FINANCING THE GREEN HYDROGEN ECONOMY

by

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I. Executive Summary

Hydrogen is a versatile energy carrier, which can leverage energy resources—renewables, nuclear, and fossil fuels paired with carbon capture and storage—to couple baseload power with variable generation to offer energy storage and resiliency. It can also be used as a clean fuel source or feedstock to replace carbon-intensive energy sources (Satyapal, 2017). This research focused on green hydrogen, which produces hydrogen from the process of electrolysis using renewable electricity.

Hydrogen is expected to play a critical role in the decarbonization of the global energy system, as the IEA projects that in order to reach net-zero emissions by 2050, low-carbon hydrogen use will need to grow six times from today's levels to meet up to 10% of total energy consumption (IRENA, 2022). Amidst growing concerns around energy security, governments and private industry are showing an appetite for tapping green hydrogen as an energy source, committing an unprecedented amount of financing to stand up a robust market in the next decade.

While projects worth nearly $240 U.S. billion in the low-carbon hydrogen pipeline have been put forward in 2022, only about 10% of these have reached final investment decision (McKinsey Sustainability, 2022). To meet decarbonization goals, investment in green hydrogen facilities at a MW and above scale will need to rapidly increase. Yet, investors are faced with significant challenges and risks. Based on an analysis of large-scale green hydrogen projects that have successfully secured financial commitment, this paper sets out a framework for evaluating potential investment opportunities.

Key Findings

Several metrics are key to evaluating, prioritizing, and de-risking potential green hydrogen investments. These metrics include:

- Strong public sector support, including national hydrogen roadmaps, or market incentives such as low-cost loans, tax credits, or grants programs.
- Access to plentiful resources including renewable resources, geologic storage, and access to water and raw materials.
- The levelized cost of hydrogen must be optimized for several key technical and financial considerations including: electrolyzer CAPEX, renewable electricity OPEX, and other financing considerations including the discount rate and debt to equity ratio.

II. Introduction to Hydrogen as a Clean Fuel Source

Hydrogen (H_2) is considered the most abundant chemical element on earth, contributing to ~75% of the mass of the universe (U.S. Department of Energy, 2022). A hydrogen atom is simple: it consists of only one proton and electron. While it can be produced from diverse sources, it does not exist by itself in nature and must be released from the chemical compounds that contain it.

Hydrogen is a versatile energy carrier, which can leverage energy resources—renewables, nuclear, and fossil fuels paired with carbon capture and storage—to couple baseload power with variable generation to offer energy storage and resiliency. It can also be used as a clean fuel source or feedstock to replace carbon-intensive energy sources (Ibid).

Hydrogen is expected to play a critical role in the decarbonization of the global energy system, as the IEA projects that in order to reach net-zero emissions by 2050, low-carbon hydrogen use will need to grow from 1 million tons (MT) produced today to 34 MT produced each year (IEA, 2022). This research focuses on green hydrogen, which uses electrolysis from renewable electricity to split water into hydrogen and oxygen, resulting in little to no carbon emissions.

Amidst growing concerns around energy security, governments and private industry are showing an appetite for tapping green hydrogen as an energy source in particular, committing an unprecedented amount of financing to stand up a robust hydrogen market. While nearly 700 low-carbon hydrogen projects worth $240 billion USD were announced last year, only 10% of them have reached the final investment decision (FID), which is the critical step to development (McKinsey Sustainability, 2022).

To meet decarbonization goals, investment in green hydrogen facilities at a MW and above scale will need to rapidly increase. Yet, potential investors are faced with significant challenges and risks. Based on an analysis of large-scale green hydrogen projects that have secured financial commitment, this paper sets out a framework for evaluating potential investment opportunities.

III. Market Landscape for Green Hydrogen

In 2022, global hydrogen demand stood at 94 MT, primarily for oil refining and the production of fertilizers (Ibid). Projected demand is estimated to grow 7.5x to nearly 660 MT in 2050 (Hydrogen Council, 2021). Nearly 96% of hydrogen is produced from fossil fuels today (IRENA, 2022) and thus, there is interest in low-carbon production methods to support decarbonization efforts.

