet Specialty Products Partners, through subsidiary Montana Renewables (MRL), recently closed a $50 million project finance transaction for the construction of a renewable hydrogen plant for Calumet's renewable diesel business in Montana. All permits have been received and construction began in September 2021, with expected operations commencing in the fourth quarter of 2022.[125]

Additional hydrogen projects currently moving forwards in the U.S. include the development of a 550 MW hydrogen facility in Oklahoma. Woodside Petroleum has currently entered the front-end engineering and design phase for the project and expects to make a final investment decision in the second half of 2022,

---

[124] Air Products, 2021, Louisiana Governor Edwards and Air Products Announce Landmark U.S. $4.5 Billion Blue Hydrogen Clean Energy Complex in Eastern Louisiana
https://www.airproducts.com/news-center/2021/10/1014-air-products-blue-hydrogen-clean-energy-complex-in-louisiana

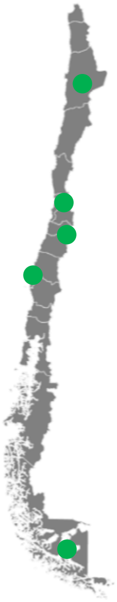
[125] PFI, 2022, Early Hydrogen financing mechanisms emerge, https://www.pfie.com/story/3203002/early-hydrogen-financing-mechani

with expected operations beginning in 2025. The projects will be net-zero and powered by electrolyzers utilizing energy from Oklahoma’s grid which contains a high share of renewable energy from wind.[126]

---

[126] Proximo, 2022, Woodside enters FEED on potential 550 MW US hydrogen development, https://www.proximoinfra.com/news/46435/Woodside-enters-FEED-on-potential-550MW-US-hydro

Chile



Country Statistics

LCOH (Green)	~$1.9 – 3.5/kg
Solar LCOE	~$30/MWh
Wind LCOE	~$40/MWh
LCOH (Blue)	~$2.1 – 2.6/kg

National Hydrogen Target

Chile National Energy and Hydrogen Roadmap (2020) - 25GW by 2030

Regional Market Drivers	
Availability of low-cost renewables	✓
Availability of natural gas	X
Carbon storage options	✓
High comparable energy cost	X
Existing infrastructure	✓
Access to market	✓

Policy Drivers	
National hydrogen strategy	✓
Hydrogen fuel targets	✓
Financial incentives	✓
Hydrogen hubs	✓
Public investment	✓
Carbon pricing	✓

COUNTRY-SPECIFIC MARKET DRIVERS

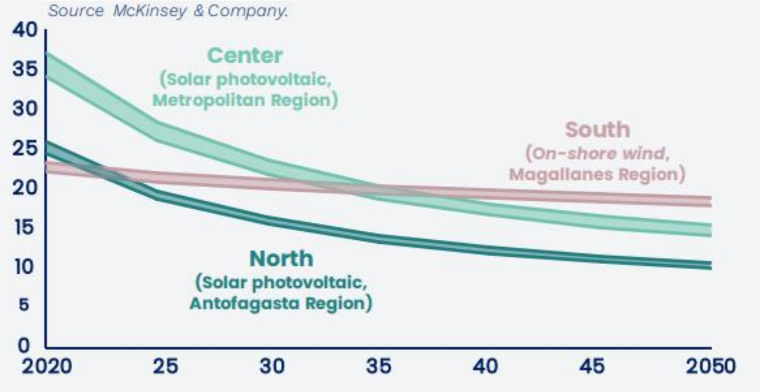
Chile is identified as a global leader in terms of prospective green hydrogen production, mainly due to the competitive advantage of low-cost renewable energy production. The most powerful solar radiation in the planet is found in Chile’s North. According to the Ministry of Energy, capacity factors in the Atacama region can achieve 35% in monofacial solar photovoltaic plants with 1-axis tracking[127]. But the potential is

---

[127] Ministry of Energy. National Green Hydrogen Strategy. Chile, a clean energy provider for a carbon neutral planet. https://energia.gob.cl/sites/default/files/national_green_hydrogen_strategy_-_chile.pdf

not only concentrated in this region: solar generation in the central part of Chile is already more competitive than fossil-powered electricity generation. This renewable potential is located close to large consumption centers (Santiago), gas pipelines and logistical hubs. On the other hand, wind in the far South of the country generates the same capacity on land as off-shore. 120-meter-high wind turbines are able to achieve capacity factors of over 60% on-shore, equivalent to off-shore performance in other countries.

Figure 21 LCOE of Solar in Chile



The solar and wind power sectors have been growing fast. During the past 6 years, Chile has increased the generation capacity from these sources by five-fold and, by 2030, 70% of the power grid is expected to be produced by renewable energy. The increasing investment in renewable energy, as well as in energy storage and transmission infrastructure is a clear indicator of Chile’s decisive transition to a more sustainable power system.

While the hydrogen economy is still taking shape, and the world is waiting for the costs of the technology to fall, the Chilean government is preparing its capabilities to actively participate in the hydrogen value chain. Mining companies in the region are looking to hydrogen in place of expensive imported diesel fuel to slash operational costs. They also believe green hydrogen can be used for electricity at mining sites alongside cheap renewable energy resources. Any success would have global implications for the energy transition away from fossil fuels: Not only would it demonstrate that the world's polluting industries can cut costs with hydrogen, but it would also help decarbonize a global supply chain that is heavily dependent on copper and lithium, of which Chile is a top exporter[128].

In Chile, the whole case for hydrogen investment is based on the expected reduction in electrolyzer and renewable power costs to create a competitive market for domestic use and export. According to McKinsey & Company[129], green hydrogen produced in the Atacama Desert and in the Magallanes Region will achieve the lowest levelized cost on the planet by 2030. The same report says that “the quality an

---

[128] S&P Global Market Intelligence. Rich in renewable energy, Chile seeks to become global hydrogen powerhouse. https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/rich-in-renewable-energy-chile-seeks-to-become-global-hydrogen-powerhouse-66012212

[129] McKinsey & Company. Hydrogen Insights: A perspective on hydrogen investment, market development and cost competitiveness. https://hydrogencouncil.com/wp-content/uploads/2021/02/Hydrogen-Insights-2021-Report.pdf

abundance of the renewable resources found in these regions will enable a large-scale competitive production".

Figure 22 LCOH of Green Hydrogen in Chile (USD/kg H2)

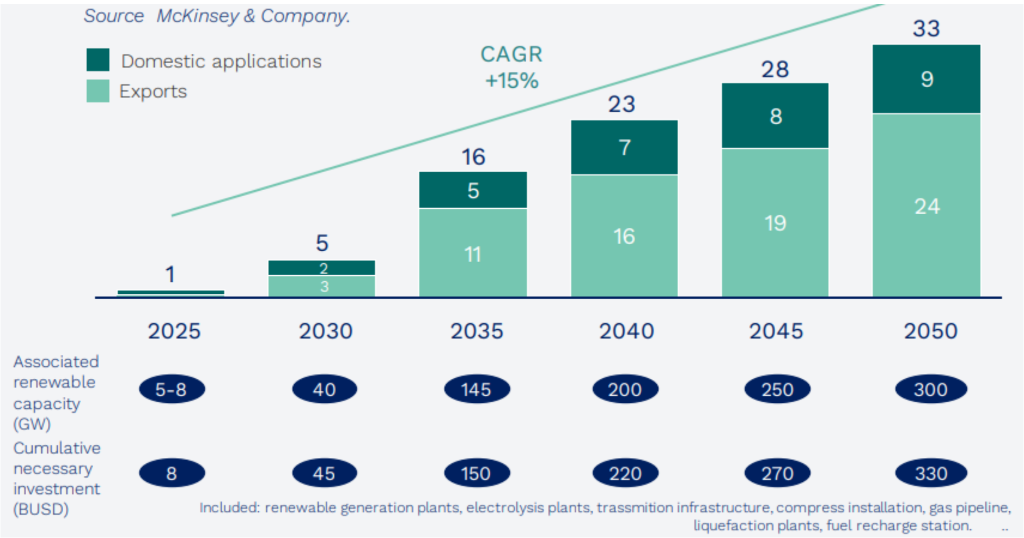
COUNTRY-SPECIFIC POLICY DRIVERS

The Chilean government published its *Green Hydrogen National Strategy* in November 2020. The goal is to have 5 GW of electrolysis capacity under development by 2025 and to create the cheapest hydrogen on the planet by 2030. The competitiveness of Chile in renewable energy production and the global need for clean energy carriers will open the door to the creation of an economic sector that could rival the size of the Chilean mining sector.[130] According to the National Strategy, the hydrogen opportunity will be developed in three different stages: (i) the first wave will include domestic usage with existing large energy and hydrogen demand by replacing imported ammonia and grey hydrogen used in oil refineries; (ii) before the decade is over, the country could export ammonia and start blending hydrogen with liquid fuels for land transportation, (iii) new export markets open in the long-term, enabling a massive scale-up in production.

---

[130] Ministry of Energy. National Green Hydrogen Strategy. Chile, a clean energy provider for a carbon neutral planet. https://energia.gob.cl/sites/default/files/national_green_hydrogen_strategy_-_chile.pdf

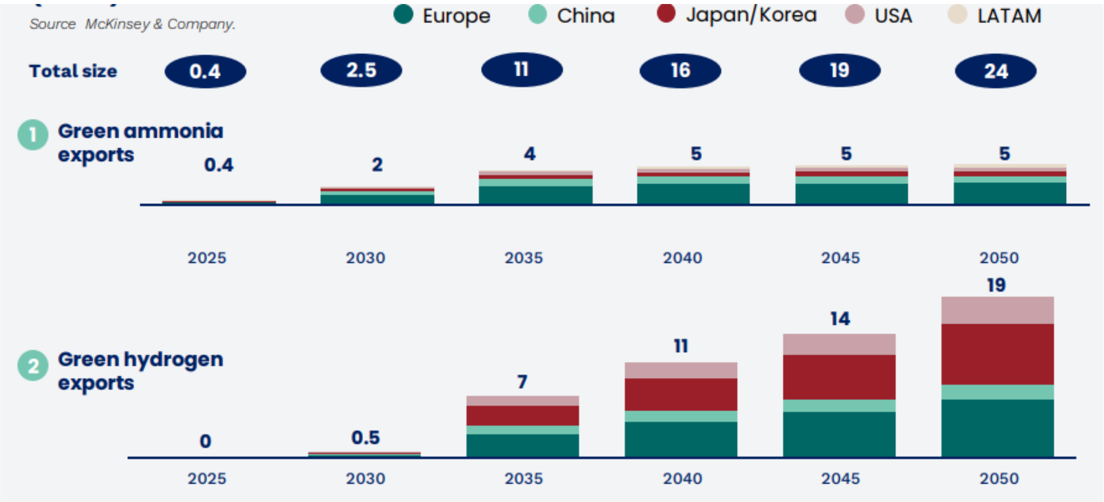
Figure 23 Projection of Chilean markets for green hydrogen and its derivatives (BUSD)



In *Wave I (2020 – 2025)* the government expects to ramp up domestic production and export preparation. The policy focus will be on 6 prioritized applications: oil refineries, ammonia production, mining haul trucks, heavy-duty trucking, long-range buses and blending into gas grids (up to 20%). The policy will kickstart the local hydrogen industry by incentivizing production and create tangible demand for hydrogen and its derivatives.

