Citi GPS: Global Perspectives & Solutions

HYDROGEN

A Reality Check on the Hydrogen Craze

Despite nearly a century of allure, hydrogen has not been used to its full potential. Hydrogen shows particular promise in the transportation, hard-to-abate industrial, and power generation sectors, but still faces obstacles around scalability, cost, and public perceptions. However, as investment and policy momentum have been building in recent years, signs of breakthrough are emerging. Amid these high hopes, we discuss technical, political, and cost developments to better understand hydrogen's potential future trajectory.

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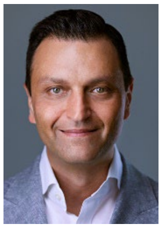

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HYDROGEN FUEL 101

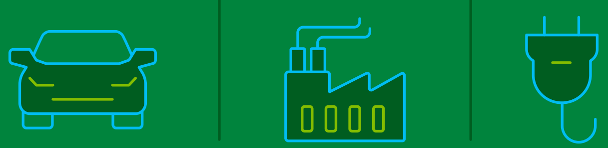
GRAY HYDROGEN is derived from natural gas – CO_2 is emitted in the process

BLUE HYDROGEN is derived from natural gas, with the resulting CO_2 captured via CCUS

GREEN HYDROGEN is derived in a carbon-neutral manner via renewable energy

HYDROGEN SHOWS PARTICULAR PROMISE IN THREE SECTORS

1. Transportation
2. Hard-to-Abate Industries
3. Power



THE SUBSIDY ARMS RACE IS ON

Hydrogen-Boosting Initiatives Are Accelerating Globally

September 2020 – Saudi Arabia sends world's first shipment of blue ammonia to Japan to be used as a green fuel

November 2020 – Chile releases National Green Hydrogen Strategy identifying Europe as the biggest market for its green ammonia exports

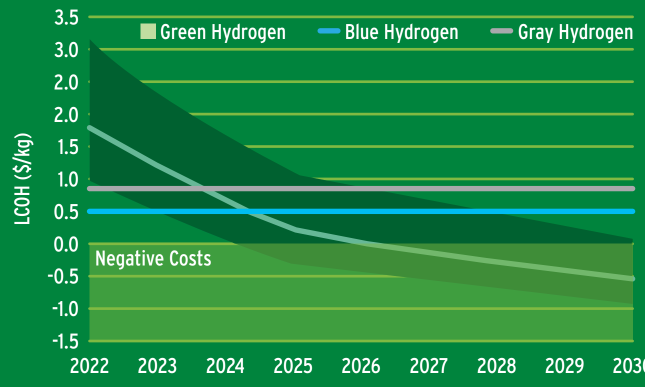
August 2021 – China's coal-producing Inner Mongolia region sets target for green hydrogen production to reach 500 kilotons per year by 2025

October 2021 – Japan releases Sixth Strategic Energy Plan stating hydrogen and ammonia should account for 1% of the country's total electricity supply in 2030

August 2022 – The U.S. Inflation Reduction Act (IRA) provides tax credit booster shots for blue and green hydrogen

February - March 2023 – The EU passes the European Green Deal Industrial Plan and the Net Zero Industry Act, which offer production tax credit-like hydrogen subsidies

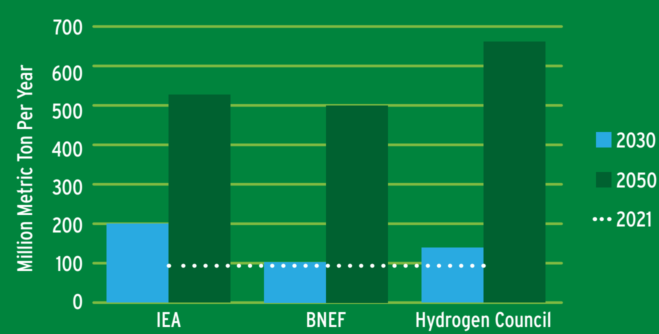
WE SEE U.S. GREEN HYDROGEN COSTS TURNING NEGATIVE BEFORE 2030 DUE TO TAX CREDITS



Note: Assuming natural gas price of $3/MMBtu. Green hydrogen is powered with dedicated solar power. LCOH=levelized cost of hydrogen.

Source: Citi GPS, Citi Research Estimates

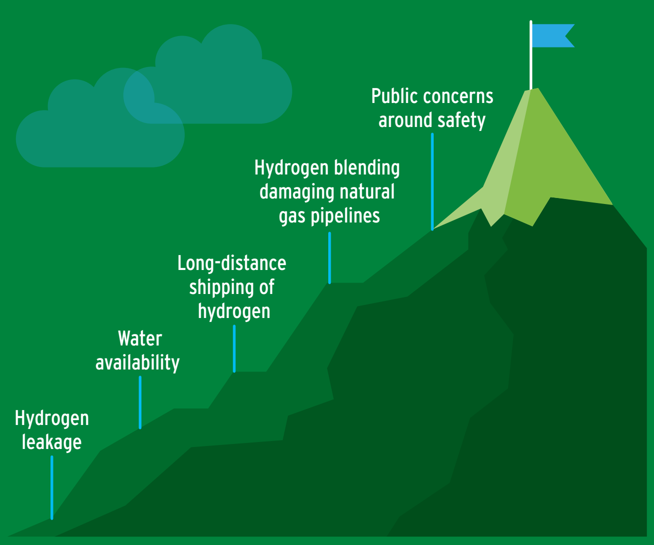
PROJECTIONS SHOW GLOBAL HYDROGEN DEMAND RISING SUBSTANTIALLY IN "NET ZERO BY 2050" SCENARIO



Note: Chart shows actual 2021 demand and IEA, BNEF, and Hydrogen Council projections assuming the world is on track to reach net zero emissions by 2050.

Source: IEA, BNEF, Hydrogen Council

DESPITE MOMENTUM, CHALLENGES REMAIN AHEAD



Contents

Introduction

Since the 1930s, hydrogen has run into application difficulties in implementing what has appeared, on the surface, to be its great allure: in theory, it is more abundant and more versatile than all other fuel sources outside of petroleum. Hydrogen can be — and has been — a transportation fuel; it makes up 2.5% of all energy consumed due to its critical use in refining as an upgrading ingredient to turn heavy products, like residual fuel oil, into light products, like gasoline and diesel; it can be a source of power generation and can be stored longer and more efficiently as a last resort replacement for interruptible renewables like wind, solar, and hydro than utility-scale batteries; and since it burns at high temperatures, it can be a clean replacement for coking coal.

Obstacles surrounding its explosivity began to confront hydrogen with the Hindenburg disaster in 1937, which rapidly brought its promise as a light, clean fuel for zeppelin airships to an end. Despite this, it has been tamed as the principal fuel for rockets. Hydrogen now confronts scalability issues in creating electrolyzers, leakage issues when it comes to pipelines and storage, and cost hurdles along with "not-in-my-backyard" (NIMBY) obstacles. And the high cost of scalable projects has certainly slowed down the development of hydrogen projects globally.

But signs of breakthroughs have emerged over the past few years. This partly stems from an overall acceleration in green technology investments, which Bloomberg NEF (BNEF) indicates reached $1.1 trillion with 30% financing growth in 2022. Although very little of that acceleration was in hydrogen, the beginning of 2023 brought the first large-scale global hydrogen financing with an $8.5 billion hydrogen project in Saudi Arabia.

Between 2021 and 2022, the U.S. enacted a series of new laws, including the Inflation Reduction Act, which together with prior legislation and existing authorities are expected to provide as much as $1.7 trillion in investment incentives. A significant proportion of these incentives are for hydrogen projects, including via the support of hydrogen hubs around the country. The tax credits provided by the Inflation Reduction Act are so generous that net production costs of green hydrogen after adjusting for tax benefits could be negative later this decade. In response, Europe enacted its own Green Deal Industrial Plan, and government incentives are being offered in a growing list of countries already endowed with renewable resource potential and/or with the incentives to reach net zero, including Australia, Chile, China (the leading producer of hydrogen in the world), India, Japan, Oman, Saudi Arabia, and the UAE. It looks like it is time for hydrogen's doubting Thomases to retreat.

A Reality Check on the Hydrogen Craze

Investment and policy momentum to develop blue and green hydrogen have been exceptional, with capital spending growing at an extraordinary rate.[1] According to BNEF, global funding commitments for the sector through to 2030 totaled $146 billion as of December 2022, up by 46% since BNEF's previous update in January 2022.[2] Globally, total spending on clean energy hit $1.1 trillion in 2022, led by China at $546 billion followed by the EU ($180 billion) and the U.S. ($141 billion). We expect this spending gap between China and the rest of the world to close, as new policies adopted in the OECD generate increased spending in the second half of 2023.[3] Globally, there is increased interest in clean hydrogen, with the exception of Russia, which has largely turned its back on clean energy for the time being. In the U.S., increased interest is embodied in three major pieces of legislation — the Infrastructure Investment and Jobs Act of 2021 (also referred to as the Bipartisan Infrastructure Law) and both the Chips and Science Act (CHIPS Act) and the Inflation Reduction Act (IRA) of 2022. European interest reflects a doubling down on the energy transition in the wake of the Russia-Ukraine conflict.

Not only did the EU quadruple its 2030 target for renewable hydrogen supply, but the U.S. also came out with one of the world's most generous green hydrogen subsidies through the IRA.[4] The U.S. legislation then prompted a new round of responses from European governments playing catch-up on the spending game. Other countries are also very much in the clean hydrogen arena, including China given its commanding overall lead in clean energy and significant overspending on electrolyzer capacity far exceeding foreseeable demand. Australia, Chile, India, and Japan are also involved, as well as some of the main oil exporters of the world in the Middle East, where Saudi Arabia and the UAE have enhanced their already robust plans to be the world's major exporters of hydrogen in some form (including blue and green ammonia). In early January of 2023, Saudi Energy Minister Prince Abdulaziz bin Salman reiterated the country's plan to be the world's largest exporter of hydrogen and other green energy and to spend 1 trillion riyals (US$267bn).[5]

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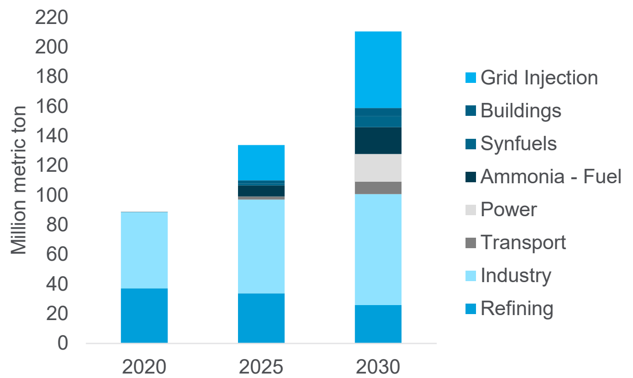
[1] Depending on production methods, hydrogen can be "gray", "blue," or "green." Gray hydrogen is produced from natural gas through steam methane reforming (SMR). So is blue hydrogen, but with carbon capture, utilization, and sequestration (CCUS). Green hydrogen is produced from water electrolysis powered by renewables, which eliminates carbon emissions in the production process.
[2] BNEF, "1H 2023 Hydrogen Market Outlook: US Takes the Lead," March 2, 2023.
[3] BNEF, "Global Low-Carbon Energy Technology Investment Surges Past $1 Trillion for the First Time," January 26, 2023.
[4] According to the European Commission, renewable hydrogen can be produced either from water electrolysis powered by renewables or from biomass as raw material.
[5] Currency conversions in this report are approximate as of July 24, 2023. Hydrogen Council, "Hydrogen Insights 2023," January 31, 2023.

Momentum has been building, and 2022 was a banner year for hydrogen, with multiple milestones set. In February, the world's first shipment of liquid hydrogen set sail from Australia to Japan. In August, the first hydrogen-powered commuter trains were commissioned for full-time service in Germany. Just before the year ended, the world's first industrial-scale power-to-hydrogen-to-power project, the HYFLEXPOWER project, completed its initial tests in France, with hydrogen blended with natural gas at a 30:70 volume mix for power generation. The next trials, in 2023, are set to increase the hydrogen ratio to 100%.