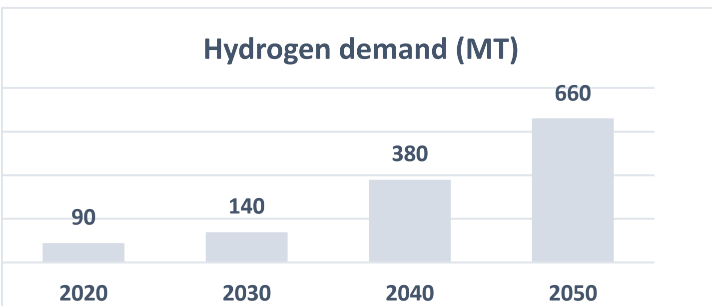
In all scenarios produced by the International Energy Agency (IEA) and International Renewable Energy Agency (IRENA), green hydrogen is expected to be the dominant method of hydrogen production and will contribute anywhere between 12-22% of all energy demand by 2050 (Ibid). Green hydrogen is expected to outperform the gray method, which uses steam methane reformation from natural gas to produce hydrogen, and is the most common and cheapest form of hydrogen production today. Blue hydrogen facilities are retrofitted with carbon capture and storage technologies to capture and store carbon dioxide emissions from steam methane reformation of natural gas. The blue method of production is touted as the other low-carbon alternative to gray hydrogen, yet poses risks of leaking methane into the atmosphere, a potent greenhouse gas, and continues reliance on fossil fuels.

Figure 1. Color Codes of Hydrogen Technologies

Color code[1]	Technology utilized to produce hydrogen	Carbon Intensity
Black/Brown	Black coal or lignite (brown coal) is gasified to produce hydrogen.	High
Blue	Steam reforming brings together gas and heated water with CCS used to trap and store carbon.	Moderate
Green	Electrolysis of water to produce hydrogen from renewable electricity	Low
Gray	Uses steam methane reformation from natural gas. Most common and cheapest form of H2 production today.	High
Pink	Nuclear-powered electrolysis to produce hydrogen.	Low
Turquoise	Methane pyrolysis produces hydrogen and solid carbon using heat.	Low

Global electrolyzer capacity stood at 2 GW in 2022, however, the pipeline of announced projects in the last few years indicate that capacity could rise to 242 GW by 2030. Europe currently leads the world in announced projects, followed by Asia, then North America.

Figure 2. Cumulative Electrolyzer Capacity (2022-2030)[2]



The majority of the electrolyzer projects in development are designed for industrial applications, particularly in Europe, driven by strong decarbonization policies and government support. Ammonia and methanol present the largest potential for green hydrogen production, but hydrogen also offers the opportunity to mitigate other carbon-intensive sectors including steel or cement production. Transport, power generation, and heating also hold promise but are viewed as a secondary priority given the challenges with transport and storage.

Figure 3. Noteworthy GW-scale projects that plan to produce hydrogen via electrolysis

Project	Description	Country	End use	Capacity	COD
AREH (bp)[3]	Produce 1.6 MT of green hydrogen or nine MT of green ammonia.	Australia	Industry	260 MW	2027
Egypt Green (Fertiglobe)[4]	Produce 15,000 MT H_2 annually from solar and wind as feedstock for ammonia.	Egypt	Industry	100 MW	2030

[1] https://www.acciona.com.au/updates/stories/what-are-the-colours-of-hydrogen-and-what-do-they-mean/?_adin=02021864894
2 https://about.bnef.com/blog/a-breakneck-growth-pivot-nears-for-green-hydrogen/
3 https://www.bp.com/en/global/corporate/news-and-insights/press-releases/bp-to-lead-and-operate-one-of-the-worlds-largest-renewables-and-green-hydrogen-energy-hubs-based-in-western-australia.html
[4] https://www.ebrd.com/work-with-us/projects/psd/53558.html

H2fifty (bp)[5]	Produce 20,000-30,000 MT H_2 annually from X power. FID expected in 2023.	Netherlands	Industry, transport	250 MW	2026
Holland Hydrogen I (Shell)[6]	Produce up to 60,000 kg of H_2 per day from wind power. Reached FID in July 2022.	Netherlands	Industry	200 MW	2025
Hysenergy (Everfuel)[7]	Power-to-X facility executed in stages to support Denmark's 70% C02 reduction target. 20 MW installed in 2022.	Denmark	Industry, transport	300 MW 1 GW	2025 2030
Kuqa (Sinopec)[8]	Produce 20,000 MT H_2 annually from solar PV. Includes storage, transport and refining.	China	Industry, transport	260 MW	2023
REFYHNE 2 (Shell)[9]	Produces 1,300 H2 per year from a 10 MW facility already constructed. Second phase reached FID in late 2022.	Germany	Industry, power generation, building heating	100 MW	2026

The green hydrogen projects currently active or in development are clustered in industrial zones, from chemical facilities to refineries. Many countries are facilitating the development of "hydrogen hubs" through grants and loans programs. A hub is a cluster of local hydrogen, production, storage and demand, concentrated across industrial, transport, and energy markets.