Wave II (2025 – 2030) will leverage the domestic base to scale up Chile as a key player in export markets. An industry of green ammonia production and exportation will be put in place through support for large-scale consortiums. Offtake and investment commitments for ammonia and hydrogen exports will be secured. Finally, *Wave III (2030 onwards)* will exploit synergies and economies of scale to expand Chile as a global supplier of clean fuels.

Figure 24 Estimated market size for Chilean exports (BUSD)



The action plan promoted by the Chilean government has, as expected, important participation by the private sector. Chile is well recognized by the strength of its institutions and the historic relationship between different governments and private sector. This is supported by a stable legal system and taxes regimes. The action plan of deploying hydrogen investments in the country includes:

Promotion of domestic and export markets:

- The government launched a special fund of US$ 50 million to support early and efficient green hydrogen projects focused on the whole value chain to close economic gaps. Selected projects will receive support to achieve the target of US$ 1.5/kg of H_2. This funding will support companies and national and international consortiums to invest in scalable and replicable green hydrogen projects in Chile.
- A public-private roundtable will be established to discuss the path towards a carbon price and taxes that better reflect the externalities of fossil fuels used in Chile. Proper pricing of carbon emissions will level up the field for competition between conventional fuels and new energy carriers.

Capacity building and innovation:

- The government will identify the competences and technical skills required along the value chain of green hydrogen, jointly with private sector actors.
- A roadmap with milestones, pilots, and necessary activities to develop required knowledge for an accelerated deployment of green hydrogen will be elaborated.
- State-owned enterprises (Codelco and ENAP) will lead the transition effort of the government.

INFRASTRUCTURE DEVELOPMENT

Chile is a net importer of oil, natural gas, gasoline, and other oil subproducts. The current natural gas transport infrastructure is mostly used to import gas from Argentina to the main consumer centers in Chile. In fact, most of the transport infrastructure that provides the resource to the northern industrial hub and the center and south regions (most populated ones), are connected to the networks of TGS and TGN (Argentinian natural gas transport companies). There are a lot of opportunities in greenfield infrastructure. Chile will need to construct pipelines connecting the south region (where wind resources are expected to be located) with the consumer centers and the same will occur in the Atacama region. Bidirectionality of the current infrastructure with Argentina could be a possibility to export hydrogen to this country and/or other countries in South America connected to the Argentinian network (Uruguay, Brazil, Bolivia, and Paraguay).

EMERGING BUSINESS OPPORTUNITIES FOR FINANCIAL PLAYERS

The Chilean government, through its investment promoter agency *InvestChile*, has identified 21 projects so far. They are mostly green hydrogen production projects from solar and wind sources. The hydrogen produced by these projects is planned to be used in the production of ammonia and e-fuels, and for heating processes in the iron and steel production.

Table 11 List of recent hydrogen projects announced in Chile

Project name	Expected date online	Status	Energy source	Product	End-use	Announced Size	CAPEX US mn
HIF Project	2024	Pilot Phase	Onshore Wind	H2 + CO2 Capture	eMethanol and eGasoline	300 MW	755
HNH Energy	2026	Feasibility Study	Onshore Wind	H2 + N	Ammonia	1,800 MW	3,000
AES Andes Project	2025	Feasibility Study	Solar PV and Onshore Wind	H2 + N	Ammonia	800 MW	1,500
HyEx	2025 - 2030	Feasibility Study	Solar PV	H2 + N	Ammonia	2,000 MW	2,000
Atacama Hydrogen Hub	2030	Pilot Phase	Solar PV	H2	H2 powered freight train	NA	18 first phase
ACH - MRP	2027	Feasibility Studies	Solar PV and Onshore Wind	H2 + N	Ammonia	3,000 MW	5,000
Green Steel Project	2027	Feasibility Studies	Solar PV and Onshore Wind	H2	Direct Reduced Iron	Na	40
H1 Magallanes	2028	Feasibility Studies	Onshore Wind	H2 + N	Ammonia	2,200 MW	NA
Quintero Bay H2 Hub	2030	Prefeasibility Studies	Solar PV and Onshore Wind	H2	Blending into gas pipelines	NA	NA
Hoasis	2024	Prefeasibility Studies	Solar PV	H2 + O2	Ammonia	NA	3,700
H2 Solar	2022	Pilot Phase	Solar PV	H2	Fuel Cell	1.2	10
Selknam	2026	Prefeasibility Studies	Onshore Wind	H2 + N	Ammonia	1,150 MW	2,000
Hydra	2030	Prefeasibility Studies	Solar PV	H2	eFuels for mining trucks	40	NA
H2GN	2022	FID	Solar PV and Onshore Wind	H2	Blend H2 and Natural Gas	NA	1
Vientos Magallanicos	2030	Prefeasibility Studies	Onshore Wind	H2 + N	Ammonia	700	1,850
Hydrogen Forklifts	2022	Under Construction	Solar PV	H2	Fuel Cells	0.6 MW	15
USCS	2022	Under Construction	Solar PV and Onshore Wind	H2	Fuel Cells	0.025	0.8
Zorzal	2023	FID	Solar PV and Onshore Wind	H2	H2	10.5	30
Renewstable Kosten Aike	2025	Feasibility Studies	Onshore Wind	H2	Fuel cell + Battery	36	190
HyPro Aconcagua	2024	Prefeasibility Studies	Renewable Energy from grid	H2	Refinery	20	41
Pauna Greener Future	2025	Prefeasibility Studies	Solar PV	H2	Ammonia	400	500

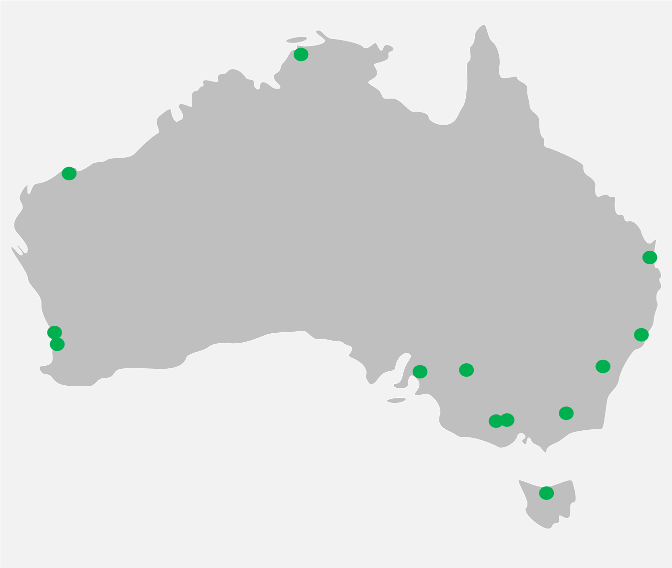
PROJECT HIGHLIGHT

HIF Project

The HIF (Highly Innovative Fuels) project aims to build the world's first industrial-scale plant that produce synthetic climate-neutral fuels for export. A wind farm will power the electrolyzers for green hydrogen production. Hydrogen produced will be combined with captured carbon dioxide to produce synthetic methanol. A portion of this methanol will be converted into synthetic gasoline (eGasoline). The pilot phase is under construction and is expected to enter operation by May 2022. Phase I is currently in development and the environmental assessment is being prepared. Porsche is planning to use the eFuels produced in the pilot project, including using eFuels in Porsche's Experience Centers and sports cars. Mabanaft, the Marquard & Bahls trading division which focuses on oil, announced an MoU highlighting the purchase of up to 500 million liters of carbon neutral eGasoline per year from this project.

Source: HIF. https://www.hif.cl/en

AUSTRALIA



Country Statistics

LCOH (Green)	~$4.5/kg
Solar LCOE	~$39/MWh
Wind LCOE	~$43/MWh
LCOH (Blue)	~$2.5/kg
Aus LNG Price	~$10.52/MMBtu

National Hydrogen Vision (2018)

Australia aims to become a major global player in Hydrogen by 2030

Regional Market Drivers	
Availability of low-cost renewables	✓
Availability of natural gas	✓
Carbon storage options	✓
High comparable energy cost	✓
Existing infrastructure	X
Access to market	✓

Policy Drivers	
National hydrogen strategy	✓
Hydrogen fuel targets	X
Financial incentives	✓
Hydrogen hubs	✓
Public investment	✓
Carbon pricing	X

COUNTRY-SPECIFIC MARKET DRIVERS

Australia is particularly well-positioned to evolve as a major player in the global hydrogen export market with its abundant renewable resources and trading connections. It has historically been a major exporter of coal and other fossil-fuel based energy resources like coal, LNG, and crude oil with strong bilateral trade ties with Japan, Korea, and China.[131] The nascent hydrogen sector presents a unique opportunity for Australia to transition to clean energy exports, especially as global and national measures for decarbonization make these sectors economically viable. Hydrogen could also help Australia to decarbonize it domestic electrical grid, transportation sector and other industries.[132]

Australia has a significant supply of renewable resources which can be used to develop green hydrogen. The Australian continent has the highest solar radiation per square meter of any continent in the world. Its annual solar radiation 58 million PJ and solar resources are concentrated in the desert regions in northwest and central Australia.[133] Inland regions of Western Australia, South Australia and western Victoria all have good wind resources.[134] Currently, 99.2% of Tasmania's electricity (mostly from hydro-power) and 59.2% of South Australia's electricity comes from renewable energy: material deployment of rooftop solar plus wind.[135] The estimated LCOE from onshore wind and solar in Australia are $39/MWh and $43/MWh respectively.[136] Transmission lines represent a significant component of the LCOE calculation owing to the remoteness of renewable energy resources.