Amid the eye-grabbing headlines for hydrogen in 2023, skeptics abound. While some believe that in the hindsight of 2050, hydrogen will be seen as the main factor in getting close to net-zero goals, others suspect it will have had little to do with the progress made. The global hydrogen market remains at a nascent stage, with both great prospects and great uncertainties around the pace of expected cost decline and the rate of technical development. To start, water availability presents a challenge for green hydrogen production in the Middle East. Questions also remain around how fast the cost of electrolysis can fall and which technology will win. Hydrogen storage and transportation are both tough nuts to crack, with cost and leakage issues looming. Traditional demand for hydrogen includes upgrading petroleum products in refining and as an ingredient in ammonia and fertilizers. Beyond this there is also theoretical demand for hydrogen as (1) a replacement transport fuel for oil, (2) a source of clean energy storage, (3) a replacement for thermal coal and natural gas in power generation, and (4) a replacement for coking coal in steel manufacturing as well as use in other hard-to-abate sectors. However, demand in these new applications has yet to be fostered, with public perceptions of hydrogen facilities also a likely hurdle.

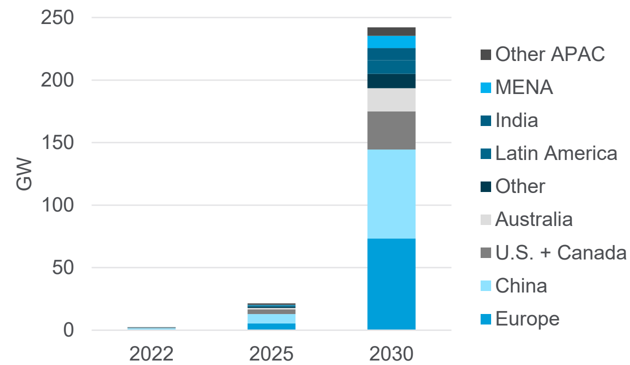
Hydrogen is certainly appealing due to its versatility, and shows particular promise in the transportation, hard-to-abate industrial, and power generation sectors. However, amid the exuberance, it is worthwhile to take a step back and evaluate current technical, political, and cost developments to better understand hydrogen's potential future trajectory.

Figure 1. IEA Projection of Global Hydrogen Demand by Sector in the "Net Zero by 2050" Scenario, 2020-30



Source: IEA, Citi GPS

Figure 2. BNEF Forecast of Cumulative Electrolyzer Capacity by Region Based on Announced Projects and Policies



Source: BNEF, Citi GPS

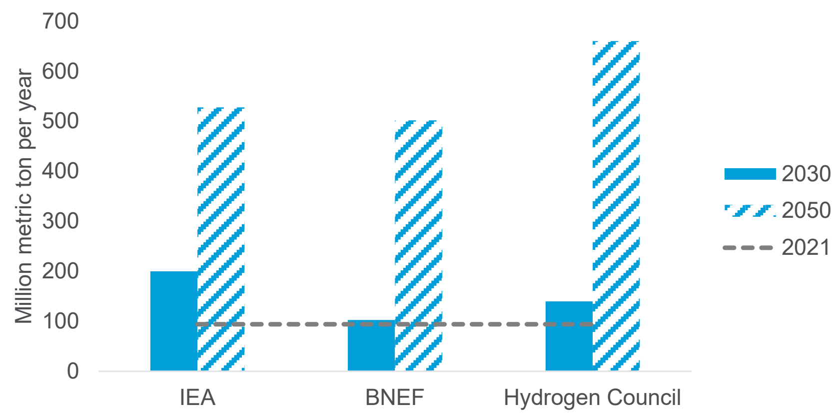
High Hopes, Great Momentum

(1) Demand: Hydrogen Makes Forays Into New Uses

Global hydrogen demand by 2030 could range between 103 million metric tons per year (MMt/yr) and 200 MMt/yr if the world is to be on track to reach net zero emissions by 2050, up from 94 million metric tons (MMt) in 2021, according to the International Energy Agency (IEA), BNEF, and the Hydrogen Council.[6] Some analysts project growth to accelerate post-2030, reaching around 500 MMt/yr to 660 MMt/yr by 2050. Beyond its traditional use in the refining and chemicals industries, hydrogen is making inroads across sectors like steel production, power generation/energy storage, and transportation. For example:

- On the industrial side, the world's first fossil-free steel has already been delivered in Sweden. While the green hydrogen-based direct reduced iron-electric arc furnace (DRI-EAF) project — HYBRIT — is still in the pilot phase, with its clean power heavily subsidized, it is expected to reach industrial scale by 2026.[7]
- On the power side, the Advanced Clean Energy Storage hub in the U.S. could be generating power in 2024 through an 840-megawatt (MW) gas turbine burning a blend of 30% green hydrogen and 70% natural gas.
- On the transportation side, while hydrogen-powered fuel cell electric vehicles (FCEVs) remain a much smaller market than battery EVs (BEVs), the number of FCEVs on the road reached over 51,000 at the end of 2021, a 50% year-over-year increase, with promise in both heavy-duty trucks and passenger vehicles.[8]

Figure 3. Projections of Global Hydrogen Demand by 2030 and 2050 in the "Net Zero by 2050" Scenario



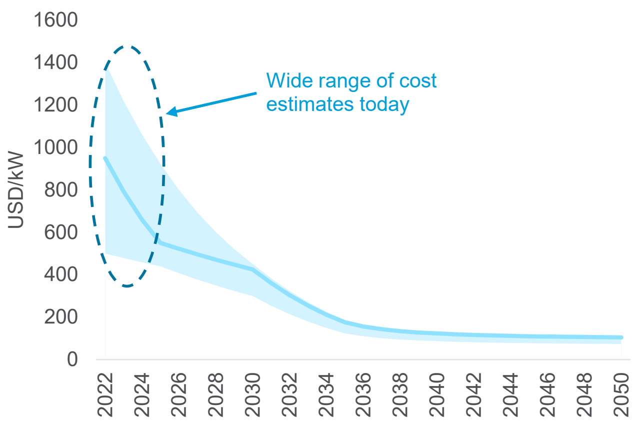
Source: Citi GPS, IEA, BNEF, Hydrogen Council

[6] IEA, *Global Hydrogen Review 2022*, September 2022; IEA, *Net Zero by 2050 – A Roadmap for the Global Energy Sector*, May 2021; BNEF, *New Energy Outlook 2022*, December 7, 2022; Hydrogen Council, *Global Hydrogen Flows*, October 2022.
[7] Conventional DRI-EAF uses hydrogen and carbon monoxide produced from fossil fuels as reduction agents. The Sweden project, HYBRIT, will use 100% green hydrogen as a reduction agent. The first fossil fuel-free steel was delivered by the plant in July 2021.
[8] IEA, *Global EV Outlook 2022*, May 2022.

(2) Investments: Supply-Side Projects Dominate

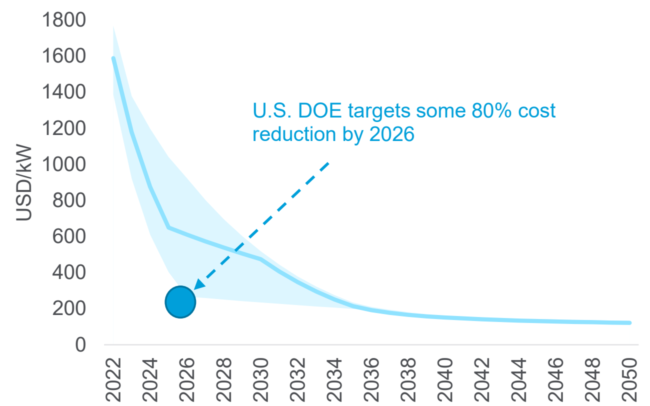
Investments are also ballooning. Clean hydrogen investments likely tripled year-over-year in 2022, albeit from a low base, with the majority focusing on electrolyzers, according to BNEF.[9] Out of the $1.11 billion of clean hydrogen investments in 2022, 99% went to electrolyzers, while hydrogen pipelines, underground storage, and thermochemical hydrogen production projects together received a little over $13 million. Correspondingly, global electrolyzer shipments topped 1 gigawatt (GW) in 2022, more than doubling from 2021, and could again double or even triple in 2023, driven by demand from China, Europe, and Australia.

Figure 4. Alkaline Electrolyzer System Costs Could Fall Rapidly Within this Decade Thanks to Rising Investments in Electrolyzer Installations and Expanding Manufacturing Capacities



Source: Citi GPS, IEA, BNEF, Company reports

Figure 5. The Projected Costs of Proton Exchange Membrane (PEM) Electrolyzers, Which are Challenging the Dominance of the Incumbent Alkaline Electrolyzers, Could Also Fall



Source: Citi GPS, IEA, BNEF, Company reports

Yet, rising interest rates and the recent banking-sector woes could pose some challenges, especially for clean-tech startups. Clean energy projects could be more susceptible to the negative impacts of rising interest rates, as much of the total project costs are front-loaded with minimal operating costs compared to conventional fossil fuel power projects.[10] They can also be perceived as riskier investments due to the uncertainty of nascent technologies. In fact, the collapse of some regional banks in the U.S. already has raised concerns that early-stage and even late-stage tech startups may start to find it more difficult to raise funding.[11] On the other hand, the formidable subsidies and other support mechanisms available via the Bipartisan Infrastructure Law, CHIPS, and IRA legislation in the U.S., as well as by the European Green Deal Industrial Plan and Net Zero Industry Act (both adopted in the first quarter of 2023), could actually be supportive of enhanced private equity investment as well as sustainable debt issuance.

[9] BNEF, *Energy Transition Investment Trends 2023*, January 2023. The scope of clean hydrogen investments cover costs of electrolysis systems, thermochemical production facilities (excluding costs of CCUS), hydrogen pipelines and underground storage sites. Only projects that reached final investment decisions (FID) or were under construction were included.
[10] Citi Research, *Beware! Rising Interest Rates Could Be an Overlooked Driver in Lifting Renewables Energy Costs*, April 29, 2021.
[11] Corbin Hiar and Avery Ellfeldt, “Bank Collapse Throws a Chill Over Clean Energy Industry,” Politico, March 14, 2023.

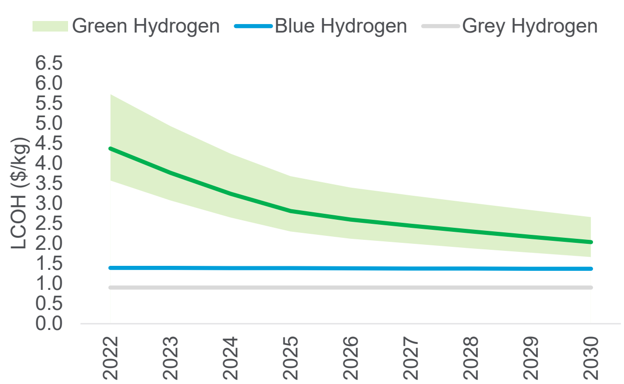
(3) Policies: The Subsidy Arms Race Is On

The U.S., Europe, China, and other hydrogen exporters — especially in the Middle East (Saudi Arabia, UAE, Oman, and Bahrain to some degree) but also in Latin America (Chile and Brazil) and the Asia Pacific region (particularly Australia in cooperation with Japan and South Korea) — are all providing subsidies that are fast-tracking developments. This section examines policy support in the U.S., Europe, China, and elsewhere and assesses current and potential impacts.