The U.S. Department of Energy (U.S. DoE) has committed $7 billion to support six to eight regional clean hydrogen hubs—incentivizing development of green, blue, and pink hydrogen facilities across the country. The majority of applicants currently in line for DoE funding have proposed to develop green hydrogen projects (Resources for the Future). Similarly, the Government of Australia has pledged AUD $526 million to develop up to eight hydrogen hubs with a focus on green hydrogen production due to the country's abundant renewable energy potential (CSIRO, 2022). The European Commission has approved 5 billion Euros to develop 41 projects across potential European hubs (European Commission, 2022). Similar to the Liquified Natural Gas (LNG) market, hydrogen hubs could serve as springboards for production—as import or export hubs or storage sites—displacing fossil fuels and reshaping global energy trade.

The Port of Rotterdam's Vision to Develop World's Leading Hydrogen Hub

The Port of Rotterdam demonstrates what the future of green hydrogen might look like. Currently Europe's largest seaport and home to the world's leading industrial clusters**,** it supplies 27 million tons of oil and natural gas from Russia to Netherlands and the rest of Europe. Following the war in Ukraine, it is positioning itself to be the world's largest "hub" for green hydrogen import and export providing by Europe with 4.6 million tons of hydrogen per year by 2030 (Port of Rotterdam, 2022)**.** It has already approved 2.5 GW of electrolytic hydrogen projects by 2030. It would produce up to 600,000 tons for Europe with the remaining 4 MT imported from 10 countries.

[5] https://www.h2-fifty.com/
[6] https://www.shell.com/media/news-and-media-releases/2022/shell-to-start-building-europes-largest-renewable-hydrogen-plant.html
[7] https://www.everfuel.com/projects/hysynergy/
[8] https://www.prnewswire.com/news-releases/sinopec-lands-worlds-largest-photovoltaic-green-hydrogen-production-project-in-kuqa-xinjiang-301433733.html
[9] https://www.refhyne.eu/

IV. Green Hydrogen Project Financing

Despite impressive public announcements, less than 10% of hydrogen projects announced in the last year have reached final investment decision (FID) – where the company (or companies) owning or operating the project have made the financial commitment necessary to proceed to development (McKinsey Sustainability, 2022). At MW or above scale, these projects follow the same general steps of other infrastructure projects which can take several years after announcement to reach the FID stage due to the level of due diligence investors require.

Project finance raises long-term equity or debt financing of a single, capital intensive, and long-lasting project, with cash flows and assets that can be distinctly identified. Project finance is a methodology that can be used to finance large-scale energy and industrial projects, that often involve high construction costs, such as wind and solar installations. Unlike corporate finance, where equity and debt are secured on the firm's balance sheet, project finance involves structuring capital around one or more Special Purpose Vehicles (SPV), which shield project partner from bankruptcy risks.

The capital-intensive nature of large energy projects often requires financial commitment and shared risk-taking from multiple partners. This is critical in the case of green hydrogen which faces significant risks including: commercialization, monetization, high capital expenditure costs, technological limitations, and regulatory concerns. Green hydrogen projects are technically complex, as they might involve building pipelines, liquification plants, storage facilities, or onsite renewables. Further, there is no financial market for trading hydrogen or its derivatives. Therefore, it is challenging for producers to guarantee a price for hydrogen or predict future revenues. Finally, there are concerns around the longevity of government support, including tax credits and low-cost loans, which are bringing down the price of hydrogen relative to fossil fuels.

To ensure commitment and minimize risks among multiple partners, several steps are necessary. The first step involves conducting a feasibility study to test the viability of the initial concept. This study will determine the resources required for development, the project cost, and financing sources. It will assess potential issues related to local regulatory requirements and opposition.
Once the feasibility study is completed, project sponsors will sign a memorandum of understanding (MOU) to establish the basic framework for a joint venture. The MOU will allocate the capital expenditures for multi-billion dollar projects, specify shared technology and resources, and assign project risks such as price and regulatory uncertainties.

Following the MOU, project partners and companies will enter the engineering and design phase. This phase will involve communication between project owners and contractors to determine the optimal technical configuration for the project. The project must also apply for the necessary permits and comply with local regulatory requirements, such as environmental assessments. Once a company or project partners have successfully completed the steps above and addressed all potential concerns around financing, engineering and construction, and compliance with local regulations, their leadership team will take FID.

V. Evaluating the Financing Potential of a Green Hydrogen Facility

A new wave of potential project sponsors are excited by the market potential of green hydrogen, but lack a framework for evaluating, prioritizing and de-risking potential investments. Below, I present four pillars of an evaluative framework based on an analysis of the shared characteristics of MW and above scale projects that have successfully secured FID.