As Solar PV and batteries are projected to continue experiencing the fastest cost reductions of any source of energy technology,[137] green hydrogen is likely to become more competitive in Australia. Australia also has fossil fuel resources across northern, western, and southern states and the below-surface geology to undertake carbon capture storage. Therefore, it could also be a center for blue hydrogen production.

In addition to the availability of resources for hydrogen production, Australia's low existing sovereign risk and trade partnerships in the Asia Pacific region, coupled with a highly skilled labor force could afford it a competitive advantage in the race to becoming a global hydrogen leader.

COUNTRY-SPECIFIC POLICY DRIVERS

Australia introduced its national hydrogen strategy and roadmap in 2019. It provides a blueprint for the development of the hydrogen industry in Australia, by informing investment so the industry can scale in a coordinated manner.[138] The Australian government's measures treat the hydrogen sector not only as a path for greenhouse gas mitigation but also as a key economic driver.

---

[131] Deloitte. November 2019. Australian and Global Hydrogen Demand Growth Scenario Analysis COAG Energy Council – National Hydrogen Strategy Taskforce. https://www2.deloitte.com/content/dam/Deloitte/au/Documents/future-of-cities/deloitte-au-australian-global-hydrogen-demand-growth-scenario-analysis-091219.pdf

[132] Deloitte. November 2019. Australian and Global Hydrogen Demand Growth Scenario Analysis COAG Energy Council – National Hydrogen Strategy Taskforce. https://www2.deloitte.com/content/dam/Deloitte/au/Documents/future-of-cities/deloitte-au-australian-global-hydrogen-demand-growth-scenario-analysis-091219.pdf

[133] Department of Resources, Energy and Tourism (Aus). 2010. Australia Energy Resource Assessment. https://d28rz98at9flks.cloudfront.net/70142/70142_complete.pdf

[134] Geoscience Australia. 2020. Wind Energy. https://www.ga.gov.au/scientific-topics/energy/resources/other-renewable-energy-resources/wind-energy

[135] Green Markets Energy, 2020 Share of energy acquired from renewable sources in Australia in 2020, by state. https://www.statista.com/statistics/1087804/australia-renewable-energy-penetration-by-state/

[136] IEA. 2020. Levelised Cost of Electricity Calculator. https://www.iea.org/articles/levelised-cost-of-electricity-calculator

[137] Paul Graham, Jenny Hayward, James Foster and Lisa Havas. 2020. GenCost 2020-21: Consultation draft. https://www.csiro.au/en/news/news-releases/2020/renewables-still-the-cheapest-new-build-power-in-australia

[138] CSIRO. 2018. National Hydrogen Roadmap. https://www.futurefoodsystems.com.au/wp-content/uploads/2020/12/18-00314_EN_NationalHydrogenRoadmap_ExecutiveSummary_WEB_180815.pdf

The policy prioritizes innovation, with a goal of reducing green LCOH from $4.5/kg to $2/kg.[139] The state has also committed funds of up to $1.4 billion to the sector and has entered international partnerships for technology advancement.[140] For example Australia and Germany are working together on a new initiative to strengthen bilateral cooperation on the development of hydrogen technology. The Australian Renewable Energy Agency (ARENA) will lead the new joint Hydrogen Innovation and Technology Incubator known as HyGATE, supporting real-world pilot, trial, demonstration, and research projects along the hydrogen supply chain.[141]

Australia is also incentivizing the growth of hydrogen hubs and the National Energy Resources Australia (NERA) is driving industry-led hydrogen clusters to support small and medium enterprises to avail of opportunities in the hydrogen sector.[142] This will help build capabilities and drive industry collaboration across the hydrogen value chain. The focus of Australian hydrogen policies is on building a conducive environment for the growth of the hydrogen sector through R&D, financing, and incentives. This bodes well for potential new investors in the space.

However, these efforts are in their early stages and need to be bolstered with regulatory action at the state and national level – including by way of developing uniform hydrogen specific regulations based on best practices, hydrogen blending mandates and potentially carbon pricing provisions. Currently, Australia does not levy an explicit carbon price and fuel excise taxes only cover 22.4% of total emissions.[143]

INFRASTRUCTURE DEVELOPMENT

Hydrogen can be used in gas transmission and distribution pipelines to decarbonize natural gas use and eventually replace it. Hydrogen allows ‘sector coupling’, which allows planners to choose between electricity and gas infrastructure for different needs, across greenfield and existing assets. This enables economic efficiency and resilience and could also prevent natural gas infrastructure from turning into stranded assets. Most plastic pipes utilized in the Australian gas distribution networks are different grades of polyethylene (PE): primarily PE63 (high density) and PE80 (medium density), though the use of PE100 (most advanced) is expected to increase in the future. A key concern with transporting hydrogen in plastic pipes is potential leakage. However, this will not be economically significant or lead to safety risks at levels of hydrogen up to 30%.[144] Therefore, while these may be used in the short-run, pipelines will have to be replaced, in the long run to enable the transition from natural gas to 100% hydrogen.

---

[139] CSIRO. 2018. National Hydrogen Roadmap. https://www.futurefoodsystems.com.au/wp-content/uploads/2020/12/18-00314_EN_NationalHydrogenRoadmap_ExecutiveSummary_WEB_180815.pdf

[140] COAG Energy Council. 2019. Australia’s National Hydrogen Strategy. https://www.industry.gov.au/sites/default/files/2019-11/australias-national-hydrogen-strategy.pdf

[141] Ministry of Industry, Australia. 2021. Australia-Germany to support hydrogen supply chain projects. https://www.minister.industry.gov.au/ministers/taylor/media-releases/australia-germany-support-hydrogen-supply-chain-projects

[142] COAG Energy Council. 2019. Australia’s National Hydrogen Strategy. https://www.industry.gov.au/sites/default/files/2019-11/australias-national-hydrogen-strategy.pdf

[143] OECD. 2021. Carbon Pricing in Times of COVID. https://www.oecd.org/tax/tax-policy/carbon-pricing-australia.pdf

[144] Energy Pipelines CRC. 2017. Research Report Identifying the commercial, technical and regulatory issues for injecting renewable gas in Australian distribution gas networks. https://www.energynetworks.com.au/resources/reports/identifying-the-commercial-technical-and-regulatory-issues-for-injecting-renewable-gas-in-australian-distribution-gas-networks-research-report-energy-pipelines-crc/

There are at least 86 projects underway/announced on hydrogen ranging from small feasibility studies to large export projects. The hydrogen sector is still nascent in Australia and will require multiple investments across the value chain: from largescale electrolyzers, renewable electricity, hydrogen storage, water and water pipelines, electricity infrastructure, CCS as appropriate, and hydrogen pipelines/retrofits. Industrial and port facilities need to be developed for the export of hydrogen and its derivatives, including ammonia. Mineral and chemical companies will invest in new production processes, and transport and logistics companies will procure new vehicle technologies. Refueling stations will be required to supply hydrogen for vehicles. It is likely that the capital investments for production of hydrogen alone could run to the tens of billions of dollars. Set out below are some major hydrogen projects that have been announced in Australia.

Table 12 List of recent projects announced in Australia[145]

	Expected date online	Status	Energy source	Product	End-use	Announced Size	Normalized capacity (kt H2/year)
H2U - Eyre Peninsula Gateway Hydrogen Project at Port Bonython.	2022	Feasibility study	Renewable	Ammonia	Ammonia	75MW - 40kt NH3/y	13.0
Asian Renewable Energy Hub	2028	Feasibility study	Renewable	H2	Not shared	14000MW	2425.5
Murchison	2028	Feasibility study	Renewable	H2	Mobility, power, other industry	5000MW	749.7
Project NEO	2027	Concept	Renewable	H2	Not shared	1000MW	173.3
Hydrogen Park South Australia - HyPSA	2021	Operational	Renewable	H2	Grid inj.	1.25MW	0
Jemena Western Sydney - H2GO project	2021	Under construction	Grid	H2	Grid inj.	0.5MW	0
Queensland Government HRS	2021	Under construction	Other/Unknown	H2	Mobility	0.22MW	0
Engie - Yara Pilbara test	2023	Feasibility study	Renewable	Ammonia	Ammonia	10MW	2
Crystal Brook Energy Park, South Australia	2024	FID	Grid (excess renewable)	H2	CHP	50MW	9
Origin Energy - Kawasaki Heavy Industries Townsville project	2025	Feasibility study	Renewable	H2	Not shared	300MW	52
H2-hub Gladstone (Queensland) - phase 1	2025	Feasibility study	Renewable	Ammonia	Ammonia	150W	26
Sun Metals Zinc Refinery	2022	FID	Renewable	H2	Other industry	1MW	0
Douglas PUD - industrial area north of East Wenatchee	2021	FID	Grid (excess renewable)	H2	Grid inj.	5MW	1
Hydrogen Park Gladstone	2022	Under construction	Other/Unknown	H2	Grid Inj.	0.175MW	0
Toyota Hydrogen Centre, Altona, Victoria	2021	Operational	Grid (excess renewable)	H2	Mobility	0.2MW	0
Hazer group CH4 pyrolysis	2021	Under construction		H2	Not shared	100t H2/y	0

---

[145] International Energy Agency (IEA). Hydrogen Projects Database. https://www.iea.org/data-and-statistics/data-product/hydrogen-projects-database

Arrowsmith Hydrogen Project	2022	Feasibility study	Renewable	H2	Not shared	50MW	9
Origin Energy Tasmania's Bell Bay	2025	Feasibility study	Renewable	Ammonia	Ammonia	500MW-420 ktnNH3/y	76
Camberra HRS	2021	Operational	Renewable	H2	Mobility	10 m3/h	0
Pacific Solar Hydrogen	2024	Concept	Renewable	H2	Not shared	200kt H2/y	200
Project Haber	2022	FID	Renewable	H2	Grid inj.	10MW	2
H2TAS	2023	Feasibility study	Renewable	H2	Mobility	10 MW	2
Sumitomo Queensland	2023	Feasibility study	Renewable	H2	Mobility and other industries	0.25-0.3 kt H2/y	0
Hydrogen Park Murray Valley, Victoria	2023	Feasibility study	Renewable	H2	Not shared	10MW	2
Clean Energy Innovation Park	2023	Feasibility study	Renewable	H2	Not shared	10MW	2
Eco Energy World Quenssland project	2023	Feasibility study	Renewable	H2	Not shared	200 MW	35
Green Hydrogen Systems - Skai Energies	2022	Under construction	Other/Unknown	H2	Not shared	60-90kg H2/d	0
Badgingarra Renewable Hydrogen Project	2023	Feasibility study	Renewable	H2	Mobility, power, other industry	10MW	2
BHP Nickel West Green Hydrogen	2023	Feasibility study	Renewable	H2	Other industry	10MW	2
Dawson Mine	2023	Feasibility study	Renewable	H2	Mobility	10MW	2
Manilla Solar & Renewable Energy Storage Project	2022	FID	Renewable	H2	Power	2MW	0
APA Renewable Methane Demonstration Project	2023	DEMO	Renewable	CH4	CH4 Mobility	0.005MW	0
Christmas Creek Renewable Hydrogen Mobility Project	2022	Under construction	Renewable	H2	Mobility	0.7MW	0
ABEL Energy Bell Bay Powerfuels Project	2023	Feasibility study	Renewable	MeOH	Methanol	100MW	17
Swinburne University of Technology Victorian Hydrogen Hub – CSIRO Hydrogen Refuelling Station	2022	Feasibility study	Grid	H2	Mobility	20 kg H2/d	0