(a) U.S.: Tax Credit Should Lead to *Negative* Green Hydrogen Costs, Even Before 2030

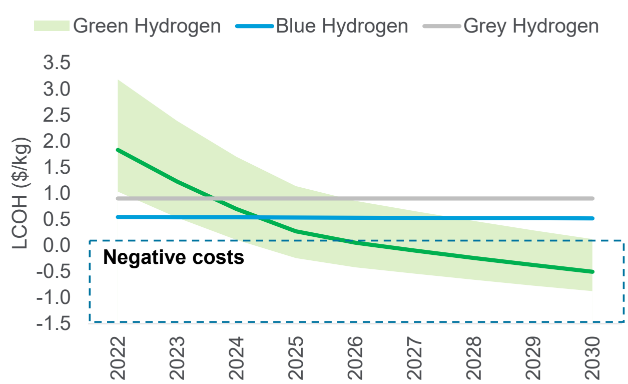
Green hydrogen could emerge as the biggest winner, as the expected Levelized Cost of Hydrogen (LCOH) is set to turn negative by 2030 amid the mobilization of investment capital in 2023. Currently, blue hydrogen — in which carbon capture, utilization, and sequestration (CCUS) is used to capture CO_2 emissions during production — still enjoys cost advantages over green hydrogen in the U.S. This is due to the availability of cheap natural gas as well as tax benefits, including the 45Q CCUS tax credit and the clean hydrogen production tax credit (PTC), although the two tax credits cannot be stacked. However, the strict criteria of lifecycle carbon emissions for the clean hydrogen PTC means that blue hydrogen, with a 90% carbon capture rate, will only receive around $1 per kilogram (kg) of tax credit, rather than the top-tier $3/kg that green hydrogen receives. Our projected LCOHs see blue hydrogen losing its edge to green hydrogen from the mid-2020s. In fact, green hydrogen's LCOH could fall below zero even before 2030 after accounting for tax credits for both renewables and clean hydrogen production!

Figure 6. Projected LCOH for Gray, Blue, and Green Hydrogen (Powered With Dedicated Solar Power) in the U.S. *Without* Tax Credits



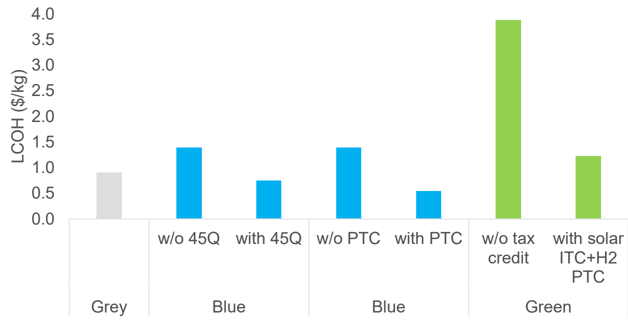
Note: Assuming natural gas price of $3 per million British Thermal Units (MMBtu)
Source: Citi Research estimates

Figure 7. Projected LCOH for Gray, Blue, and Green Hydrogen (Powered With Dedicated Solar Power) in the U.S. *With* Tax Credits



Note: Assuming natural gas price of $3/MMBtu
Source: Citi Research estimates

Figure 8. Current LCOH for Gray, Blue, and Green Hydrogen (Powered With Dedicated Solar Power) in the U.S. With and Without Tax Credits



Note: Assuming natural gas price of $3/MMBtu
Source: Citi Research estimates

Figure 9. 2030 LCOH for Gray, Blue, and Green Hydrogen (Powered With Dedicated Solar Power) in the U.S. With and Without Tax Credits

Note: Assuming natural gas price of $3/MMBtu
Source: Citi Research estimates

The IRA passed in August 2022 has provided tax credit booster shots for both blue and green hydrogen.[12] For the first time, it provides clean hydrogen tax credits of up to $3 for each kilogram of qualified hydrogen. More importantly, clean hydrogen production plants will be able to enjoy stacked tax credits if hydrogen is produced via water electrolysis powered by renewable electricity. The legislation has also extended and raised the existing investment tax credits (ITCs) and PTCs[13] for renewable power including solar and wind, as well as the 45Q tax credits for CCUS.[14]

Figure 10. Production Tax Credit (PTC) and Investment Tax Credit (ITC) for Clean Hydrogen Offered by the Inflation Reduction Act (IRA)

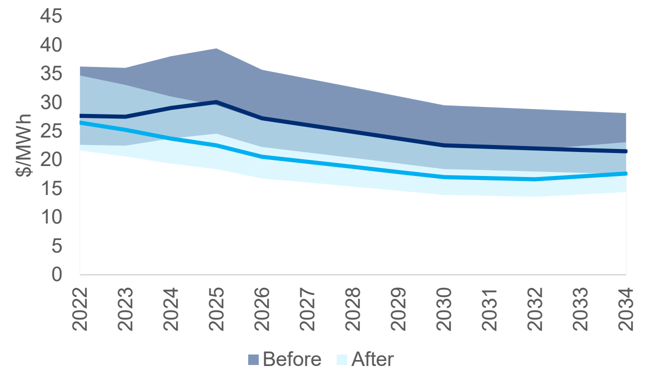
Lifecycle GHG Emission Rate (kgCO2/kgH2)	Base Rate		Increased Credit Amount When Conditions are Met		Types of Hydrogen Qualified (estimated)
	PTC ($/kgH2)	ITC	PTC ($/kgH2)	ITC	
Greater than 4	0	0.0%	0	0%	Grey hydrogen; blue hydrogen with <55% carbon captured
Not greater than 4 and not less than 2.5	0.12	1.2%	0.6	6%	Blue hydrogen with 55% to 72% carbon captured
Less than 2.5 and not less than 1.5	0.15	1.5%	0.75	8%	Blue hydrogen with 72% to 83% carbon captured
Less than 1.5 and not less than 0.45	0.2004	2.0%	1.002	10%	Blue hydrogen with 83% to 95% carbon captured
Less than 0.45	0.6	6.0%	3	30%	Blue hydrogen with >=95% carbon captured; green hydrogen

Source: Citi GPS

[12] Citi Research, *Manchin-Schumer Proposal Could Revive Faltering U.S. Climate Change Ambitions…If It Passes: GSMG/Equities Views*, August 3, 2022.
[13] ITC (investment tax credit) is a one-time benefit that lets businesses deduct up to 30% of investment costs from their taxes. Alternatively, renewables developers may also choose to claim PTC (production tax credit), which allows businesses to claim an inflation-adjusted credit amount for every kWh of electricity sold for a period of 10 years after the facility is placed into service. For 2022, the inflation-adjusted PTC is 2.6 cents/kWh according to the U.S. Internal Revenue Service.
[14] Before IRA, projects eligible for 45Q tax credits needed to begin construction before January 1, 2026. Once the facility is put in service, the project receives tax credits of $50 per metric ton of CO_2 permanently sequestrated or $35/metric ton of CO_2 used for enhanced oil recovery (EOR) for 12 years. Post-IRA, the deadline is extended to January 1, 2033, and the credit amounts are boosted to $85/metric ton and $60/metric ton respectively.

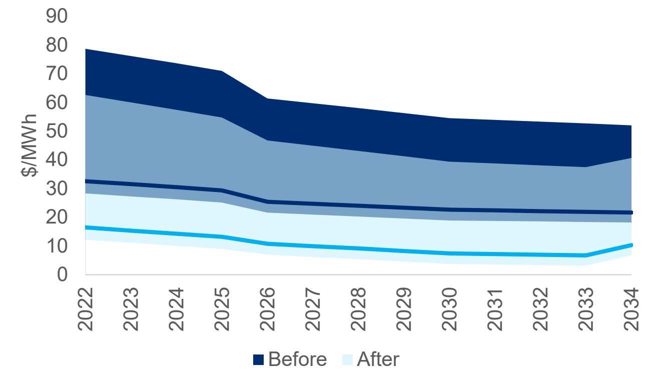
Of the two key components of green hydrogen — electrolyzers and the renewable electricity that powers electrolyzers — the extension of ITC/PTC for future solar and wind projects would further help to bring down renewables' LCOEs, expediting green hydrogen cost deflation as electricity costs could represent 50%-70% of LCOH by 2030, by which time electrolyzer costs are widely expected to drop.[15] Specifically, a solar project that starts construction in 2025 would not have received an ITC prior to the IRA, as the Section 48 ITC ends in 2024.[16] Now, new solar projects that begin construction no later than 2033 can apply for a 30% ITC, leading to around a 25% discount of solar LCOE. Similarly, PTCs for wind developers, which had expired at the end of 2021, are now extended through at least 2033, potentially cutting wind's LCOE by as much as 70%. Both ITCs and PTCs also become technology-neutral starting 2025.

Figure 11. Projected LCOE for U.S. Utility Solar PV Taking Into Account ITC Before and After Implementation of the IRA



Source: NREL, Citi GPS

Figure 12. Projected LCOE for U.S. Onshore Wind Farms Taking Into Account PTC Before and After Implementation of the IRA



Source: NREL, Citi GPS

In addition to the IRA, both the Bipartisan Infrastructure Law (BIL) and the CHIPS Act are also set to fast-track the deployment of clean hydrogen in the U.S.

- **Signed into law in November 2021, BIL allocated a total of US$9.5 billion toward clean hydrogen R&D and demonstration.** Specifically, $8 billion is targeted for region clean hydrogen hubs, where clean hydrogen producers, consumers, and connective infrastructure are located in close proximity. Undoubtedly, the hub program has already been received by the public with great enthusiasm. Since the U.S. Department of Energy launched the initial stage of the selection process in September 2022, 79 concept papers were submitted requesting nearly US$60 billion in funding, about eight times more than the US$7 billion funding provided by the government.

[15] Levelized cost of electricity (LCOE) measures the average cost per unit of electricity generated taking into account all the costs over the lifetime of the generating facility, including initial investment, operations and maintenance, and cost of fuel and capital. LCOE is a simplified way to compare the overall competitiveness of different power generation technologies. It does have limitations. For example, LCOE fails to account for the dispatchability of a given technology, i.e., the ability to quickly ramp up or down in order to match power demand profile.

[16] Bipartisanpolicy.org, *Inflation Reduction Act Summary: Energy and Climate Provisions*, October 2022.

- **The CHIPS Act became law in August 2022.** The Act authorized up to US$12 billion towards research and development (R&D) for the Department of Energy, including for the Advanced Research Projects Agency-Energy (ARPA-E) that works on advanced energy technologies including hydrogen.

(b) EU: Intensive Policymaking Aims to Match U.S. IRA

As a direct response to the U.S. IRA, the EU came up with the European Green Deal Industrial Plan ("the Plan") and Net Zero Industry Act ("the Act") in February and March of 2023, offering PTC-like subsidies and hoping to bring net-zero technology production to the EU while avoiding a trade clash with the U.S.[17] Matching the clean hydrogen PTC offered by the U.S. IRA, the Plan would pay a fixed premium for each kilogram of renewable hydrogen produced for a period of 10 years to winners of the upcoming auction in December 2023. Domestic manufacturing capacity of net-zero technologies, including hydrogen electrolyzers and fuel cells, should approach or reach at least 40% of annual deployment needs by 2030, according to the Act.[18] Fully aware of the lengthy permitting processes that often bogs down net-zero technology manufacturing projects, the Act also sets hard time limits for the length of the permit-granting process of nine to 18 months.

Yet, these plans are lacking in implementation details and are likely not as powerful as the U.S. IRA, at least on the hydrogen front. The fixed premiums the EU would offer for each kilogram of renewable hydrogen produced depend on auction results, which are less straightforward than the universal $3/kg PTC offered by the U.S. IRA. The indicative budget for the upcoming December 2023 auction is only €800 million ($885mn), dwarfed by the theoretically uncapped funding offered by the IRA in the U.S. for clean hydrogen PTC/ITC.[19] In fact, the U.S. Congressional Budget Office estimates that cumulative clean hydrogen tax credits claimed between 2022 and 2031 could add up to over $13 billion.[20]

Nonetheless, the EU is determined to build on the REPowerEU plan, released in May 2022, which tries to meaningfully fast-track renewable hydrogen deployment. [21] Compared to the EU's Fit-for-55 package for a green transition, the REPowerEU plan raised the target of annual renewable hydrogen use from 6.5 MMt to 20 MMt by 2030. The biggest increases come from the industrial heat, petrochemical, and refinery sectors. By 2030, the shares of renewable hydrogen and renewable fuels of non-biological origin (RFNBO) should reach above 75% and 5% for the industrial and transport sectors, respectively.[22]

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[17] European Commission, "A Green Deal Industrial Plan for the Net-Zero Age," January 2, 2023; European Commission, "Net Zero Industry Act," March 16, 2023.