Figure 4. Evaluating Green Hydrogen Project Potential

A Framework for Evaluating Green Hydrogen Investments	
Public sector support	• Is there a national strategy in place for hydrogen? • Are there incentives for green hydrogen projects? • Is there potential for export? • Are there risks of stranded assets?
Access to resources	• Does the site have abundant renewable resources? • Does the site have sufficient water access? • Do geologic storage opportunities exist? • How will the project mitigate supply chain risks?
Industry application	• What is the intended end use and total addressable market? • What is the site's proximity to its intended end use? • What mechanisms will be used for transport or storage?
Levelized cost of hydrogen	• What is the ideal technical configuration of the facility? • What is the cost of renewable electricity? • Has the project secured offtake arrangements? • What is the required rate of return to invest? • What is the project's NPV? • Are adjustments needed to the discount rate?

VI. Pillar #1: Public Sector Support

This era of green hydrogen development has been referred to as the "2008 of the solar and wind industry"—it is ripe for disruption and large-scale adoption (Volts, 2023). As was the case for solar and wind technologies, government support to green hydrogen is essential by establishing market instruments that incentivize and de-risk investments, improving the permitting and regulations to encourage development, and providing a forum to address community concerns.

a) National Roadmaps for Hydrogen

At least 34 countries have published national strategies for hydrogen production since Japan issued the first national hydrogen framework in 2017 (World Energy Council, 2021). The majority of governments are immediately focused on stimulating domestic production in carbon-intensive sectors, while ten countries, noted with an asterix in the table below, are poised to be leaders in green hydrogen production by the end of the decade (Recharge Hydrogen Insight, 2021).

Figure 5. Published National Hydrogen Strategies and Ten Potential Green Hydrogen Leaders

Americas	Europe	Africa and Middle East	Asia
Brazil*	Belgium	**Egypt***	**Australia***

Canada*	Czech Republic	**Morocco***	China
Chile*	Finland	Oman	**India***
Colombia	France	Namibia	Japan
United States*	**Germany***	Saudi Arabia	New Zealand
Uruguay	Hungary		Singapore
	Luxembourg		South Korea
	Norway		Uzbekistan
	The Netherlands		
	Poland		
	Portugal		
	Spain*		
	Slovakia		
	Sweden		
	United Kingdom		

b) Government Incentives for Green Hydrogen

Historically, public sector support via grants, subsidies, low-cost loans, or tax incentives, has catalyzed private investment in clean energy technologies globally, by lowering investment risks and increasing potential returns to stakeholders. With concerns over energy security due to the crisis in Europe, governments around the world have ramped up financing in recent years to advance deployment of green hydrogen facilities. Two countries exemplify this commitment.

Figure 6. Robust incentives for clean hydrogen in Australia and the United States

	Australia	United States
National Strategy	**Australia National Hydrogen Strategy**[10]	**National Clean Hydrogen Strategy**[11]
Targets by 2030	• Produce 110,000 tons of green H_2 per year • Utilize 700MW of electrolyzer capacity • Reduce the cost of green H_2 to under $A2.80 ($2) per kg — from A$8.60 today • Install 12GW of renewable energy • 100 hydrogen refueling stations • 10,000 H_2 vehicles powered • 20% of the state government's heavy transportation fleet to run on H_2 • Blend 10% H_2 into the state's gas networks	• Target strategic, high-impact uses for clean H_2 used in the highest value applications • Achieve 10 million metric tons per year of clean H_2 by 2030. • Reduce the cost of clean H_2 and enable $2 per kilogram by electrolysis by 2026 and $1 per kg within one decade
Incentives	• $3 billion in incentives to commercialize H_2 supply chains • Waivers on government electricity levies • A 90% reduction in transmission and distribution charges for electrolyzers installed by 2030	• Production Tax Credit of 2.6 kWh and up to $3 per kg for the first 10 years of operation for producers below 4.0 kg CO_2 /kg H_2 • Authorized $9.5 billion for clean H_2 production including $7B towards regional hydrogen hubs and $2.5B towards R&D grants)

[10] https://www.dcceew.gov.au/energy/publications/australias-national-hydrogen-strategy
[11] https://www.hydrogen.energy.gov/pdfs/clean-hydrogen-strategy-roadmap.pdf

c) Export Potential

Transporting hydrogen is costly and challenging, but supportive policies, economies of scale, and technological advancements are expected to bring down cost in the future. Today, there is limited infrastructure that can support the transport of hydrogen. Hydrogen's energy density presents transmission challenges because the molecule has lower energy by volume than a molecule of natural gas. As a result, existing natural gas pipelines will need to be retrofitted. Blending hydrogen with natural gas presents safety issues, including the risks of leakage and explosion (NREL, 2023). Limited data exists on hydrogen blending research, although pilots are in place around the world. Further research is needed to address technical barriers.