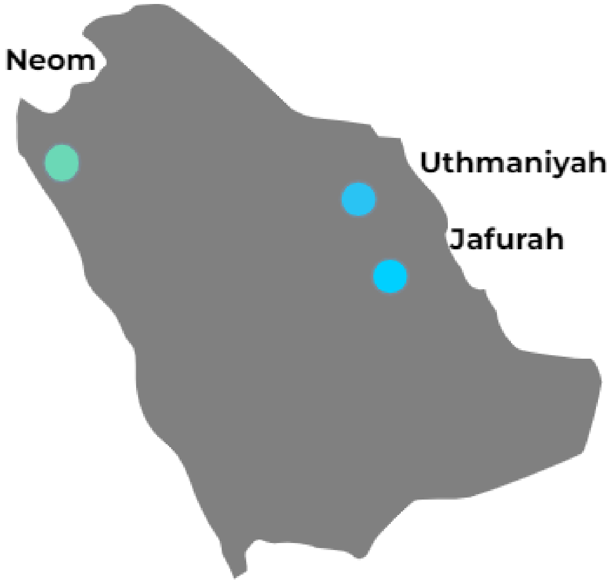
PROJECT HIGHLIGHT

Bell Bay (H2TAS) Renewable Hydrogen Project

H2TAS is a phased development aimed at supporting 1.7 GW of electrolysis for hydrogen and ammonia production. The initial phase would have capacity of up to 300 MW and target production of 200,000 ton per annum of ammonia, matched to forecast customer demand**. H2TAS uses a combination of hydropower and wind power to create a 100% renewable ammonia product for export as well as renewable hydrogen for domestic use**. In January 2021, Woodside signed a Memorandum of Understanding with the State of Tasmania, which outlined the Tasmanian Government's support for the H2TAS Project. The State recognizes the value of developing a hydrogen hub in the Bell Bay area that capitalizes on Tasmania's advantage in renewable energy generation.

Source: Woodside Press Release. November 2021. https://www.woodside.com.au/docs/default-source/media-releases/woodside-driving-forward-renewable-hydrogen-in-tasmaniaf04b8c94-f289-4670-96ff-67d1069edeb9.pdf?sfvrsn=8a16962a_3#:~:text=H2TAS%20is%20a%20phased%20development,matched%20to%20forecast%20customer%20demand.

Saudi Arabia



Country Statistics

LCOH (Green)	~$1.6 /kg
Solar LCOE	~$19.9/MWh
Wind LCOE	~$10.4/MWh
LCOH (Blue)	~$2/kg

National Hydrogen Target

Announced Developing National Hydrogen Roadmap (2022)

Regional Market Drivers	
Availability of low-cost renewables	✓
Availability of natural gas	✓
Carbon storage options	✓
High comparable energy cost	✓
Existing infrastructure	X
Access to market	✓

Policy Drivers	
National hydrogen strategy	✓
Hydrogen fuel targets	✓
Financial incentives	✓
Hydrogen hubs	✓
Public investment	✓
Carbon pricing	X

COUNTRY-SPECIFIC MARKET DRIVERS

Saudi Arabia has the potential to be one of the leaders in hydrogen production and exporting globally. As discussed in Part 1 of this report, the feedstock for green hydrogen is renewable energy, and blue hydrogen is natural gas. Saudi Arabia is one of the countries that have resource endowments to produce both blue and green hydrogen economically.[146] The country signaled its commitment to decarbonization

---

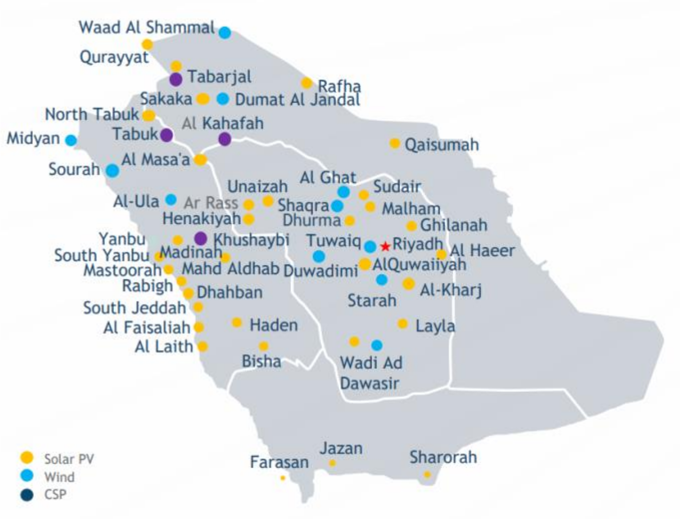
[146] Hasan, Shahid, 2022, The Economics and Resource Potential of Hydrogen Production in Saudi Arabia, https://www.kapsarc.org/research/publications/the-economics-and-resource-potential-of-hydrogen-production-in-saudi-arabia/

in its National Energy Strategy, which targets 50% renewable and 50% fossil fuel by 2030. The plan to reach the 50% target is through the National Renewable Energy Program, which plans to install 27.3 GW of solar and wind by 2023 and 58.7 GW by 2030.[147]

While the renewable energy infrastructure is underdeveloped, the country's renewable energy development momentum is promising. The country's solar capacity was only 2.35 MW in 2010, but this capacity grew to reach 84 MW in 2018 and increased to 394 MW in 2019. This momentum led to revising the country's solar energy targets to 20 GW by 2023 and 40 GW by 2030. The state is leading the financing for many of these projects through the Ministry of Energy and backs these projects through power purchase agreements (PPAs) with the Saudi Power Procurement Company as an off-taker. Unlike solar, there is less focus on developing wind infrastructure. The country has announced only ten wind projects in its National Renewable Energy Program.[148]

The levelized cost of solar energy is estimated at around $10.4/MWh and $19.9/MWh for wind. Based on this assumption of low LCOE from solar and wind, our model estimates the LCOH in Saudi Arabia to be competitive at approximately $2.4/kg, assuming $20/MWh electricity cost and 50% electrolyzer utilization of alkaline (20 MW).[149]

Figure 25 Announced Renewable Energy Projects National Renewable Energy Program



In terms of Saudi Arabia's blue hydrogen potential, the country has the largest natural gas reserves globally. These reserves are estimated to be around 233.8 trillion cubic feet, concentrated in the eastern part of the country, where crude oil is extracted. The most significant announcement about blue hydrogen initiatives comes from the Saudi Aramco Jafurah project, which is detailed further below. Saudi Arabia's

---

[147] Saiyid, Amena, 2021, Saudi Arabia recommits to 50% renewable power, https://cleanenergynews.ihsmarkit.com/research-analysis/saudi-arabia-recommits-to-50-renewable-power-by-2030.html#:~:text=The%20world's%20leading%20oil%20producer,newly%20announced%20%22green%20initiative.%22

[148] Saudi Arabia National Renewable Energy Program, https://www.ief.org/_resources/files/events/third-ief-eu-energy-day/turki-al-shehri-24.02-repdo---ief_riyadh_v2-2.pdf

[149] Kiyasseh, Lama, 2022, Strong momentum in Saudi Arabia's drive toward renewables and infrastructure, https://www.mei.edu/publications/strong-momentum-saudi-arabias-drive-toward-renewables-and-infrastructure#:~:text=All%20projects%20tendered%20by%20the,from%20clean%20sources%20by%202030

access to low-cost natural gas contributes to having a competitive levelized cost of blue hydrogen.[150] Based on Goldman Sachs Investment Research report, the levelized cost of blue hydrogen will be approximately $2/kg in the country by 2030.[151]

With the appropriate policies and suitable investments, the country could have a significant role in decarbonization. Blue and green hydrogen have the potential to be economical in the long run in this part of the world. The resurgence of natural gas demand following the pandemic plus the Ukraine crisis have pushed up global gas prices reducing the cost gap with hydrogen. Even though the crude oil prices increased because of the recent events the country is still committed to diversification including the development of its hydrogen capabilities. This can be observed by the recent announcements concerning the start-up of construction on the Helios project this month.[152]

COUNTRY-SPECIFIC POLICY DRIVERS

The country is finalizing its *National Hydrogen Strategy*, targeting $36b of investments by 2030. At an event held by the International Renewable Energy Agency "IRENA," Ahmed Aldosary, Director of the Ministry of Energy, reported that the country has priority areas in this strategy, such as expediting hydrogen-related investments and establishing a regulatory framework and government-to-government engagements to support in hydrogen mobility.[153]

Even though it does not have carbon pricing, the country plans to establish a Voluntary Carbon Market "VCM" platform, the first platform for carbon credit trading in the Middle East. It is part of the country's efforts to reach its net-zero carbon emissions target by 2060.[154]

In addition, the country launched its *Circular Carbon Economy National Program* in 2021. This program was first announced during the country's presidency of the G20. This program is relevant to the blue hydrogen production in the country since one of its main activities is to activate and fund the technologies for carbon capture and reduction in the country.[155]

Helios in Neom could be a green hydrogen hub in the future. In addition, Yanbu and Jubail industrial cities are highly suitable for hydrogen hubs. Currently, infrastructure is built to connect the two cities, as highlighted below. However, this connection is not for hydrogen. [156]

---

[150] Hasan, Shahid, 2022, The Economics and Resource Potential of Hydrogen Production in Saudi Arabia, https://www.kapsarc.org/research/publications/the-economics-and-resource-potential-of-hydrogen-production-in-saudi-arabia/

[151] Goldman Sachs Investment Research, Carbonomics: The Clean Hydrogen Revolution, https://www.goldmansachs.com/insights/pages/gs-research/carbonomics-the-clean-hydrogen-revolution/carbonomics-the-clean-hydrogen-revolution.pdf