[18] The Net Zero Industry Act identifies 8 major strategic net-zero technologies: (1) solar PV and solar thermal, (2) onshore wind and offshore renewable technologies, (3) battery/storage, (4) heat pumps and geothermal, (5) electrolyzers and fuel cells, (6) sustainable biogas/biomethane, (7) carbon capture and storage and (8) power grids.

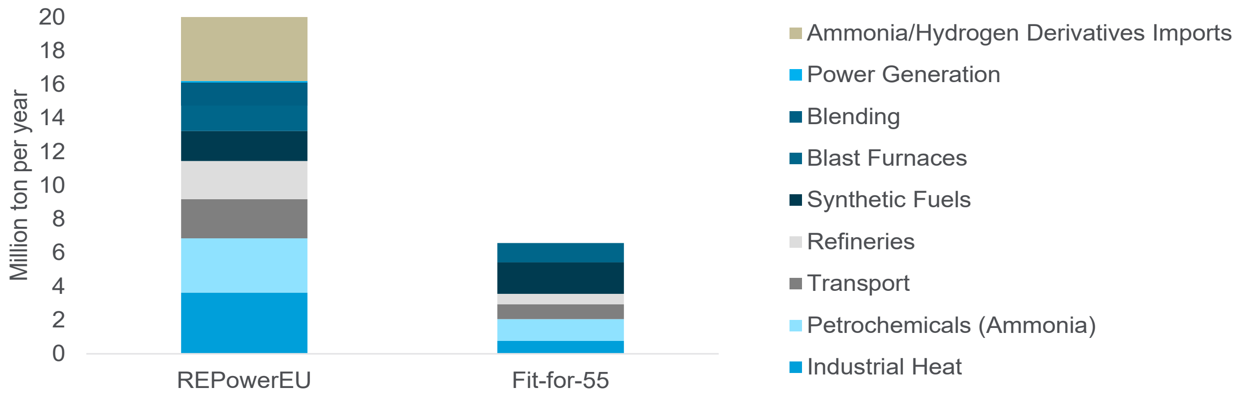
[19] Note, all currency conversions are at spot rates as of July 11, 2023.

[20] Congressional Research Service, "Inflation Reduction Act of 2022 (IRA), Provisions Related to Climate Change," October 3, 2022.

[21] Renewable hydrogen can be obtained via electrolysis using renewable electricity to split water into hydrogen and oxygen and is referred to as "renewable fuels of non-biological origin." Yet it is different from the concept of green hydrogen, in that it can also be produced from biomass sources. (The EU Delegated Acts released in February 2023 define the conditions under which hydrogen can be considered "renewable.")

[22] Renewable Fuels of Non-Biological Origin (RFNBO) are synthetic drop-in fuels. They consist of (1) pure hydrogen derived from water and renewable energy (except biomass

Figure 13. Expected Hydrogen Demand by Sector in 2030 (million metric tons of hydrogen per year)



Source: European Commission, Citi GPS

Financially, the EU has multiple funding programs in place to meet the investment needs identified by the REPowerEU plan including: €50 billion-€75 billion for electrolyzers, €28 billion-€38 billion for EU-internal pipelines, and €6 billion-€11 billion for storage, totaling €84 billion-€124 billion by 2030 ($93bn to $137bn).[23] While these programs are generally targeting broad-based, low-carbon technologies or the overall energy infrastructure systems, the REPowerEU plan did explicitly target hydrogen with the following measures:

– Set up a dedicated work stream on the joint purchasing of hydrogen.

– Devote €200 million ($221mn) to double the number of "Hydrogen Valleys" from 23 today to 46 by 2025.[24]

– Roll out carbon "contracts for difference" to help in substituting gray with green hydrogen in existing processes and introducing green hydrogen to new industrial sectors.

– Intend to complete the assessment of the first Important Projects of Common European Interest on hydrogen by summer 2022.

– Support the development of three major hydrogen import corridors: the Mediterranean, the North Sea area, and with Ukraine.

– Invest around €3 billion ($3.3bn) of the Innovation Fund to clean energy-related projects including industrial use of hydrogen, electrolyzer/fuel cell manufacturing, and others.

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sources) in the form of heat of electricity; or (2) in liquid and gaseous fuels derived from hydrogen combined with CO_2 from fossil sources such as flue gas, from Direct Air Capture (DAC) technologies or from other non-renewable and natural sources; or (3) liquid and gaseous fuels from hydrogen combined with nitrogen captured from air in the case of ammonia production. (See EU status report.)

[23] European Commission, "EU Funding Programmes and Funds 2021-2027," accessed July 11, 2023; European Commission, "Implementing the REPowerEU Action Plan: Investment Needs, Hydrogen Accelerator and Achieving the Bio-Methane Targets," May 18, 2022.

[24] Similar to the concept of hydrogen hub brought up in the U.S., hydrogen valleys bring together — in a limited geographical area — all the elements of renewable hydrogen production, storage and end-use into an integrated ecosystem.

Following the release of the REPowerEU plan, two hydrogen-focused Important Projects of Common European Interest (IPCEIs) were approved. Combined with the launch of a new European Hydrogen Bank, they represent a total €13.6 billion ($15bn) in public funding. The first IPCEI, "Hy2Tech," approved in July 2022, is providing up to €5.4 billion ($6bn) in public funding for 41 projects spanning across the hydrogen value chain with a particular focus on the transportation sector.[25] Meanwhile, the second IPCEI, "Hy2Use," supporting 35 projects with up to €5.2 billion ($5.8bn) in public funding, received approval in September 2022.[26] It promotes hydrogen infrastructure and its applications in industry. The additional €3 billion ($3.3bn) — which was allocated to the European Hydrogen Bank, launched in September 2022 — should help to assure green hydrogen producers and offtakers with fixed costs under the pilot contract-for-difference (CfD) mechanism due to start in 2023.

A distinguishing effort on the European side is the H2Global program, a "double auction scheme" launched by the German government to facilitate the import of green hydrogen and its derivatives.[27] Under the "double auction scheme," green hydrogen and hydrogen derivatives will first be purchased through competitive tenders from non-EU countries at the lowest possible price on 10-year contracts. Then they will be resold to highest bidders in European countries via short-term contracts. As green hydrogen today remains relatively expensive, public fundings will cover the gap between import costs and resale prices, with the hope that such gap will narrow over time as demand picks up and production costs decline. Rising costs of natural gas and carbon emissions have made domestically-produced green hydrogen more cost-competitive with blue and gray hydrogen in Europe. Nonetheless, Europe could also benefit from importing hydrogen from neighboring regions, particularly the Middle East and North Africa (MENA). In December 2022, the first auction was launched for the import of green hydrogen-based ammonia, helped by €900 million ($996mn) of initiative public funding with first deliveries set to arrive in Germany/Europe by the end of 2024.[28]

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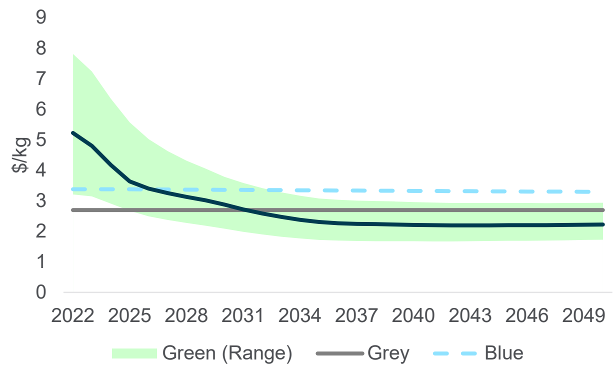
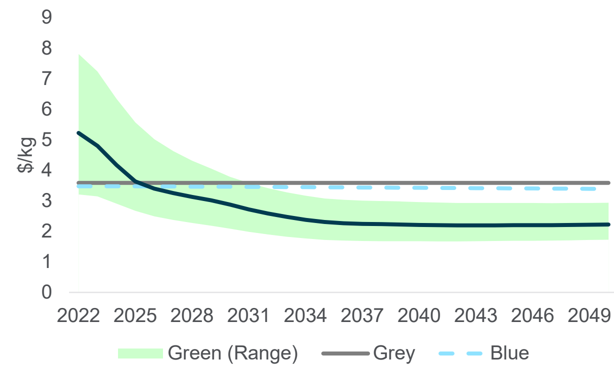
[25] European Commission, "State Aid: Commission Approves up to €5.4 Billion of Public Support by Fifteen Member States for an Important Project of Common European Interest in the Hydrogen Technology Value Chain," July 15, 2022.
[26] European Commission, "State Aid: Commission Approves Up to €5.2 Billion of Public Support by Thirteen Member States for the Second Important Project of Common European Interest in the Hydrogen Value Chain," September 21, 2022.
[27] H2Global Stiftung, "The H2Global Instrument," accessed July 11, 2023.
[28] H2Global Stiftung, "900 Million Euros for the Market Ramp-Up of Green Hydrogen," December 8, 2022.

Figure 14. LCOH of Gray, Blue, and Green Hydrogen Produced with Dedicated Onshore Wind in Germany (*Without* Carbon Emission Costs)



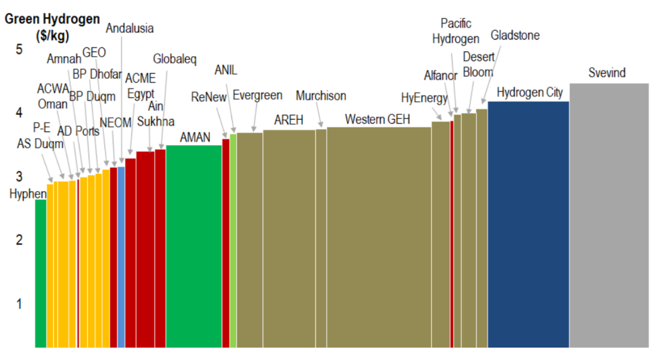
Source: Citi Research estimates (assuming natural gas price at $15/MMBtu)

Figure 15. LCOH of Gray, Blue, and Green Hydrogen Produced with Dedicated Onshore Wind in Germany (*With* Carbon Emission Costs)



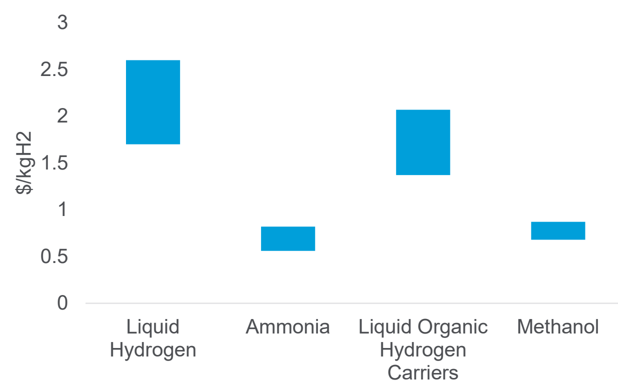
Source: Citi Research estimates (assuming natural gas price at $15/MMBtu and carbon emission cost at $100/metric ton)

Figure 16. Citi Energy Vision Green Hydrogen Cost Curve (Landed Europe, ex-offshore)



Source: Citi Research

Figure 17. LCOH of Shipping by Transport Option (i.e., as Liquid Hydrogen or First Converted Into Ammonia, Methanol, or Liquid Organic Hydrogen Carriers)



Source: Oxford Institute for Energy Studies, Citi GPS

(c) China: Stronger Growth Expected as Local Governments Release Ambitious Plans Eclipse National Targets

Provincial and local initiatives should lead to strong hydrogen development and production that blows past the highly conservative targets set by the central government. As is often the case in China, when opportunities arise, it is the local and provincial entities that drive change. Already with more wind and solar installations than any other country in the world, China is continuing with its ambitious renewable build-out program and dominating electrolyzer production — two elements that are key to green hydrogen development. Therefore, it is not hard to see how China's hydrogen development could far exceed central government targets. On the green hydrogen production side, major investments from state-owned enterprises (SOEs) are facilitating a significant overbuild in terms of production — an endemic issue in the energy transition where getting supply and demand more or less in balance has proven difficult and is an investment risk.[29]

[29] The State Council, The People's Republic of China, "State Companies Ramp Up Efforts in Hydrogen Power for Green Goals," *China Daily*, August 21, 2021; Xu Yihe,

The national headline target for green hydrogen production laid out in the national hydrogen strategy for 2021-35 appears conservative.[30] According to the national plan, by 2025, China's green hydrogen production should reach 100 to 200 kilotons (kt) per year. In comparison, the EU's hydrogen strategy released in July 2020 was calling for at least 6 GW of electrolyzer capacity producing up to 1 MMt of renewable hydrogen by 2024.[31] China's target of 100 kt to 200 kt per year also implies that green hydrogen will only account for 0.3%-0.6% of the country's current total hydrogen production, at 33 MMt per year — most of which goes into fertilizers and refining upgrading.