Nevertheless, by 2050, one-third of hydrogen will be traded internationally, with half of it transported via pipelines (including repurposed natural gas pipelines) and the other half by ships as ammonia (IRENA, 2022). The hydrogen market will resemble that of natural gas, which is split between regional pipelines and the global LNG trade. The emergence of new bilateral trade agreements between countries will have a significant impact on the geopolitical landscape of energy importers and exporters. Asia, Europe, and North America will consume hydrogen imports, while Australia, Africa, and Latin America will dominate the export market.

Developing certification schemes is critical to promoting the trade of hydrogen as a desirable commodity. Certification schemes will provide information on compliance with standards and regulatory requirements, as well as verification methods on sustainability criteria, such as carbon footprint and renewable energy content. Currently, there are eight voluntary and five mandatory schemes, mainly in Europe, but there is currently no hydrogen certification scheme suitable for international trade (IRENA, 2023).

d) Likelihood of Stranded Assets

Figure 7. Fossil-fuel exporters with plans to stimulate green H_2 production

Australia	Canada
Ghana	Norway
Oman	Russia
Saudi Arabia	UAE

Countries that have a significant fossil fuel production industry face the risk of stranded assets, which occurs when a large portion of their oil, gas, and coal resources are at risk of being unextracted and unmonetized. The Covid-19 pandemic served as a warning for fossil fuel producers, as low prices and plummeting demand caused the value of all oil and gas reserves to contract by one quarter. As demand for fossil fuels shrinks, producers will see declining revenues and credit ratings downgraded.

However, green hydrogen provides a promising transition pathway for fossil fuel producers with other adequate resource potential. These countries are well-suited to shift their focus to green hydrogen as they already have established infrastructure for exporting oil and gas, including ports, pipelines, and storage facilities. Additionally, they have a skilled workforce and existing trade relationships, which can be leveraged in a new hydrogen economy.

Pillar #2: Access to resources

a) Renewable resources

Figure 8. Countries leading in renewable installed capacity with potential for green H_2 production (GW)	
Solar[12]	**Wind**[13]
China (306)	China (328)
US (94)	US (132)
Japan (74)	Germany (63)
Germany (59)	India (40)
India, (49)	Spain (28)
Italy (23)	UK (27)
Australia (19)	Brazil (15)
South Korea (18)	France (19)
Vietnam (17)	Canada (14)
France (15)	Sweden (12)

The primary cost component associated with producing green hydrogen is the cost of renewable electricity. Given that the levelized cost to produce renewables varies significantly across different regions, the price of hydrogen is also expected to vary. The most economical production of green hydrogen is likely to occur in regions that possess a combination of abundant renewable resources, accessible land, available water supply, and the capacity to export energy to large demand centers. Countries that exhibit high energy prices and a strong commitment to renewable energy would be in a favorable position to increase their investment in green hydrogen. Renewable energy costs will decline significantly over the next decade, making green hydrogen investment attractive.

b) Water

Regions that have the best solar and wind resources for the development of green hydrogen projects are typically also the most arid. Water-stressed countries, such as Australia, Chile, Oman, Saudi Arabia, and Spain, will likely host over 70% of electrolyzer projects. Consequently, these projects will need to factor in desalination costs, which could increase the cost of producing one kilogram of hydrogen by between 0.02-0.05 USD (McKinsey Sustainability, 2022). Desalination technologies are primarily powered by fossil fuels, resulting in carbon emissions and other environmental consequences. Countries that experience frequent droughts could enhance their energy and food security by scaling up desalination, which would benefit agriculture and industry.

c) Geologic storage

Hydrogen storage is costly. A hydrogen molecule is highly energy dense by weight, but has low energy density by volume. As a result, it must be compressed and stored at high pressure to achieve the same relative energy output. Hydrogen can also be kept in a liquefied state, but it must be cooled to absolute zero (Burns McDonnell, 2023).