[152] Nereim, Vivian, 2022, Saudi Arabia to Start Building Green Hydrogen Plant in Neom, https://www.bloomberg.com/news/articles/2022-03-17/saudi-arabia-to-start-building-green-hydrogen-plant-in-neom

[153] Zawya, 2022, Saudi Arabia's hydrogen strategy targets $36bln of investments by 2030, https://www.zawya.com/en/projects/industry/saudi-arabias-hydrogen-strategy-targets-36bln-of-investments-by-2030-cgok6oye

[154] Wang, Herman, 2021, Saudi Arabia to launch voluntary Middle East carbon trading platform , https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/energy-transition/090321-saudi-arabia-to-launch-voluntary-middle-east-carbon-trading-platform

[155] Circular Carbon Economy National Program, https://www.cce.org.sa/about.html#block2

[156] Hasan, Shahid, 2022, The Economics and Resource Potential of Hydrogen Production in Saudi Arabia, https://www.kapsarc.org/research/publications/the-economics-and-resource-potential-of-hydrogen-production-in-saudi-arabia/

Figure 26 Current infrastructure between the possible two hydrogen hubs in Saudi Arabia[157]

IRENA published in November 2020 its guide for hydrogen policymaking.[158] The guide highlighted the importance of identifying the origin of the produced hydrogen. Europe is leading this effort through its GO system, which provides clear labels for hydrogen products that increase consumer awareness and guarantee the origin of production. Saudi Arabia and Australia are among the first countries to join this system. This system will help facilitate the hydrogen market and international trade transactions in clean hydrogen.[159]

INFRASTRUCTURE DEVELOPMENT

As highlighted in the first part of this report, there is a global lack of hydrogen production and transportation infrastructure which contributes to the cost gap between clean hydrogen and its carbon-intensive alternatives. Saudi Arabia's blue hydrogen infrastructure is more advanced than green hydrogen infrastructure since the country is a significant market player in crude oil production. The government is pursuing plans to produce hydrogen in ammonia form since this form has high energy efficiency and can be exported to distant countries.[160]

The greenfield infrastructure investments could be in the northwest part of the country, near the Helios project, covered in this report's case studies. The green ammonia from that project will be transported by ships. However, based on a published article, Peter Terium, CEO of ENOWA, and Saudi energy minister

---

[157] Jubail & Yanbu: The East-West Pipeline, https://www.knak.jp/big/saudi-pipeline.htm

[158] IRENA, Green hydrogen: A guide to policy making, 2020, https://www.irena.org/publications/2020/Nov/Green-hydrogen

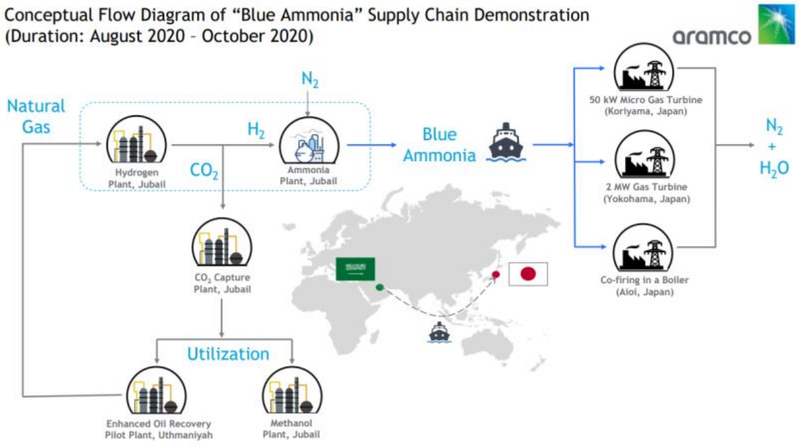
[159] Braun, Jan; Shabaneh, Rami, 2021, Saudi Arabia's Clean Hydrogen Ambitions: Opportunities and Challenges, https://www.kapsarc.org/research/publications/saudi-arabias-clean-hydrogen-ambitions-opportunities-and-challenges/

[160] Braun, Jan; Shabaneh, Rami, 2021, Saudi Arabia's Clean Hydrogen Ambitions: Opportunities and Challenges, https://www.kapsarc.org/research/publications/saudi-arabias-clean-hydrogen-ambitions-opportunities-and-challenges/

Prince Abdul Aziz bin Salman alluded that building a pipeline from Neom to Europe through Egypt and North Africa is a possible option if the demand for hydrogen is high in Europe.[161]

Based on a published report from King Abdullah Petroleum Studies and Research Center "KAPSRC," the retrofitting investments are in Jubail and Yanbu industrial cities. Jubail is in the eastern part of the country, and Yanbu is in the western part.[162] These investments started in 2015 and 2016 by Air Liquide Arabia Ltd. Air Liquide Arabia Ltd announced that the hydrogen pipeline in Jubail is 7.5 miles (21 km). It will supply large, small, and medium enterprises in the industrial city. The blue hydrogen supply chain was tested in September 2020 when Aramco shipped 40 tons of high-grade blue ammonia to Japan.[163]

Figure 27 Blue Hydrogen Supply Chain demonstration from Aramco Website[164]



EMERGING BUSINESS OPPORTUNITIES FOR FINANCIAL PLAYERS

IEA's hydrogen project database records the Helios project; however, other projects are collected in the list based on other announcements from Aramco or conferences (*Table 13*).

Unlike other countries analyzed in this report, Saudi Arabia focuses on large-scale hydrogen projects to export rather than satisfying domestic energy demand, which is fulfilled by oil and natural gas. However, to have a comprehensive projects list, the report covers eight smaller projects that were announced early this year for local demand.[165]

---

[161] Lee, Andrew, 2021, Saudi Arabia could pipe green hydrogen to Europe to keep leading energy role, https://www.rechargenews.com/markets/saudi-arabia-could-pipe-green-hydrogen-to-europe-to-keep-leading-energy-role/2-1-972920

[162] Hasan, Shahid, 2022, The Economics and Resource Potential of Hydrogen Production in Saudi Arabia, https://www.kapsarc.org/research/publications/the-economics-and-resource-potential-of-hydrogen-production-in-saudi-arabia/

[163] Arab News, 2017, Air Liquide starts Mideast's first hydrogen pipeline network in KSA, https://www.arabnews.com/node/1098721/%7B%7B

[164] Saudi Aramco, 2020, Blue Hydrogen Supply Chain Diagram, https://www.aramco.com/-/media/news/2020/sep/blue-ammonia-supply-chain-flow-diagram-web.pdf?la=en&hash=6FFE2FC0FF076E1BA65B957B1B22405BF817281A

[165] Argaam, 2022, Ministry of Energy signs several MoUs on use of hydrogen fuel for vehicles and buses, https://www.argaam.com/en/article/articledetail/id/1529259

Table 13 List of recent hydrogen projects announced in Saudi Arabia[166]

Project name	Expected date online	Status	Energy source	Product	End-use	Announced Size	Normalized capacity (kt H2/year)
Helios Green Fuels - Neom	2025	FID	Renewable-Solar PV and wind	Green Ammonia	Transportation	650t H2/d	237.3
Jafurrah	2024	NA	Natural Gas	Blue Ammonia	Not announced	NA	NA
Uthmaniyah	2023	NA	Natural Gas	Blue Ammonia	Not announced	NA	NA
Princess Nora Bint Abdulrahman University	-	MoU	NA	H2	Vehicles and buses	NA	NA
Saudi Railways Company (SAR)	-	MoU	NA	H2	Trains	NA	NA
Saudi Technology Development and Investment Company (TAQNIA)	-	MoU	NA	H2	Jet fuel	NA	NA
Royal Commission for Jubail & Yanbu	-	MoU	NA	H2	Vehicles and buses	NA	NA
NEOM	-	MoU	NA	H2	Transportation	NA	NA
Royal Commission for Makkah City and Holy Sites	-	MoU	NA	H2	Buses	NA	NA
The Red Sea Development Company	-	MoU	NA	H2	Buses	NA	NA
Saudi Ground Services Co. (SGS)	-	MoU	NA	H2	Transportation	NA	NA

---

[166] International Energy Agency (IEA). Hydrogen Projects Database. https://www.iea.org/data-and-statistics/data-product/hydrogen-projects-database. Saudi Aramco: https://www.aramco.com. Argaam: https://www.argaam.com/en/article/articledetail/id/1529259.

Jafurrah

The Jafurrah is 105 miles (170 km) long and 62 miles (100 km) of natural gas field developed by Saudi Aramco. It will be one of the main initiatives that Aramco will take to be in the hydrogen market. The overall investment for this field is $110b. This investment is not only for blue hydrogen. Instead, this field will produce gas, ethane, natural gas liquids, and condensate. This field's estimated natural gas reserve is approximately 200 trillion cubic feet. There is no specific date for blue hydrogen production. However, the area is expected to start operating in 2024.

Source: Saudi Arabia poised to tap $110bn Jafurah gas project for blue hydrogen, October25, 2021. https://www.upstreamonline.com/energy-transition/saudi-arabia-poised-to-tap-110bn-jafurah-gas-project-for-blue-hydrogen/2-1-1087974

Japan

Country Statistics

LCOH (Green)	~$7.1 - 10/kg
Solar LCOE	~$172/MWh
Wind LCOE	~$140/MWh
LCOH (Blue)	~$3.4 - 4.2/kg
EU LNG IM Price	~$28/MMBtu

National Hydrogen Target

Green Growth Strategy (2021) Basic Hydrogen Strategy (2017) – 3M tons at

Regional Market Drivers	
Availability of low-cost renewables	X
Availability of natural gas	X
Carbon storage options	X
High comparable energy cost	✓
Existing infrastructure	X
Access to market	✓

Policy Drivers	
National hydrogen strategy	✓
Hydrogen fuel targets	✓
Financial incentives	✓
Hydrogen hubs	X
Public investment	✓
Carbon pricing	X

COUNTRY-SPECIFIC MARKET DRIVERS

With fewer natural resources, Japan has viewed hydrogen as a promising energy source from the early stages of the sector’s development. Japan has supported the implementation of many pilot projects to prepare both the demand and supply sides for wide scale adoption of hydrogen.

Currently, 2 million tons of (primarily) gray hydrogen is being produced in refineries and ammonia plants for domestic consumption. The hydrogen demand is projected to rise to 3 million tons in 2030 and 20 million tons in 2050.