Meanwhile, sales of hydrogen fuel cell electric vehicles (HFCEVs) must accelerate in order to meet the 2025 national goal of having 50,000 HFCEVs on the road. The China Association of Automobile Manufacturers (CAAM) data suggest that domestic sales of HFCEVs registered 3,367 in 2022, more than doubling from 2021 and taking the accumulative sales since 2016 to above 12,000.[32] Yet, in order to meet the 50,000 target, average annual sales from 2023 to 2025 will need to be roughly 12,500, or 3.7 times higher than the 2022 sales.

However, these national targets are eclipsed by ambitious plans released by local governments. For example, Inner Mongolia, the second largest coal-producing province in China, set a target for green hydrogen production to reach 100 kt per year by 2023 and 500 kt per year by 2025.[33] Qinghai and Gansu provinces, both in Northwest China, also set targets of 40 kt per year and 200 kt per year by 2025, respectively. These three provinces alone should have 740 kt per year of green hydrogen production capacity by 2025, much higher than the national goal of 100 kt to 200 kt per year. Similarly, thirteen provinces and cities in China have a combined target of 111,000 HFCEVs on the road by 2025, more than double the national goal of 50,000 — with more targets by local governments expected to come.

"World's Largest Solar-to-Hydrogen Project Commissioned by Sinopec," Upstream, July 6, 2023.

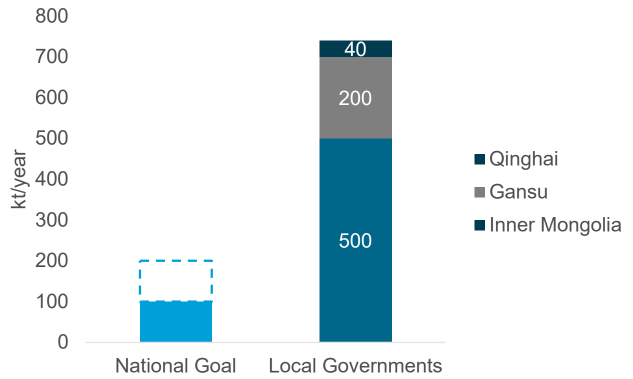
30 Argus, "China Outlines Hydrogen Development Plan for 2031-35," March 23, 2022.

31 Gregor Erbach and Liselotte Jensen, "EU Hydrogen Policy; Hydrogen as an Energy Carrier for a Climate-Neutral Economy, European Parliamentary Research services, April 2021.

32 OFweek, "The Number of Hydrogen Refueling Stations in My Country Is the First in the World, and the Number of Fuel Cell Vehicles is the Third in the World," February 7, 2023

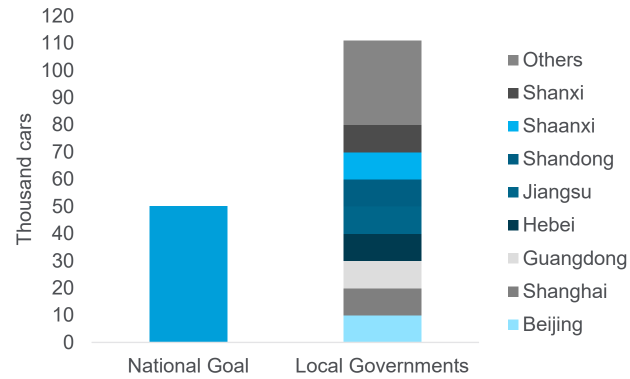
33 Argus, "China's Inner Mongolia Targets Green Hydrogen Expansion," August 20, 2021.

Figure 18. Green Hydrogen Production in Just Three Chinese Provinces Combined Could Reach 740 kt/yr in 2025, Much More Than China's National Target of 100 kt to 200 kt Per Year



Source: National Energy Administration, Local government documents, Citi GPS

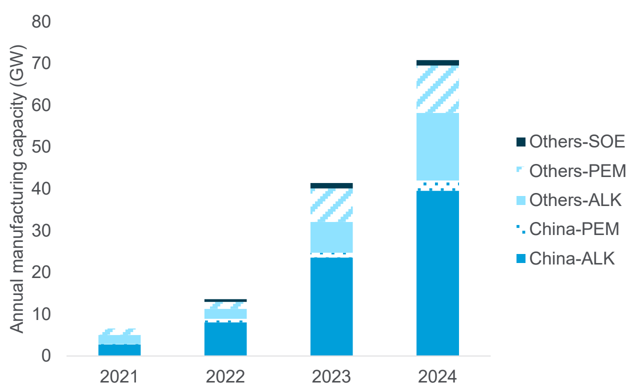
Figure 19. By 2025, China Could Have Over 110,000 Hydrogen-Fueled Vehicles on the Road Based on Plans by Provincial Governments, More Than Twice the 50,000 National Target



Source: National Energy Administration, Local government documents, Citi GPS

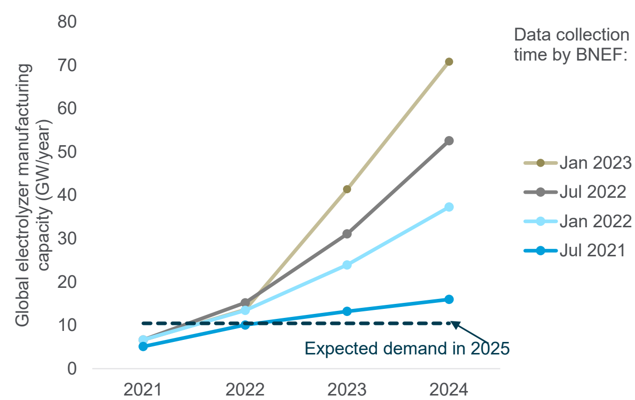
The push by local governments and corporates is bearing fruit and helping China to maintain its lead in global electrolyzer shipments. In 2022, some 60% of global electrolyzer shipments were delivered in China, according to BNEF.[34] As state-owned enterprises continue to move forward with their planned green hydrogen production projects, BNEF also estimates that 1.1 GW-1.6 GW of electrolyzers could be shipped in 2023. This will likely represent roughly half of the global electrolyzer market that year. As BNEF has reported, 71 GW of electrolyzer manufacturing capacity is scheduled to be online globally by the end of 2024, yet projected demand is only 10 GW in 2025.[35] The wide range of potential shipments attests to China's significant overcapacity to ship electrolyzers. Overcapacity is not just endemic to electrolyzer manufacturing: Consumption lags supply in hydrogen as a transport fuel and indeed in a wide range of green energy areas.[36]

Figure 20. Estimated Global Annual Electrolyzer Manufacturing Capacity by Region and Technology



Note: ALK refers to Alkaline Electrolyzer, SOE refers to Solid-Oxide Electrolyzer.
Source: BNEF, Citi GPS

Figure 21. Global Electrolyzer Manufacturing Capacity Projections Over Time vs. Expected Electrolyzer Demand



Source: BNEF, Citi GPS

[34] BNEF, "1H 2023 Hydrogen Market Outlook," March 2023.
[35] BNEF Signposts 1Q2023," p 36.
[36] BNEF, "China's Hydrogen Projects Struggle to Find Demand," April 6, 2023.

The three largest economies in the world (the U.S., the EU, and China, all discussed above) have grandiose green hydrogen projects in the works. Meanwhile, China plans to export electrolyzers and other equipment used in the manufacture of green hydrogen, and Europe aims to be an importer despite ample supplies produced at home. However, for most other countries at the forefront of hydrogen developments, trade is an essential ingredient. Some, like Japan, are planning to be largely importers of green hydrogen, while for others, the export market is essential. In the latter case, countries like Saudi Arabia and the UAE in the Middle East plan to develop a large export market; the main driver is diversification of an economy already dependent on exceptionally large exports of energy as critical element of growth. For others, like Chile, Brazil, and Australia, the export sector focus stems from their natural endowments — such as weather and abundant clean water — that enable them to develop clean hydrogen based on solar, wind, and/or hydropower.

(d) Japan: Building International Hydrogen and Ammonia Supply Chains Is a Key Priority

A key distinguishing feature of Japanese hydrogen strategy is its focus on building a large-scale global supply chain with equal emphasis on hydrogen and ammonia. The country has also executed its strategy with a sense of urgency, as the government believes being an early mover in the construction of international supply chains will enable Japan to acquire upstream interests on favorable terms and import hydrogen and ammonia at competitive prices.[37] From the very top, policymakers acknowledged that the domestic supply of clean hydrogen and ammonia is unlikely to be sufficient, as it is limited by Japan's renewable power capacity and the fact that CCUS is still in an early stage.

Japan has set ambitious targets for total supplies of hydrogen and ammonia through 2050. The country's annual supply of hydrogen and ammonia could grow from 2 MMt (hydrogen equivalent) today to 3 MMt by 2030, mainly driven by demand from fuel-cell commercial vehicles, ammonia-fueled ships, as well as co-firing with natural gas and coal by thermal power plants.[38] In fact, hydrogen and ammonia should account for 1% of total electricity supply in Japan in 2030 per the Sixth Strategic Energy Plan, released in 2021. Growth is set to accelerate post-2030, as hydrogen and ammonia are planned to be increasingly used by industrial sectors like steel-making and chemical production. Demand from the power and transportation sectors is also a target of expansion, and there will likely be a growing number of 100% hydrogen or ammonia-fueled power plants.

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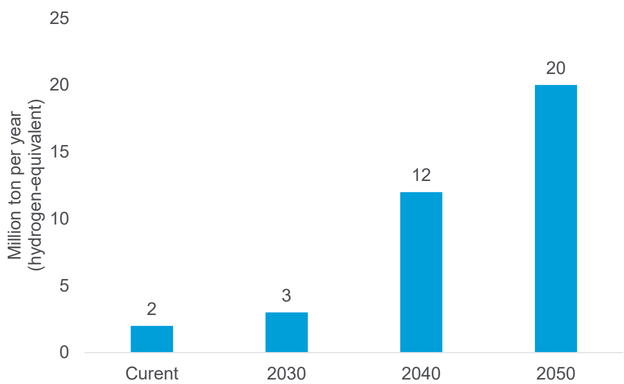
[37] Japan's Ministry of Economy, Trade and Industry (METI), "Joint Meeting of Hydrogen Policy Subcommittee/Ammonia and Other Decarbonized Fuel Policy Subcommittee Interim Report (Draft) (Secretariat Material)", December 13, 2022

[38] Co-firing is a mixed combustion technology for power generation. Japan is actively exploring mixing hydrogen into natural gas used for natural gas-fired power plants and mixing ammonia with coal for coal-fired power plants. Japan Pavillion, "Toward Zero-Emission Thermal Power Plants," PDF, supported by METI, accessed July 25, 2023; JERA, "Completion of Gas Turbine Modifications for Hydrogen Co-Firing at Linden Gas Thermal Power Station Unit 6 in the United States," June 7, 2023.