Above-ground storage containers for hydrogen are possible for industrial use, but they are expensive and present technical challenges for storing large volumes. Geologic storage, which is commonly used for natural gas, appears to be a promising solution. Undersea storage options are viable options from aquifers to rock caverns to depleted oil fields. Hydrogen has already been successfully stored in six salt caverns globally[14]. A wealth of information has been collected on

[12] https://pv-magazine-usa.com/2022/12/12/ranking-the-top-15-nations-for-solar-energy-capacity/
[13] https://www.evwind.es/2023/01/14/countries-that-produce-the-most-wind-energy/89725
[14] Three in the United Kingdom and three in the state of Texas.

underground storage facilities used for natural gas. Yet, designing pipelines and transporting hydrogen to these onshore and offshore storage facilities will add additional project complexity.

Advanced Clean Energy Storage Project

The Advanced Clean Energy Storage project leverages Utah's abundant renewable resources and geologic storage capacity. The project will build 220 MW of electrolyzers that will use excess renewable electricity to convert water to up to 100 metric tons of hydrogen (300 GW hours) stored in two massive underground salt caverns (U.S. DoE Loans Program Office, 2022). These are some of the only underground salt dome formations in the US outside of the Gulf Coast. Based on its unique storage capacity, the project was valued at $1 billion and received a $504.4 million loan guarantee from the US DoE Loans Program Office, the first such clean energy loan since 2014.

d) Access to critical materials

Renewable and hydrogen production technologies require specific raw materials, and their growth will increase demand for minerals that are produced in a limited number of countries. The material requirements vary depending on the type of electrolyzers and fuel cells used. For example, alkaline electrolyzers, which are currently the most widely used, rely on readily available materials such as steel and nickel. However, polymer-electrolyte membrane (PEM) electrolyzers requires scarce and emission-intensive metals like platinum and iridium, which are mostly supplied by South Africa. With no current substitutes for iridium, fluctuations in supply and demand have led to significant price increases over the last two decades. These price fluctuations may impact the cost of electrolyzers. Therefore, project sponsors need to carefully consider their supply chain needs, as demand for these technologies will require long lead times.

Pillar #3: Industrial Applications

Industrial demand will drive the scale-up of green hydrogen projects, which will drive down technology costs and stimulate growth in other applications from building heating to transport. Below are the three sectors where green hydrogen is projected to achieve the most growth over the next decade: ammonia, methanol, and green steel.

Figure 9. Green hydrogen value chains from production to end use

Production	Transformation	End Use
Renewable Energy	No transformation (H_2)	Industry: Steel, Chemicals, Refineries
Electrolysis	Green ammonia	Transport: Shipping, Aviation, Cars, Rail, Trucks, Buses
Storage	Other synthetic fuels	Other: Heating or Power Generation

a) Green Ammonia

The green ammonia market was valued at $152 million in 2022 and will expand at 127.9% CAGR reaching $73 billion USD globally by 2030 (Grandview Research, 2023). Currently, 175 million tons of ammonia are produced each year for use as fertilizer (Yale 360, 2022). Production of ammonia via this 'gray hydrogen' method contributes 1-2% to global emissions. The production of ammonia through the use of 'gray hydrogen' methods results in a contribution of 1-2% towards global emissions. However, as regulations for carbon-intensive industries increase, green ammonia is projected to become a commodity chemical by 2040 (Grandview Research, 2023).

Ammonia can be utilized as a fuel for power, heating, and maritime transport, via engines, gas turbines, furnaces, generators and fuel cells. Unlike pure hydrogen (H_2), ammonia (NH_3) can be easily stored as a liquid and has half the energy density of traditional fossil fuels. It is expected that green ammonia and other low-carbon hydrogen fuels will account for 30% of energy supplied to the maritime industry by 2050 (Yale 360). Moreover, it will become the primary commodity used for the transport of renewable energy between continents.

There are currently 54 renewable ammonia projects in the pipeline, amounting to a capacity of 15 million tons by 2030. By 2040, the capacity could increase to as high as 71 million tons, with renewable ammonia dominating all new capacity after 2025 (IRENA, 2022). The cost of producing renewable ammonia is currently around 720 USD per ton, but is expected to decrease to 480 USD by 2030 (when it will be at cost parity with blue hydrogen production) and to 310 USD by 2050 (Ibid). From 2017 to December 2020, ammonia produced from fossil fuels had an average price range of $200-$400 per ton. However, due to the surge in natural gas prices caused by the conflict in Ukraine, prices have increased six-fold, reaching as high as $1,300 per ton in 2022 (EIA, 2022). Surging prices in ammonia are expected to lead to higher prices of food production and potential food insecurity, which is incentivizing investment in green ammonia facilities.

b) E-Methanol

Methanol is widely used in the chemical industry due to its various industrial applications, including its use as a solvent, antifreeze, and in building materials, as well as its role in the production of synthetic fuels. Its light liquid state at room temperature makes it easy to transport and store. Bio-methanol, produced from biomass, or e-methanol, generated through electrolysis, are two ways to produce renewable methanol.