As per research from IEA,[167] Japan is expected to become a major hydrogen importer in coming years. While the Japanese government has not publicly announced the target ratio of domestic and foreign hydrogen production and only set the demand targets highlighted above, it emphasizes the importance of domestic production. In fact, a 10MW hydrogen electrolyzer, the world's second largest scale, is operating in Japan.[168] Nevertheless, Japan's lack of access to domestic renewable energy sources and lack of CCS options indicate that at least 75%[169] of its hydrogen demand must be met through imports.

Japan experiences high energy costs owing to its dependence on imported fossil fuels. This is likely to put hydrogen at a competitive advantage with respect to new applications, as compared to other countries. As indicated in Section 1.4, in terms of the cost per unit of energy, the model price range of blue hydrogen is more competitive than imported natural gas, and that of green is comparable to imported diesel in Japan. Notably, with FCEVs' efficient energy conversion rate (see *ROAD TRANSPORTATION* in Section 1.3), road transportation is likely to be the first sector to see a large-scale hydrogen adoption.

However, costs associated with international trade (including costs of marine transport and port infrastructure) could undermine the potential competitiveness of hydrogen in the domestic market. Therefore, both Japan's government and industries have focused on establishing an efficient global supply chain of hydrogen and searching for the ideal hydrogen carrier.

Instead of relying on a single technology, Japanese companies are examining a supply chain of ammonia, liquified hydrogen, and methylcyclohexane (MCH). Irrespective of the nature of the carrier, Japan intends to procure hydrogen in large quantities at an affordable price while ensuring safety and stability. At present, no such import system has been established. For example, Japan's import of ammonia is now about 0.2 million tons and is projected to become 20 million tons, which is equivalent to the current trade volume of the entire world. Thus, as a large potential importer, Japan will require several investments in infrastructure and importing site facilities.

COUNTRY-SPECIFIC POLICY DRIVERS

Japan is the first country to establish nationwide hydrogen framework by introducing *The Basic Hydrogen Strategy*[170] in December 2017. The government also formulated the *Strategic Roadmap for Hydrogen and Fuel Cells* in March 2019 to identify technological trajectories, and after declaring its intention to achieve

---

[167] International Energy Agency. Global Hydrogen Review 2021. November 2021. https://iea.blob.core.windows.net/assets/5bd46d7b-906a-4429-abda-e9c507a62341/GlobalHydrogenReview2021.pdf

[168] At present, by far the largest hydrogen electrolyzer in the world is Baofeng Energy's 150 MW plants in China, which was completed in February 2022. More larger projects are already under construction around the world

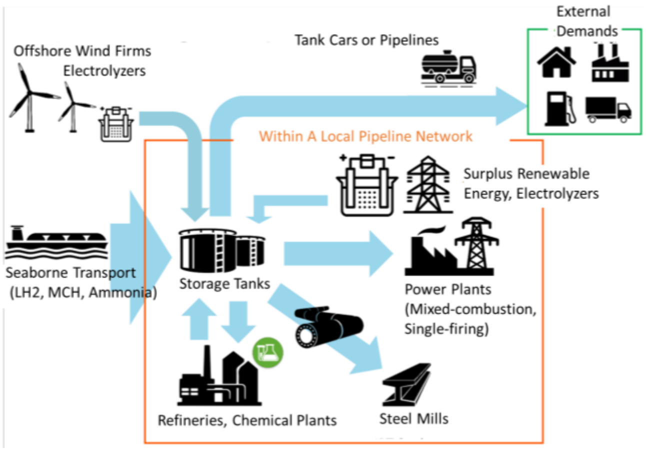
[169] Interview to people familiar with the matter

[170] Ministry of Economy, Trade, and Industry. The Basic Hydrogen Strategy. 2017. https://www.meti.go.jp/english/press/2017/pdf/1226_003b.pdf

carbon neutrality by 2050, updated its hydrogen policy by way of the *Green Growth Strategy Through Achieving Carbon Neutrality in 2050*[171] announced in June 2021. These steps suggest Japan's keen political interests in hydrogen. Historically, hydrogen has gained attention not only for its environment-friendly characteristics but also for its potential to contribute to national energy security. Endowed with fewer resources, energy security for Japan relies on energy diversification. Given the multiple paths to clean hydrogen options, Japan has prioritized hydrogen through policies and strategies. Japan's Prime Minister Kishida acknowledged the impact of the Ukraine crisis on Japan when he visited Kobe port to attend the celebration of the HESC project – the first successful example of transportation of liquid hydrogen. He mentioned that "stable energy supply is being seriously questioned against the backdrop of the situation in Ukraine. It is necessary to achieve decarbonization in tandem with stable supply, and the key to this is hydrogen." He also recommended that Japan strengthen support measures for hydrogen.[172]

In March 2022, a hydrogen-focused subcommittee was set up at the Ministry of Economy, Trade, and Industry of Japan (METI), where stakeholders like government agencies, industrial partners, and consumer organizations came together to discuss support measures for hydrogen in detail. Below is a simple diagram of expected large-scale social implementation in the near-term future shared among those relevant stakeholders, focusing on imported hydrogen.

Figure 28 Example of Social Implementation of Hydrogen in Japan[173]



The most urgent topic now is effective demand creation. Although the Japanese government has not given a breakdown of the total demand target, some examples of potential hydrogen demands were shown in the Green Growth Strategy for the first time. Conventionally, Japan has been ahead of other global leaders in the commercialization of FCEVs and household fuel cells with wide application of small-scale fuel cells likely to emerge as a primary focus. At the same time approaches for stimulating large-scale demand by the following means are gaining traction.

---

[171] Ministry of Economy, Trade, and Industry. Green Growth Strategy Through Achieving Carbon Neutrality in 2050. 2020 (updated in 2021). https://www.meti.go.jp/english/press/2021/0618_002.html

[172] Sankei Shimbun. April 4, 2022. https://www.sankei.com/article/20220409-VNDTE3RFZNLXRLMEHYDC5XR4SY/

[173] Ministry of Economy, Trade, and Industry. Hydrogen and Fuel Cells Strategy Committee. March 22, 2021. https://www.meti.go.jp/shingikai/energy_environment/suiso_nenryo/025.html

Table 14 National Hydrogen Demand Target and Potential Hydrogen Demand in Various Sectors[174]

National Target	Hydrogen Volume [t/year]	Hydrogen Cost[$/kg]
2030	3 million *With low-carbon hydrogen accounting for 0.42M *2M at present, dominated by gray hydrogen	3.0
2050	20 million	2.0

<Potential Domestic Demands for Hydrogen>

- Hydrogen power generation	5~10 million [t/year]
- Industry (steelmaking)	7 million [t/year]
- Mobility	6 million [t/year]

First, according to Japan's new plan of generation mix, hydrogen and ammonia are projected together account for 1% in 2030 rising to 10% by 2050 of total power generation[175]. To realize that goal, mixed combustion technologies for hydrogen and ammonia are being steadily developed through demonstration projects, and some Japanese companies have become global leaders in the space. For example, JERA, Japan's biggest power generator, announced one of the global largest auctions to buy ammonia fuel for the long term. As JERA has already started the demonstration of a 20% ammonia fuel mix and aims to expand its use, it plans to buy up to 500,000 tons of ammonia until sometime in the 2040s.[176] At the same time, Mitsubishi Heavy Industry aims to convert a gas turbine unit to run on pure hydrogen by 2027 in Netherlands, and develop gas turbines that can operate with a 30% hydrogen fuel mix in 2025 and run on 100% hydrogen in 2045 for a large-scale green hydrogen project being developed in Utah, USA.[177] The company also plans to penetrate the domestic market in the future. Market participants interviewed for this report expect that Japan and other nations (including in Europe) are expected to see a rise of interest in hydrogen generation, especially after the severe turmoil caused by the Ukraine crisis.

Second, following the example of regional hydrogen hubs planning in the US and other countries, Japan has introduced the goal of creating hydrogen bases that accumulate hydrogen demand by connecting importing ports with steel mills and other chemical plants in the existing industrial complex on coastal areas. So far, the reduction of iron ore using hydrogen has not been commercially implemented, and securing the stable, largescale, and low-cost hydrogen supply through imports will be essential to expand the use in these industries.

Third, Japan has introduced a series of policy measures to stimulate hydrogen demand. In terms of financial support, Japan has created the Green Innovation Fund comprising approximately $18 billion to achieve carbon neutrality by 2050. Hydrogen features as the first project amongst its 11 investment

---

[174] Ministry of Economy, Trade, and Industry. Green Growth Strategy Through Achieving Carbon Neutrality in 2050. 2020 (updated in 2021). https://www.meti.go.jp/english/press/2021/0618_002.html

[175] Ministry of Economy, Trade, and Industry. The Sixth Strategic Energy Plan. October 22, 2021. https://www.meti.go.jp/english/press/2021/1022_002.html

[176] JERA. JERA to Conduct International Competitive Bidding for the Procurement of Fuel Ammonia. February 18, 2022. https://www.jera.co.jp/english/information/20220218_853

[177] Mitsubishi Heavy Industry. Development of Hydrogen/Ammonia Firing Gas Turbine for Decarbonized Society. September 2021. https://www.mhi.co.jp/technology/review/pdf/e583/e583030.pdf

targets, with up to $ 4 billion allocated[178]. This project encompasses the development of the hydrogen import and supply chain and hydrogen/ammonia mixed combustion technologies at power plants. METI has proposed a law reform to position hydrogen and ammonia as clean energy resources under the Japanese legislation that requires energy retailers to procure a certain proportion of their energy supply from non-fossil resources. This reform is intended to align regulatory provisions with Japan's hydrogen targets and will ensure that Japan's new energy mix includes hydrogen and ammonia. The bill is currently being debated in the national parliament.

Lastly, several measures to provide long-term stability and predictability to investments in hydrogen infrastructure such as receiving terminals and dehydrogenation facilities are being discussed at the METI committee mentioned above, in reference to the CfD scheme adopted in the UK and Germany. The Japanese government's continued and strong commitment to the hydrogen sector suggest that investors are likely to receive strong policy support.

INFRASTRUCTURE DEVELOPMENT

It is essential for Japan to develop import infrastructure to connect to large-scale global hydrogen supply chains. Some Japanese companies are also taking the leading role in developing the necessary infrastructure designed for hydrogen shipment in hydrogen export countries, with the aid of the Japanese government.

As previously mentioned, ammonia, liquid hydrogen, and MCH are pursued as hydrogen carriers. Notably, as both liquid hydrogen and MCH necessitate a new infrastructure, approximately $2 billion from the Green Innovation Fund (the single largest allocation from the fund) will be used for domestic and foreign infrastructure development for these new supply chains. The international transport of liquid hydrogen from Australia to Kobe port and MCH from Brunei to Kawasaki port, respectively, has already taken place with the use of pilot facilities.