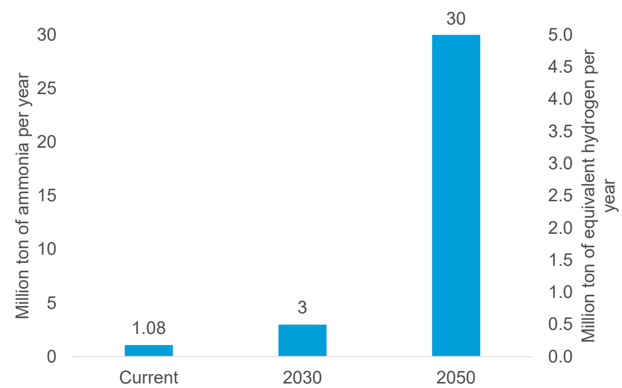
However, there are several caveats to Japan's ambitious targets. The country does not exclusively target green hydrogen: Hydrogen produced from fossil fuels without CCUS also counts. This is actually one of the aspects of the targets under critical scrutiny by environmental groups, besides the controversy around extending the lifeline of natural gas and coal power plants through co-firing and questions about the economics of long-haul shipments, particularly of ammonia. In March 2023, Japan committed $1.6 billion to the Hydrogen Energy Supply Chain (HESC) project, which would import hydrogen from Australia to Japan. The move was met with mixed feelings, with some doubting whether CCUS would actually work and reduce the carbon emissions in the process when hydrogen is produced out of lignite, a type of coal.[39]

Figure 22. Annual Hydrogen Supply Targets Set by the Sixth Strategic Energy Plan in 2021 (Including Supplies in the Form of Hydrogen Derivatives Like Ammonia, etc., That Is Directly Combusted)



Source: Ministry of Economy, Trade and Industry (METI) of Japan, Citi GPS

Figure 23. Annual Ammonia Supply Targets Set by the Sixth Strategic Energy Plan in 2021 (LHS: million metric ton of ammonia; RHS: million metric ton of equivalent hydrogen)



Source: Ministry of Economy, Trade and Industry (METI) of Japan, Citi GPS

Nonetheless, there have been major initiatives from both the public and private sectors in promoting clean hydrogen and ammonia:

- In February 2023, Japan's Cabinet approved the Basic Policy for the Realization of Green Transformation (GX), which aims to generate over ¥150 trillion ($1.1trn) from public and private investments over the next 10 years.[40] Specifically, ¥7 trillion ($50bn) is set aside for hydrogen subsidies, including ¥5 trillion ($35bn) toward building a large-scale supply chain and ¥1 trillion ($7.1bn) each for infrastructure and R&D.

- The government is also mulling over a 15-year subsidy for hydrogen and ammonia supplies to close the gap between their production costs and those of alternative fossil fuels that are currently used.[41] Specifically, natural gas prices will serve as the benchmark for hydrogen subsidies, and coal for ammonia. In principle, subsidies will be granted for clean hydrogen and ammonia production, with a target of reducing lifecycle carbon emissions by 60%-70% by 2030.

[39] AFP, "Japan Commits $1.6 Billion to Controversial Australia Hydrogen Project," *Barron's*, March 7. 2023.
[40] Dennis Engbarth, "Japan Forks Out Lots of Cash to Advance Cleantech," Energy Intelligence, March 1, 2023.
[41] METI, "Joint Meeting of Hydrogen Policy Subcommittee/Ammonia and Other Decarbonized Fuel Policy Subcommittee Interim Report (Draft) (Secretariat Material)," December 13, 2022

- The Green Innovation (GI) Fund, launched by the Ministry of Economy, Trade and Industry (METI) in 2021 with a total funding of ¥2 trillion ($14bn), has allocated up to ~¥653 billion ($4.6bn) for five projects dedicated to hydrogen, focusing on establishing supply chains as well as hydrogen's use in steelmaking and aircrafts.[42] There is also up to ~¥113 billion ($800mn) earmarked for building a smart mobility society through battery and hydrogen fuel cell electric vehicles.

- Major Japanese energy and utility companies are also making progress. For example, a group of seven companies are jointly investigating the possibility of converting a liquified petroleum gas (LPG) import terminal into one that can receive ammonia.[43] JERA — a company started as an alliance between two giant Japanese utilities, TEPCO and Chubu, in 2014 — has focused not only on the use of hydrogen at home, but also in sourcing materials abroad, especially from Australia. It also signed Memorandums of Understanding (MoUs) for clean ammonia imports of one million metric tons per year from the U.S. to Japan.[44]

Potential Future Leading Exporters Vie for a Head Start

Countries with superior renewable resources or access to cheap natural gas are also actively positioning themselves as future leaders of hydrogen exports. MENA countries in particular are set to benefit from their proximity to Europe, which results in much cheaper shipping costs.

(e) Saudi Arabia: Hydrogen Provides an Outlet to Diversify Away From Oil and Gas

The Kingdom of Saudi Arabia (KSA) is continuing the momentum it started with the 2016 announcement of its Vision 2030 objectives and reforms, as well as its planned creation of the futuristic megacity NEOM near the borders of Egypt and Jordan in 2017, with NEOM set to become a 1 million-person green economic zone to be completed by 2030.[45] That momentum was based on the urgency of the Kingdom, the country at the heart of both the OPEC and OPEC+ producer groups, to transform its economy so as to remain a critical — if not the most critical — supplier of energy to world markets as the world moved away from fossil fuels, and also to lead the global economy transition to clean technology-based fuels.

By mid-summer of 2020, the Kingdom reiterated its intention of becoming the world's largest producer of clean hydrogen via a $5 billion investment (the world's largest hydrogen investment at that time) led by U.S.-based Air Products, local power company ACWA, and NEOM, to which the KSA itself would provide some $2 billion for new infrastructure.

[42] METI, "Green Innovation Fund," accessed July 11, 2023.
[43] Ajsa Habibic, "Japanese Partners Study Turning Namikata Terminal Into Ammonia Hub," *Offshore Energy*, April 14, 2023.
[44] Julian Atchison, "JERA Closes in on Clean Ammonia Fuel Supply," Ammonia Energy Association, January 26, 2023.
[45] Vision 2030 is an economic and social blueprint for Saudi Arabia. One of its key objectives is to diversify the Saudi economy by supporting promising sectors, such as expanding renewables power capacity in the country and building local supply chains for renewables energy.

Now, the plans by the same companies — even before the first project is completed — are to build an additional three such giant plans, each producing 600 metric tons daily, largely for the export market — two at NEOM and a third at another location.[46] Even before that announcement, it had become clear that producing green hydrogen was going to be more expensive than originally planned, with the costs of solar panels having skyrocketed due to supply chain issues that arose during the COVID-19 pandemic and final financing for the first plant rising to $8.5 billion from the original $5 billion plan. All of the hydrogen produced from these four plants would be "green" assuming solar and wind power as the baseload, and green hydrogen itself would be the supplemental source for fueling the electrolyzers that would create hydrogen from water.

The Kingdom's plans for clean hydrogen have, from the start, included a significant amount of "blue hydrogen" to be produced in the Eastern part of the country — the heartland of its integrated oil production, refining, and petrochemical facilities, as well as a central part of the country's long-established adoption of the Circular Carbon Economy (CCE).[47] Indeed, the way the Kingdom decided to jump-start its program to become the world's largest exporter of clean hydrogen was to make a first shipment of 40 metric tons of blue ammonia to Japan in 2020, to be used as a green fuel.[48] As has been clear since the near simultaneous announcement by Saudi Oil Minister HE Prince Abdulaziz bin Salman when Saudi Arabia chaired the G-20 in 2020, the initiative is based on "4-R's:" *reducing* carbon emissions via higher reliance on renewables and nuclear power, *reusing* carbon via CCU, *recycling* carbon by embodying it in ammonia or cement, and *removing* carbon and storing it via CCS. The kingdom also announced a CCE-Index in 2021 and issued a second addition at COP27 in 2022.

The country's hydrogen ambitions are both global and local. Globally, it intends to be the world's largest exporter of combined blue and green hydrogen, while domestically it seeks to use clean hydrogen not only as a fuel for power generation, but also for industry and transportation. In fact, the original plans at NEOM involved fueling 50,000 vehicles with hydrogen fuel cells. The Kingdom's international plans target both Europe (where it has a joint venture with Germany) and Japan.

While the country has plans to spend some $266 billion overall to develop clean hydrogen, the obstacles to overcome are daunting, for both Saudi Arabia and other countries. To be sure, Saudi Arabia has massive advantages, including an ability to produce extremely inexpensive energy from solar and wind. It is also alluring to large companies committing to large-scale investments, boasting a resource base that warrants the requisite spending whether from companies in the U.S., South Korea, Japan, China, Europe, or elsewhere.

[46] Matthew Martin and Fahad Aduljadayel, "Saudi Arabia's ACWA Power Eyes Three More Giant Hydrogen Projects." Bloomberg, March 2, 2023.
[47] Circular Carbon Economy provides a framework to manage and reduce carbon emissions along the fossil fuel value chain. It includes 4Rs: Reduce, Reuse, Recycle and Remove.
[48] KAPSARC, "CCW Guide Overview," September 27, 2020; Verity Ratcliffe, "Saudi Arabia Sends Blue Ammonia to Japan in World-First Shipment," *Bloomberg*, September 27, 2020.

While BNEF has forecast over $11 trillion of investment could be required through 2050 for hydrogen production, transportation, and storage, it remains the case that demand forecasts for hydrogen — which comprised about 1% of all energy used in 2020 — vary widely.[49] BNEF's own most optimistic forecast is for hydrogen to reach just under 25% of final energy demand by mid-century. The Hydrogen Council's 2°C scenario sees hydrogen reaching 18% by then, while forecasts from the Intergovernmental Panel on Climate Change (IPCC) and the International Energy Agency (IEA) are both well under 10%.[50] Yet, from a Saudi perspective, not only have plans for NEOM-type initiatives in the West, and a number of places in oil and natural gas-producing areas elsewhere in the Kingdom multiplied, but so have areas under investigation for hydrogen usage (e.g., for maritime and aviation fuel). All these developments have piqued investor interest from abroad. A recent workshop discussion on Chinese-Saudi cooperation on supply chains identified a large number of areas for potential Chinese investment in the Kingdom, including "power transformers, photovoltaic (PV) modules, solar inverters, the balance of systems, concentrated solar power (CSP) pressurized systems, wind tower installations, and maintenance equipment, as well as rotor blades and steam turbines."[51]

(f) UAE: Like Neighboring Saudi Arabia, the UAE Intends to Dominate Global Green Hydrogen

The Emirates' entry into the clean hydrogen arena front ran much of the rest of the world, with the UAE creating Masdar in 2006 — which was both a clean energy company and a planned city — under the leadership of HE Dr. Sultan Ahmed Al Jaber (now Minister of Industry and Advanced Technology as well as Group CEO of ADNOC and the UAE's special envoy for climate change) who is heading up COP28 in late 2023. Al Jaber is still head of Masdar, a controversial precursor to NEOM. The UAE and Masdar also became the seat of the International Renewable Energy Agency (IRENA) in 2015. The agency, founded in 2009, now has 168 member countries with 16 more in accession. IRENA focuses on renewable energy in emerging markets — a special focus of attention for the UAE, which, together with IRENA, announced a $400 million fund at COP26 to finance 1.5 GW of new renewable energy in emerging markets by 2030. Al Jaber and Masdar established UAE leadership well beyond the region, as the country started the world's largest concentrated solar plant (Shams 1) and was also responsible for the London Array — one of the largest wind farms in the world. In keeping with the leadership that the UAE intends to sustain well beyond COP28, in late 2021, Masdar, the Abu Dhabi National Oil Company (ADNOC), and the sovereign wealth fund Taqa joined Mubadala, the largest sovereign wealth fund (SWF) in the UAE, in creating a new national partnership to enhance the UAE's efforts to achieve net zero via investments at home and abroad.