The market for green market will reach $3.1 billion by 2031 up from $122 million in 2022, growing at a CAGR of 39% during this period (PR Newswire, 2022). Similar to the market for ammonia, demand for green methanol is expected to come from the shipping and logistics industry.

c) Green steel

Every year, 2 MT of steel are produced for use in cars, buildings, cutlery, tools, and other everyday goods, making it one of the most widely used materials in the world. However, steel production primarily relies on fossil fuels such as coal, oil, and natural gas, which contribute 7% of global CO_2 emissions. The market for green steel was valued at $83 million in 2021 and is expected to grow at a CAGR of 132% to reach $386 billion by 2031. Several pilot projects are currently underway to explore the use of hydrogen in steel production (McKinsey & Company, 2020).

Pillar #4: Optimizing the Levelized Cost of Green Hydrogen

Once the end use application and a suitable project site is identified, the most challenging aspect of project planning is optimizing the configuration of the facility to meet expected hydrogen demand at the lowest cost to the sponsor. Firms will use a combination of technical and financial approaches to assess the project's levelized cost of hydrogen, Net Present Value (NPV), and internal rate of return (IRR), which are key metrics to securing financial commitment. A robust model (or set of models) will consider the following components below, at a minimum.

Figure 10. Modelling the Levelized Cost of Hydrogen

<table>
<tr><th colspan="2">Key Parameters to Assess the Optimal Configuration of a Green Hydrogen Facility</th></tr>
<tr><td>Renewable Power Generation
- Solar/wind energy generation data
- Capacity
- Degradation rate
- CAPEX
- OPEX</td><td>Battery Storage
- Storage Capacity
- CAPEX
- OPEX
- State of Charge
- Roundtrip Efficiency</td></tr>
<tr><td>Electrolyzer
- Capacity
- CAPEX
- OPEX (O&M, replacement)</td><td>Other Parameters
- Water costs (incl. desalinization)
- Compression/storage
- Transport</td></tr>
<tr><td colspan="2">Financing Parameters
- Discount rate
- Project life
- Capital structure (debt/equity ratio)
- Grants or tax credits
- Additional liabilities (interest on loan, inflation, tax, depreciation, salvage)
- Offtake agreements
- Additional sales (oxygen, surplus renewables)</td></tr>
</table>

The levelized cost of hydrogen (LCOH) indicates how much it costs to produce 1 kg of hydrogen taking into account investment costs and the assets involved in its production. New open-source toolkits can help investors to estimate the LCOH of proposed facilities as they weigh locations and technical configurations (Electric Hydrogen, 2023). Critical variables include estimated electricity, CAPEX, and OPEX costs. Green hydrogen production costs range from $3-6 per kilogram, while blue hydrogen production lies in the range of $2.8-$3.5 per kilogram (GEP, 2023). LCOH is driven by the capital cost of electrolyzers (CAPEX), their capacity or utilization factor and the procurement cost of renewable electricity (OPEX). Electrolyzer CAPEX drives 30-35% of the LCOH while renewable electricity drives 50-55% of LCOH estimates (Ibid).

a) CAPEX and OPEX cost reductions

Figure 11. Cheapest locations per kilogram of green H2[15]

Australia	$2.36
Qatar	$2.62
Saudi Arabia	$3.23
Oman	$3.58
UAE	$4.51

Access to low-cost renewable electricity will be the most important factor in driving the cost of green hydrogen costs to less than $1.50/kg to compete with natural gas. Green hydrogen facilities need access to low-cost renewable energy as well as high capacity factors—situated in sites with a steady supply of wind, sun, and water flow. Solar-powered hydrogen may now compete with blue hydrogen in sunny locations, such as Australia, where an LCOH of $2.36 is considered to be achievable (Recharge, 2022). Novel research also indicates that off-grid, utility scale solar and electrolyzer plants coupled with battery storage in locations with strong photovoltaic capacity, could be cheaper than investing in an interconnection to purchase electricity from the grid (Ibid).

Electrolyzer CAPEX will decrease significantly due to technological advancements and improved manufacturing capacity. These technologies have existed for over 100 years and were previously located near dams to take advantage of inexpensive electricity. In the 1960s, renewable hydrogen was used to produce most fertilizers in Europe. While thousands of plants were installed globally, by 2014 the industry had contracted and could not outcompete fossil fuels.