While Japan's investments in such carrier infrastructure may seem contrarian to the use of ammonia -- increasingly viewed as a prospective candidate for marine transport and storage medium in the rest of the world (see *LONG DISTANCE TRANSMISSION* in Section 1.3) -- the rationale for Japan's alternative infrastructure investments, especially for liquid hydrogen, would be as follows.

Theoretically, liquid hydrogen is more energy efficient than ammonia. In terms of the total energy loss during the conversion and reconversion process, IEA indicates that liquid hydrogen would potentially have the lowest losses among other carriers including ammonia[179]. Liquid hydrogen doesn't require a reconversion facility at receiving sites as opposed to ammonia, which consumes considerable energy at

---

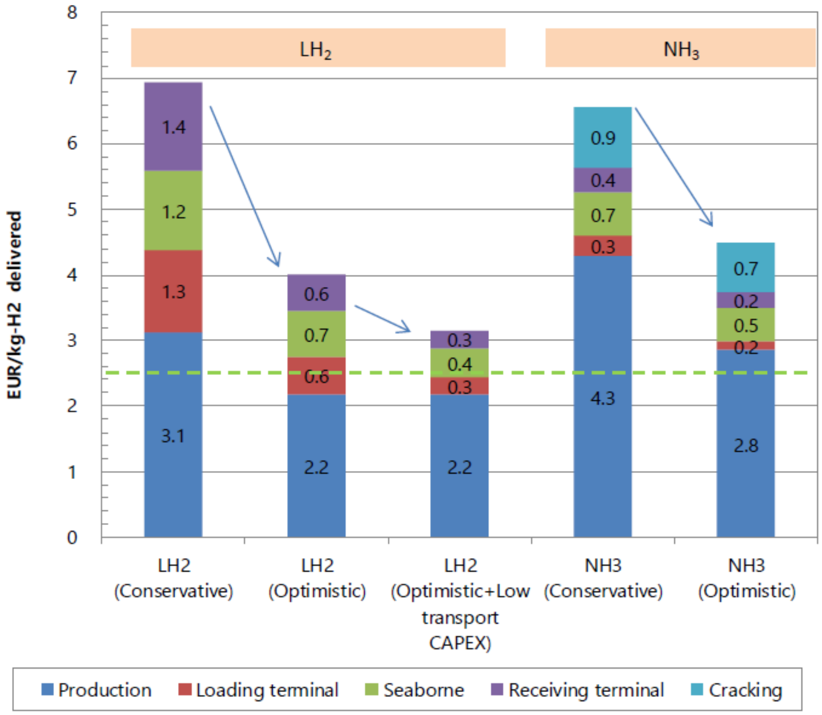
[178] New Energy and Industrial Technology Development Organization. Green Innovation Fund Project, the first project to launch a demonstration research project on hydrogen. August 26, 2021. https://www.nedo.go.jp/news/press/AA5_101471.html

[179] IEA. The Future of Hydrogen. 2019. https://www.iea.org/reports/the-future-of-hydrogen
The total energy loss of liquified hydrogen is currently 25-35% and potentially 20% while that of ammonia is 7-18% for conversion process and less than 20% for reconversion process.

dehydrogenation facilities. On the other hand, a major issue would be to close the gap between the current efficiency of liquefaction processes and the ideal level by scaling up the relevant facilities.[180]

Along with the energy efficiency of liquid hydrogen, some researchers point out that as liquefaction facilities are scaled-up, the cost of liquid hydrogen would be comparable to that of ammonia at demand sites. Moreover, it has been argued that the cost can potentially be lowered below that of ammonia by optimizing capacity size and operation given that the current CAPEX share in the total cost is assumed to be larger for the liquid chain than for the ammonia alternative. The figure below shows an example of the estimation of cost and reduction potential of both liquified hydrogen and ammonia chains, assuming transportation from Northern Europe to Japan. It implies that liquified hydrogen can become cheaper than ammonia in an optimistic scenario and closer to Japan's target price, represented by the green line.

Figure 29 Hydrogen Applications Cost Comparison and Reduction Potential of Liquid Hydrogen and Ammonia Supply Chain from Northern Europe to Japan[181]



Japan, as a leading LNG importer, saw over a 40-year term that its LNG costs reduced by half, as the size of its liquefaction capacities increased 10 times. Therefore, as suggested in the HESC Case Study in Section 1.5, Japanese companies are strongly committed to improving the efficiency of the process required for liquid hydrogen and are taking the lead in establishing new infrastructure both at home and abroad.

---

[180] Lutz Decker. Latest Global Trend in Liquid Hydrogen Production. 2019. https://www.sintef.no/globalassets/project/hyper/presentations-day-1/day1_1430_decker_latest-global-trend-in-liquid-hydrogen-production_linde.pdf

[181] Isimoto, Yuki. Large-scale production and transport of hydrogen from Norway to Europe and Japan: Value chain analysis and comparison of liquid hydrogen and ammonia as energy carriers. 2020. https://www.sciencedirect.com/science/article/abs/pii/S036031992033384X

With respect to the domestic transport infrastructure of imported hydrogen, creating local hydrogen pipe networks is seriously being considered since targeted demands such as power generation and industry complexes are concentrated on limited coastal areas. Tank lorries will be mainly used to supply hydrogen to refueling stations. The idea of blending into the existing gas networks across the country is still at a very early stage and both direct injection of hydrogen and the use of synthetic fuels are being discussed.

EMERGING BUSINESS OPPORTUNITIES FOR FINANCIAL PLAYERS

The following table is a list of international hydrogen trade projects related to Japan identified in IEA's report. As a major potential importer, Japan has focused on establishing a global hydrogen supply chain. Hydrogen investment opportunities related to Japan can emerge in domestic demand creation such as the implementation of hydrogen or ammonia fueled generation, key import facilities like receiving terminals, and overseas export infrastructure like large-scale hydrogen liquefaction plants. International chains of liquid hydrogen and MCH have already been set up and tested through several demonstration projects. Japan's commitment to the hydrogen sector and accumulated technologies could create significant opportunities for financial players to contribute to international hydrogen trade, which will be critical for global decarbonization.

Table 15 List of expected hydrogen projects in Japan[182]

Project name	Expected First Shipping Year	Export Country	Import Country	Energy Source	Carrier	Normalized capacity [kt H2/year]
Hydrogen Energy Supply Chain (HESC)	2030* (commercial phase)	Australia	Japan	Brown coal	Liquid Hydrogen	238
Stanwell Iwatani Gladstone project	2026	Australia	Japan	Renewable	Liquid Hydrogen	280
Asian Renewable Energy Hub	2028	Australia	Japan or Korea	Renewable-Solar PV	Liquid/ Ammonia	1,800 (+ 10,000 for Ammonia)
Origin Energy KHI Townsville project	2025	Australia	Japan	Renewable - Solar PV and Wind	Liquid Hydrogen	36
Eyre Gateway	-	Australia	Japan or Asia	Renewable	Ammonia	13

---

[182] International Energy Agency, 2021, Global Hydrogen Review 2021, https://iea.blob.core.windows.net/assets/5bd46d7b-906a-4429-abda-e9c507a62341/GlobalHydrogenReview2021.pdf (updated by other relevant resources)

Other Countries

While not discussed in-depth, this study also identified several other countries which are emerging markets for hydrogen activity and show promising potential for growth and investment opportunities in the coming decades:

UNITED KINGDOM

Market Drivers: Green Hydrogen production in the UK would benefit from its abundant wind resources onshore and offshore, with offshore generation among the lowest cost sources today. Technically its variable renewable electricity production potential could be ten times higher than the expected electricity demand in 2030. The UK is home to some of the leading technology companies for electrolyzer production for green hydrogen. It is also one of the few countries that have prepared for the wide-scale development of CCS for low-carbon blue hydrogen production.

Policy Drivers: The UK published its national hydrogen strategy in 2021, with the goal of reaching 5GW of low carbon hydrogen production capacity by 2030 supported by a £240m ($333.95m) hydrogen fund, hoping that will trigger £4bn in private investment. The government has a twin track approach to develop both green electrolysis and blue CCS[183]. The UK government also has started assessing feasibility and cost of hydrogen blending and launched public consultation on a hydrogen business model that might have revenue support similar to the 'Contracts for Difference' supporting offshore wind.

Infrastructure Development: The UK has several emerging hydrogen Hubs: clusters of industrial players within which hydrogen is produced, stored and distributed largely implementing CCS technology. In the future, hydrogen networks will be developed based on connecting these different hubs and clusters across different regions throughout the development of new and repurposing the existing infrastructure.

Hydrogen Demand: With its relative low wind energy prices and leading role in technological innovation, UK has the potential to become an exporter of both blue and green hydrogen in the future.

GERMANY

Market Drivers: Germany has mediocre energy resources from wind and solar combined with a relatively large potential domestic renewable energy market. Technically its variable renewable electricity production potential could be only twice as high as the expected electricity demand in 2030. At the same time Germany currently plans to phase out nuclear at the end of 2022 and phase out coal by 2038; it intends to fill the gap with renewable energy. Germany is also an energy importing country with 61% of net energy import.

---

[183] UK Secretary of State for Business, Energy & Industrial Strategy, 2021, UK Hydrogen Strategy, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1011283/UK-Hydrogen-Strategy_web.pdf

Policy Drivers: Germany published its national hydrogen strategy in 2020, intending to reach 5GW of low carbon hydrogen by 2030 with an additional 5GW by 2040. The German government has committed EUR 8 billion of public investment to support large-scale hydrogen projects and infrastructure developments. These public investments are expected to leverage EUR 33 billion of private investments to support the development of local hydrogen value chains[184]. Germany also introduced the national emissions trading scheme for fuels in 2021 in addition to its participation in the EU ETS, which could potentially provide further advantages to the development of the local hydrogen market.

Infrastructure Development: With government funding support, Germany has set up the EUR 3.5 billion plan to build 1,500km of pipeline infrastructure to transport the green hydrogen across the country. Future infrastructure demand might come from the import infrastructure including hydrogen storage at ports and the mid and downstream infrastructure such as green ammonia dissociation plants, consumption facilities, and hydrogen refueling stations.

Hydrogen Demand: Germany set up an ambitious goal of consuming more than 90 TWh of hydrogen in 2030. It also focuses on pressing industrial players to decarbonize in the hard-to-abate sectors. However, the estimated production capacity only covers a seventh of the projected hydrogen demand[185]. Therefore, Germany plans to secure future energy supply through international cooperation and partnerships. In sum, Germany has the great potential to become a hydrogen importer in the future.