With 2023 a special year for the UAE in light of its chairing of COP28, the country is also seeing a record amount of foreign investment, including from Israel, Germany, China, and a good bit of the rest of the world. The UAE has finally inaugurated its first nuclear plant (along with a commitment to forswear nuclear weapons) and is aiming for renewables to provide some 75% of its total energy by 2050.

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[49] BNEF, "Hydrogen Economy Outlook," March 20, 2022.

[50] Jan Frederik Braun and Rami Shabaneh, "Commentary: Saudi Arabia' Clean Hydrogen Ambitions: Opportunities and Challenges," KAPSARC, June 2021.

[51] KAPSARC, "Saudi-China Collaboration on Renewable Energy Supply Chains," December 2022.

This is all part of its goal, similar to Saudi Arabia's, to preserve its global position in energy by monetizing its fossil fuel resources as quickly as it can in order to accelerate investments in clean energy technology and maintain a leading position as a provider of, and investor in, energy globally.

The investment flows into the UAE from abroad, as well as UAE's energy investments in the larger region and more globally, rest explicitly on the growth of domestic fossil fuel resources to finance a responsible energy transition. This is key given the country knows, like neighboring Saudi Arabia, that its resources are less expensive and less carbon-intensive than global averages. Hence, the country plans to expand oil production capacity to at least 5 million barrels per day (mb/d) and possibly to 6 mb/d from somewhat over 4 mb/d today. They also plan to expand gas production and processing and enter liquified natural gas (LNG) exports both at home, where it aims for 9.6 million metric tons per annum (mtpa), and abroad, where it is partnering with Chevron in Israel and potentially in Egypt and elsewhere.[52]

But the UAE's clean energy initiatives at home and abroad are exceptional. The country is taking a leadership position on finding ways for emerging market countries to ideally avoid (or, at minimum, limit) the use of coal for power generation, and in that realm is fostering both renewables and natural gas as essential ingredients in managing a smooth energy transition. In 2023 alone, it plans to inaugurate the Al Dhafra Solar Project before the start of COP28, with 2 GW of capacity. The UAE's nuclear capacity continues to grow, based on agreements with the U.S. and Korea, including a full safeguard against making nuclear weapons. The Barakah nuclear center consists of four reactors — long delayed from the first planned operation in 2017. The goal is for the four plants to provide 25% of the country's electricity needs, avoiding over 20 million metric tons of carbon emissions (about the same emissions as 3.2 million passenger vehicles). The first reactor started up in the summer of 2020, with the second unit at Barakah on the Gulf Coast near Qatar becoming operational with another 1,400 MW of power in the spring of 2022. The third unit obtained its operating license in the summer of the same year. Unit 4 should be operating in 2023, another milestone in the year of COP28. Other projects include the $3.9 billion 950-MW Noor Energy 1 farm as well as the Hatta Wind Power project in Dubai.[53]

(g) Chile: Can a Privileged Geography Make the Country a Top-Three Exporter?

Chile is also eyeing the huge potential for hydrogen in European and Asian markets. In its National Green Hydrogen Strategy, released in November 2020, Chile expects its green ammonia exports is likely to reach $2 billion by 2030, with Europe likely being its biggest market.[54] The country also targeted green hydrogen production of 200 kilotons per year (kt/yr) by 2025, with electrolysis capacity reaching 5 GW and 25 GW by 2025 and 2030, respectively.[55]

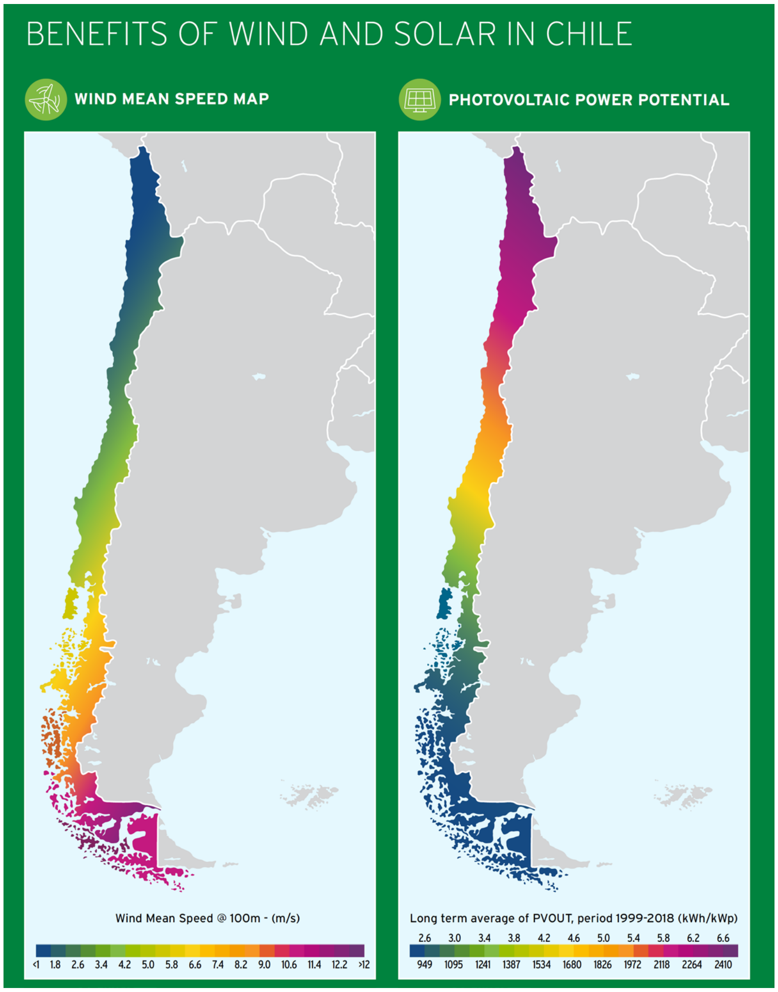
[52] Robin Mills, "Fossil Fuels and the Gulf Energy Transition," AGSIW, April 13, 2023.
[53] Felicity Bradstock, "The Middle East is Looking to Dominate the Green Hydrogen Market," OilPrice.com, March 16, 2023.
[54] Government of Chile, "National Green Hydrogen Strategy: Chile, A Clean Energy Provider for a Carbon Neutral Planet," November 2020.
[55] Ibid.

Its efforts are starting to pay off, with the production of first liters of synthetic gasoline completed in December 2022 from the Haru Oni Demonstration Plant in southern Chile. Once fully operational in March 2023, the plant will produce 350 t/yr of eMethanol and 130,000 liters/yr of eGasoline, all of which will be used by Porsche.[56]

In announcing the country's new strategy in 2020, then Minister of Energy and Mines, Juan Carlos Jobet, pointed to the country's extraordinary endowment of wind and solar, which could enable an LCOH close to that of gray hydrogen at just above $1 per kilogram by mid-decade. It could also put Chile in a position to be among the top three global exporters of green hydrogen.[57] Jobet pointed to the "solar drenched" Antofagasta region in the north, "blessed by" what he referred to as the "world's most powerful solar irradiation" in the northern desert (others call it "fierce solar radiation"), but also by over 4,000 miles of windy coast, especially in Southern Patagonia near the Antarctic Circle, locus of the Haru Oni project mentioned above, where winds can sustain speeds of over 75 miles per hour (120 km/hr).[58] Other natural advantages include strong ocean currents potentially providing tidal-sourced electricity, as well as untapped geothermal along with abundant clean water and hydroelectricity from rivers in central and southern Chile. Chile also appears to be the world's most abundant source of lithium. These natural advantages are already apparent from the fact that the country now has renewables sourcing more than 50% of its power generation.

[56] HIF Global, "HIF Global and Its Partners Celebrate the First Liters of Synthetic Fuels From Haru Oni, Chile," PDF, December 20, 2022.
[57] *Mining Journal*, "Jobet details Chile's National Mining Plan," September 20, 2020
[58] Sherry Ahn, "Chile's Green Hydrogen Ambitions on Show in Patagonia," BNEF, Feb. 16, 2023.

Figure 24. Benefits of Solar and Wind in Chile



Source: Vortex, World Bank Group, Citi GPS

By the end of the first quarter of 2023, Chile already had over 100 companies active in 41 hydrogen projects, including in the transportation sector (making gasoline and methanol) and in fertilizers, with ammonia shipments planned for both Japan and Germany (including, in Japan's case, ammonia bunkering and strong use of ammonia in shipping supply chains). The plans to ship ammonia to Europe were announced more or less at the same time that two of the largest ammonia plants in Europe were being shut down.

While Chile aims to develop some $45 billion in green hydrogen projects by 2030, reaching $330 billion by 2050, there are inevitable snags that will likely develop at home. For example, planned wind projects alone already involve 13,000 square kilometers of wind turbines in southern Patagonia — with more slated to come. Concerns are mounting about Chile's pristine coastline, as are worries about some 60 species of migratory birds, as well as the impacts of increased shipping on the robust whale and dolphin populations of the area. As one conservationist put it, "Socially, culturally, physically, and economically this place will be unrecognizable. And I'm not sure we've thought about that enough."[59]

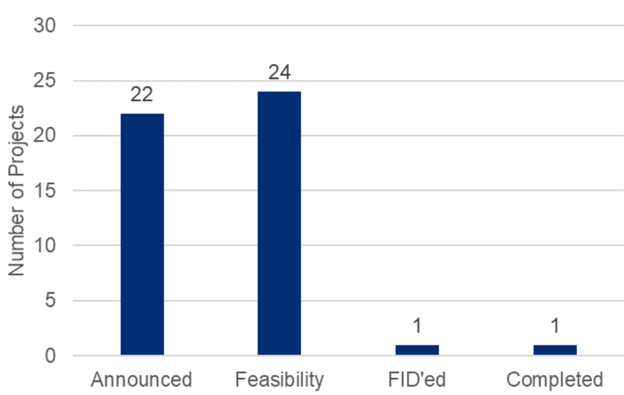
[59] Diego Luna, as quoted in John Bartlett, "Chile's Bet on Green Hydrogen," in IMF's *Finance and Development*, December 2022.

(h) Australia: Leader to Laggard? Government Is Calling for Action

As the third country in the world to release its national hydrogen strategy in 2019, Australia is an early mover, with over 100 hydrogen projects worth A$230 billion ($155bn) to A$300 billion ($202bn) of potential investment in the pipeline as of October 2022.[60] Australia has fostered close relationships with international partners in recent years, leading to breakthroughs on multiple fronts. In February 2022, it sent the world's first shipment of liquefied hydrogen to Japan as part of the Hydrogen Energy Supply Chain (HESC) project, which received ¥220 billion of funding (around A$2.3bn, or $1.6bn) from Japan in March 2023, on top of the A$500 million ($335mn) committed already in the pilot phase.[61] Later in September 2022, ENGIE took the Final Investment Decision (FID) on the Yuri Renewable Hydrogen to Ammonia Project. When the project is completed in 2024, it will produce up to 640 metric tons per year of renewable hydrogen in the first phase. All the hydrogen will feed into Yara Australia's ammonia facility.