The manufacturing capacity of electrolyzers is expected to increase to 16 GW by 2024 from 135 MW, which will drive down costs. Equipment design improvements have led to more efficient use of materials, improving electrolyzer efficiency. Improved manufacturing capacity and declining costs have broadened industry participation across the supply chain.

Figure 12. Electrolyzer Considerations and Commercial Status

Type	Considerations	Commercial Status
Alkaline	• Simple design used for other applications and easily scaled • Less suited for VREs	Mature market
Proton exchange membrane (PEM)	• Platinum and iridium required • More suitable for VREs and voltage regulations	Fast growth
Solid oxide electrolyzer cells (SOEC)	• Ramping up or down not required • Apt for constant base load hydrogen production	Pilots underway
Anion Exchange Membrane (AEM)	• Critical metals not required • Less expensive membrane than that used for PEM	Limited use

[15] https://www.rechargenews.com/energy-transition/green-hydrogen-now-cheaper-than-blue-in-middle-east-but-still-way-more-expensive-in-europe/2-1-1173423

While Europe is the leading manufacturer of electrolyzers, China dominates shipments due to as Chinese electrolyzers are cheaper than their European counterparts. Given that the hydrogen market is still relatively small, scaling up hydrogen production and shifting trade dynamics could swiftly change the manufacturing landscape.

a) Financing considerations

Securing long-term revenue contracts will be a crucial step for early green hydrogen projects to obtain financing. Although the criteria for hydrogen revenue contracts can be flexible and are projected to undergo rapid change, many experts have compared the green hydrogen offtake market to that of liquefied natural gas (LNG).

To ensure their financial viability, hydrogen offtake contracts are expected to adhere to either a take-or-pay or take-and-pay model. In a take-or-pay agreement, the buyer and seller agree on a set contract quantity to be delivered at regular intervals. The buyer is obligated to receive the agreed-upon amount or reimburse the seller for any amount unused. If the buyer pays for the entire contract quantity but fails to take the quantity delivered, they may be given the opportunity to make up for the unused amount at a later time. Alternatively, in a take-and-pay contract, the buyer takes delivery of the specified quantity and pays for it. Failure to pay results in substantial penalties or fines.

There are no spot prices for hydrogen given the limited market demand. As the majority of hydrogen on the market today is derived from fossil fuels, contracts are based on the cost of feedstock, generally natural gas, plus fixed and variable expenses, with a profit component. Thus, contract prices for green hydrogen will likely include fixed plus variable expenses incurred.

Access to debt is also needed to scale green hydrogen. Similar to how the LNG and renewable energy markets have developed, equity investments must be paired with bank or project finance debt to mobilize the capital required for these large-scale projects. Several governments are supporting the “bridge to bankability” by offering loans to de-risk hydrogen investments. The European Commission announced 5.2 billion Euros in public support for projects focused on industrial usage (H2Use) and announced the creation of the European Hydrogen Bank, with $3 billion to invest (Société General, 2022). In the United States, the U.S. DoE’s Loans Program Office recently awarded a $504.4 million loan to the Advanced Clean Energy Storage project in Utah, with more loans likely on the way (U.S. DoE Loans Program Office, 2022).

Another critical metric for financing is the cost of capital, also known as the weighted average cost of capital (WACC). The cost of capital can differ significantly across countries. Most financial models assume that prevailing rates will continue to exist in 2050. Yet, as new countries become hydrogen exporters instead of importers, their WACC will likely fluctuate. For instance, if the Middle East boosts its hydrogen export capabilities, countries such as Australia and Chile, which currently have a relatively low WACC estimated for hydrogen production, may see an increase.

VII. Conclusion: A Bright Future for Green Hydrogen

The market for green hydrogen is in its infancy and all emissions-reduction scenarios project rapid growth over the next decade to meet emission reductions goals. We have yet to see whether the green hydrogen market will follow in the footsteps of liquified natural gas, or renewables, or a combination of both as large-scale projects seek financing from major financial institutions.

Green hydrogen is a $3 billion dollar market today (Grandview Research, 2022) and is expected to reach as high as $59 billion by 2030 (PR Newswire, 2022). The costs of electrolyzers will continue to be driven down as manufacturing reaches economies of scale and new gigafactories spring up around the world (Recharge, 2022). Innovations in new and improved technologies enabling green hydrogen production will flourish, as over $3.1 billion VC and private equity deals closed in 2022, despite the turmoil in those markets (Pitchbook, 2023). Several billion dollars for research and development grants from governments will inspire a wave of innovation across the sector. Such that by 2030, if not sooner, green hydrogen is expected to be $1/kg and will be able to compete with fossil fuels. A new era for green hydrogen has just begun.

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