CHINA

Market Drivers: China has the world's largest deployed renewable capacity, with 634 GW in 2021. It is expected to expand to 1600 GW by 2030, which implies the possibility of lower renewable electricity pricing through with the economies of scale. Moreover, China is currently the largest electrolyzer manufacturer with 47% of the global capacity[186], and with this scale has the potential to achieve the lowest electrolyzer costs in the market.

Policy Drivers: China just released its national hydrogen strategy in March 2022 with goals to produce 200,000 tons of green hydrogen by 2025. China's national hydrogen strategy highlights the importance of building up a domestic supply chain with sufficient end-user demand and less reliance on hydrogen imports[187]. The central government does not provide any direct funding for the hydrogen development, but on the local level many governments have set subsides and incentives along with massive investments made by the state-owned enterprises.

Infrastructure Development: The application of green hydrogen in China is mainly focused on the transportation sector. For example, China’s largest hydrogen producer Sinopec announced that it would

---

[184] IEA, 2021, Package for the future – Hydrogen Strategy, https://www.iea.org/policies/11561-package-for-the-future-hydrogen-strategy

[185] Center for Strategic & International Studies, 2021, Germany’s Hydrogen Industrial Strategy, https://www.csis.org/analysis/germanys-hydrogen-industrial-strategy

[186] Bloomberg NEF conference

[187] Center for Strategic & International Studies, 2022, China unveils its first long-term hydrogen plan, https://www.csis.org/analysis/china-unveils-its-first-long-term-hydrogen-plan

invest $4.6 billion in green hydrogen infrastructure development and build 1,000 refueling stations in the next five years.

Hydrogen Demand: China is the largest hydrogen producer and consumer globally – almost entirely produced from unabated fossil fuels. With the central government's goal to achieve self-sufficient energy consumption and production, China seems unlikely to become an exporter or importer of green hydrogen.

SOUTH KOREA

Market Drivers: South Korea has limited high-cost renewable sources. Korea also has high population density which imposes challenges for deployment of solar power stations, with its offshore wind development still at a very early stage. Korea is highly energy dependent and imports more than 80% of its total energy consumption. It currently produces no low-carbon hydrogen and domestic production forecasts at very low levels.

Policy Drivers: The Korean government is one of the pioneers in developing its national strategy for hydrogen use, focusing on the hydrogen-powered vehicle and large-scale fuel cells for power generation. It aims to produce 6.2 million fuel cell electric vehicles (FCEV) with more than 1200 hydrogen refueling stations by 2040[188]. The Korean government earmarked $9 billion in targeted hydrogen funding. With enacting the world's first hydrogen law, the government provides financial assistance to companies that focus on hydrogen development. Korea also has a robust emissions trading scheme covering 74% of its national GHG emissions in 2021[189].

Infrastructure Development: The Korean government also aims to build the hydrogen pipeline across the country along with its 1200 hydrogen refueling stations to support the growing FCEV industry. Since Korea is very likely to rely on importing hydrogen from other countries, it has started to develop infrastructures for importing hydrogen. The established ammonia and LNG import infrastructures serve as starting points for hydrogen value chain facilities.

Hydrogen Demand: Korea will likely have a significant demand for hydrogen from industrial usage and transportation. It is one of the largest steel manufacturing and oil refining markets globally, and these sectors are very likely to de-carbonize using green hydrogen. With the Korean government's ambitious goal to develop the local FCEV markets, the demand for hydrogen will require massive imports from the likely producing countries such as Australia and Saudi Arabia.

---

[188] Netherlands Enterprise Agency, 2019, Hydrogen Economy Plan in Korea, https://www.rvo.nl/sites/default/files/2019/03/Hydrogen-economy-plan-in-Korea.pdf

[189] H2i, 2021, Hydrogen Investability index report, https://www.h2-index.com/

CONCLUSION: OUTLOOK TO THE FUTURE OF HYDROGEN

To achieve the global climate objectives outlined in the Paris Agreement, governments around the world have introduced national and sectorial carbon neutrality goals and decarbonization policies. These measures are poised to impact not only the global energy mix and consequently energy trade, but also carbon intensive industries and businesses. Although policymakers have shown a growing interest in expanding the role of hydrogen in their mitigation toolkits, private investors and project developers perceive clean hydrogen as a nascent and high-risk sector and are hesitant to make investment decisions.

To alleviate these concerns, this report first provided a comprehensive view of hydrogen energy including technologies and cost gap issues that currently challenge its wide-scale adoption. It identified and highlighted a series of regional and policy drivers as a measurable framework for analyzing the potential to close the cost gap. Then, the report conducted a detailed analysis of Chile, Saudi Arabia, Australia, United States, Spain, and Japan, six promising hydrogen markets in terms of regional priorities, regulations, and scalable investment opportunities.

Looking toward the future, green hydrogen is a remarkable alternative to fossil fuel for a successful energy transition in the sectors such as iron and steel, refineries, chemicals, road heavy transportation, maritime transportation, and power storage, where renewable energy alone is not sufficient or applicable to replace carbon-intensive energy sources. As low carbon hydrogen technologies evolve, economies of scale and optimization of electrolyzer capacity can contribute towards reducing the cost of hydrogen. Moreover, as learned from this report’s case studies and country analyses, regional market and policy factors will play a key role in making large-scale hydrogen projects commercially viable.

APPENDIX: LEVELIZED COST OF GREEN HYDROGEN ANALYSIS

METHODOLOGY

The Columbia Capstone Team has modeled the levelized cost of green hydrogen under various scenarios by largely adopting the assumptions listed below. These assumptions are informed by the recently published Lazard's Levelized Cost of Hydrogen Report, by estimates published by the National Renewable Energy Laboratories (NREL), and in consideration of expert advice from Columbia Center on Global Energy Policy (CGEP) which has also published on this topic.

Table below provides a summary of key inputs used in the LCOH analysis, and there are several assumptions need to be noticed here:

- The LOCH is calculated based on the production costs from two types of electrolyzers: Alkaline and PEM without consideration of additional costs of handling hydrogen for markets such as conversion, storage or transportation costs, etc.
- The project life is assumed to be 20 years, with one stack replacement at the end of year 10, where the replacement cost is the same as the original cost of the stack.
- In a departure from the LAZARD model, the Columbia Capstone Team model eliminates adjustments for inflation and includes other modifications (highlighted in blue below) informed by our research and interviews.
- The assumptions scenario below yields an LCOH of **$3.70/kg** for the alkaline process and **$4.84/kg** with the polymer electrolyte membrane (PEM) process.

Key Assumptions (2022)

		Alkaline	PEM
Capacity	*kW*	20,000	20,000
Total Capex ($ per kw)	*$/kW*	$860	$1,110
Electrolyzer stack ($ per kw)	*$/kW*	$345	$450
Plant lifetime	*Years*	20	20
Stack lifetime	*Hours*	67,500	60,000
Heating value	*kWh/kg H2*	33	33
Electrolyzer Utilization	*%*	***40%***	***40%***
Electrolyzer Efficiency	*%*	67%	58%
Water Costs	*$/kg H2*	$0.021	$0.021
Electricity Cost	*$/MWh*	***$40***	***$40***
Annual H2 Produced	*million tons*	***1,409***	***1,220***
Annual Energy Consumption	*MWh/year*	***171,696***	***171,696***
Warranty & Insurance	*%*	1.0%	1.0%
O&M (% of CAPEX)	*%*	1.5%	1.5%
WACC	*%*	***6.4%***	***6.4%***

The tables below were generated from the Capstone team's model for calculating the levelized cost of green hydrogen under various combinations of renewable energy input costs and electrolyzer utilization rates.

In the tables below, the Alkaline Electrolyzer is assumed to have a CAPEX of $860/kW and PEM Electrolyzer is assumed to have a CAPEX of $1,110/kW. A manufacturing process run by wind and solar would likely have limited utilization rates. Lower utilization would increase the allocation of capital costs per unit of production, with higher LCOHs resulting.

Sensitivity Analysis to Electricity Cost and Utilization Rate at CAPEX level assumed for 2022

Alkaline (20 MW)

Energy Cost ($/MWh)	$/kg	Electrolyzer Utilization 60%	50%	40%	30%	20%
	$20	$2.14	$2.37	$2.71	$3.27	$4.40
	$30	$2.64	$2.87	$3.20	$3.77	$4.89
	$40	$3.14	$3.36	$3.70	$4.27	$5.39
	$50	$3.64	$3.86	$4.20	$4.76	$5.89
	$60	$4.13	$4.36	$4.70	$5.26	$6.39

PEM (20 MW)

Energy Cost ($/MWh)	$/kg	Electrolyzer Utilization 60%	50%	40%	30%	20%
	$20	$2.85	$3.19	$3.69	$4.54	$6.22
	$30	$3.43	$3.76	$4.27	$5.11	$6.79
	$40	$4.00	$4.34	$4.84	$5.69	$7.37
	$50	$4.58	$4.91	$5.42	$6.26	$7.94
	$60	$5.15	$5.49	$5.99	$6.83	$8.52

The Columbia Capstone team reassessed the impact of reduced electrolyzer CAPEX in the future on the cost of hydrogen by running the two scenarios further below which reduce the Alkaline Electrolyzer CAPEX to $430/kW and the PEM Electrolyzer to $555/kW. All other inputs are assumed to stay the same as shown in the assumption table.

Sensitivity Analysis to Electricity Cost and Utilization Rate with 50% reduction in CAPEX

Alkaline (20 MW)

Energy Cost ($/MWh)	$/kg	Electrolyzer Utilization 60%	50%	40%	30%	20%
	$20	$1.58	$1.69	$1.86	$2.14	$2.71
	$30	$2.08	$2.19	$2.36	$2.64	$3.20
	$40	$2.57	$2.69	$2.86	$3.14	$3.70
	$50	$3.07	$3.18	$3.35	$3.64	$4.20
	$60	$3.57	$3.68	$3.85	$4.13	$4.70

PEM (20 MW)

Energy Cost ($/MWh)	$/kg	Electrolyzer Utilization 60%	50%	40%	30%	20%
	$20	$2.01	$2.18	$2.43	$2.85	$3.69
	$30	$2.59	$2.75	$3.01	$3.43	$4.27
	$40	$3.16	$3.33	$3.58	$4.00	$4.84
	$50	$3.74	$3.90	$4.16	$4.58	$5.42
	$60	$4.31	$4.48	$4.73	$5.15	$5.99