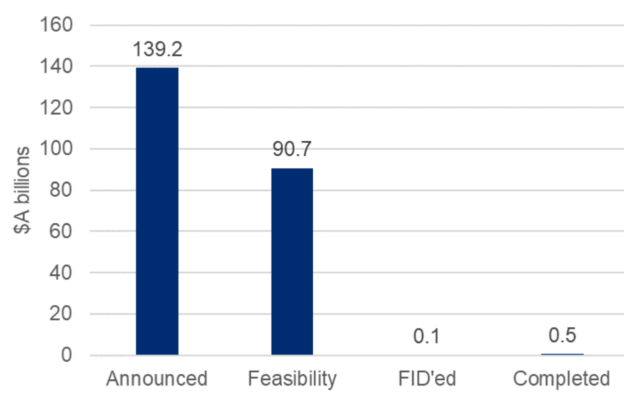
However, out of the 48 announced major hydrogen projects announced through October 2022, only the aforementioned HESC pilot phase was completed, and the Yuri ammonia project was the only other project FID'ed and under construction.[62] In fact, Australia is trailing a few countries including the U.S., France, Germany, Sweden, Spain, and China in terms of the number of clean hydrogen projects (10 MW or greater) that reached FID. Therefore, the government's *State of Hydrogen 2022* report identified Australia as a laggard on several metrics, such as public and private funding, as well as project scale.

Figure 25. Out of the 48 Active Hydrogen Major Projects in Australia, 22 Remained at the Stage of Public Announcement, With Another 24 Undergoing Feasibility Assessment and Only 1 Under Construction (FID'ed)



Source: Department of Industry, Science and Resources (DISR) of Australia, Citi GPS

Figure 26. The Stakes Are High, as Projects Pending FID Represent at Least A$230 Billion of Estimated Investments



Source: Department of Industry, Science and Resources (DISR) of Australia, Citi GPS

[60] COAG Energy Council, *Australia's National Hydrogen Strategy*, November 2019; Australian Government Department of Climate Change, Energy, the Environment and Water, *State of Hydrogen 2022*, April 13, 2023.
[61] Australian Government, "Australia Exports World's First Shipment of Liquified Hydrogen to Japan," February 2022; HESC, "Japan Commits AUD$2.35 Billion to Establish World's First Liquified Hydrogen Supply Chain," March 7, 2023.
[62] According to the Department of Industry, Science and Resources (DISR) of Australia, major projects should have at least A$50 million in investment.

Recognizing its slow progress, the Australian government is currently reviewing its national hydrogen strategy, taking into account the impacts of the U.S. IRA and policies by other countries as well. More funding, including foreign direct investment, will be necessary. As of January 2023, federal and states governments have provided a total of A$6.3 billion ($4.2bn) of hydrogen-specific funding, along with another A$35.2 billion ($23.7bn) that is hydrogen-eligible. In particular, A$1.02 billion (less than $700m) is dedicated to creating eight hydrogen hubs and nine feasibility studies in support of potential future hydrogen hubs. For reference, the U.S. Department of Energy (DOE) will provide up to $7 billion for six to 10 clean hydrogen hubs across the U.S. Overall, BNEF has estimated it would take nearly A$300 billion ($202bn) to build all of the required renewables (solar, wind, and batteries) to power electrolyzers, as well as another A$29 billion ($19.5bn) and A$10 billion ($6.7bn) for power grids and hydrogen pipelines, respectively.[63]

Notably, other countries that have released new development plans for clean hydrogen include Canada, Germany, India, Oman, Portugal, and the UK.

[63] BNEF, "Australia's Hydrogen Dreams: Dashed Without Infrastructure," May 23, 2023.

Challenges Ahead Nonetheless: Two Steps Forward, One Step Back

Despite the progress that hydrogen has achieved in the past two years, it remains at an early stage, with no globally traded markets. Apart from costs, hydrogen also faces technical challenges, both existing ones and others that could emerge as it expands its markets. Without careful planning and robust project risk management, hydrogen may face negative public perception due to safety issues, and its "green" reputation could suffer due to the problem of hydrogen leakage and the pressures the technology puts on water-stressed areas. The following sections shed light on some of these challenges.

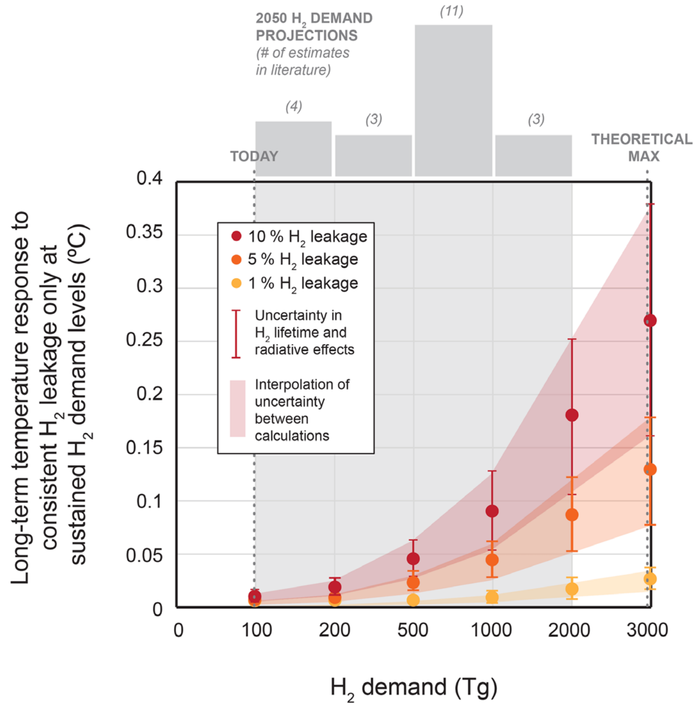
(1) Hydrogen Leakage

Hydrogen has an indirect global warming potential (GWP), often overlooked, that could be 100 times stronger than that of carbon dioxide (CO_2) over a 10-year period.[64] Although the GWP of hydrogen weakens over time, it remains powerful. Over a 20-year horizon, hydrogen's GWP could be 22 to 44 times that of CO_2, and six to 16 times over a 100-year horizon.[65] While hydrogen is not a direct greenhouse gas (GHG) like CO_2 or methane, it can extend the lifetime of these GHGs by reacting with atmospheric hydroxyl radicals (OH), which are key to the neutralization of GHGs. Leakage of hydrogen may happen during every stage along the supply chain, from production and delivery to consumption. Yet studies about leakage rates are rare, particularly regarding the leakage rates associated with production as well as potential new end-use sectors.

Therefore, without proper measures, hydrogen leakage could cancel out efforts to reduce carbon emissions and limit global warming. A 2022 study by the Environmental Defense Fund suggested that a 10% leak rate could lead to 0.05°C -0.1°C warming, assuming global hydrogen demand of 500 MMt/yr to 660 MMt/yr by 2050, as projected by IEA, BNEF, and the Hydrogen Council.[66] The actual impact could vary, as the total value-chain emissions estimated by various studies have a wide range, from 0.3% to 20%. In fact, the production of green hydrogen alone could see some 3%-4% of hydrogen leakage. A study done by the National Renewable Energy Laboratory (NREL) found that the loss of hydrogen could reach 3.5%, as wet hydrogen goes through the drying stage in the prototype proton exchange membrane (PEM) electrolyzers.[67]

[64] Zhiyuan Fan et al., "Hydrogen Leakage: A Potential Risk for the Hydrogen Economy," Columbia University Center on Global Energy Policy, July 5, 2022.
[65] UK Department for Energy Security and Net Zero and Department for Business, Energy & Industrial Strategy, "Atmospheric Implications of Increased Hydrogen Use," April 8, 2022.
[66] Ilissa B. Ocko and Steven Hamburg, "Climate Consequences of Hydrogen Emissions," *Atmospheric Chemistry and Physics*, Vol. 22, No. 14, July 20, 2022.
[67] NREL, "FY2013 Annual Progress Report: Renewable Electrolysis Integrated Systems Development and Testing," PDF, 2013.

Figure 27. Long-Term Temperature Responses to Different Levels of Hydrogen Leakage Based on Projected 2050 Hydrogen Demand



Source: Environmental Defense Fund

(2) Water Availability

Water, as pure as possible, is a key input in green hydrogen production. Theoretically, 1 kg of green hydrogen takes an input of 9 kg of water. However, in reality it can take 18 kg to 24 kg of water to produce 1 kg of green hydrogen due to process inefficiencies and water demineralization.[68] Further, water impurities can lead to higher degradation rates for both alkaline and PEM electrolyzers, therefore increasing the operating costs of green hydrogen production. In the case of PEM, poor water quality could also cause stack failures and lower efficiencies.

Among the most ambitious countries looking to dominate future hydrogen exports, many are water-stressed. Therefore, a careful examination of water supply is critical to assess the potential growth of hydrogen in these countries. Apart from the MENA region, which is already the most water-stressed region in the world, northern China, southwestern Australia, and other arid zones are also likely to face water constraints on the production of green hydrogen, according to IRENA.[69] Indeed, concerns over water supply have stalled the 6-GW Moolawatana plant, a green hydrogen production project planned for hydrogen exports from the northern desert part of the state of South Australia.[70]

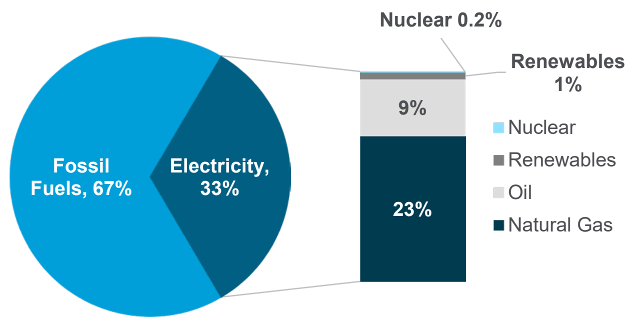
[68] IRENA, *Green Hydrogen Cost Reduction: Scaling up Electrolyzers to Meet the 1.5C Climate Goal*, December 2020.

[69] According to UNICEF, 14 out of the 17 most water stressed countries globally were from the MENA region, based on 2018 data; IRENA, *Global Hydrogen Trade to Meet the 1.5°C Climate Goal: Part III – Green Hydrogen Cost and Potential*, May 2022.

[70] Argus, "Water Supply Scuppers South Australia 6GW Hydrogen Plan," May 31, 2022.

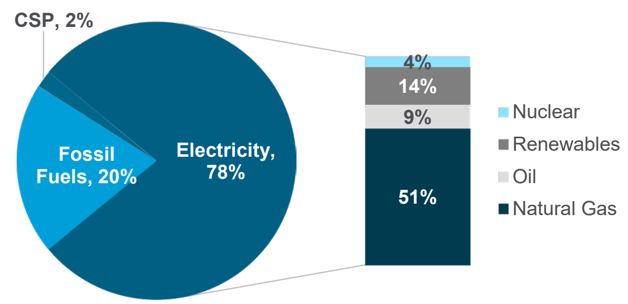
Desalination presents a possible solution, but it is costly and energy intensive. An IEA report estimated that desalination could account for almost 15% of the total final energy consumption in 2040 in the Middle East, up from 5% in 2016, as production of desalinated water is set to grow fourteen-fold from 5 billion cubic meters per year (bcm/yr) in 2016 to 70 bcm/yr in 2040.[71] While the region is shifting from a fossil fuel-based thermal desalination process to electricity-based reverse osmosis technology, its power sector remains heavily dependent on fossil fuels today and may still be so in 2040, according to the IEA.

Figure 28. Energy Sources for Seawater Desalination in the Middle East in 2016



Source: IEA, Citi GPS

Figure 29. Expected Energy Sources for Seawater Desalination in the Middle East in 2040, Under IEA "New Policies Scenario"



Source: IEA, Citi GPS, Note: CSP refers to concentrating solar power.

There are also environmental consequences related to both seawater intake and brine disposal. When desalination plants extract seawater for processing, fish or other organisms could get stuck in the intake screen and get killed. The brine that is left behind post-desalination could lead to serious pollution to the ocean if not disposed of properly. In fact, high costs and energy consumption, loss of marine life, and pollution are the exact reasons that shuttered the desalination project in Huntington Beach, California, which was rejected by the California Coastal Commission.[72]

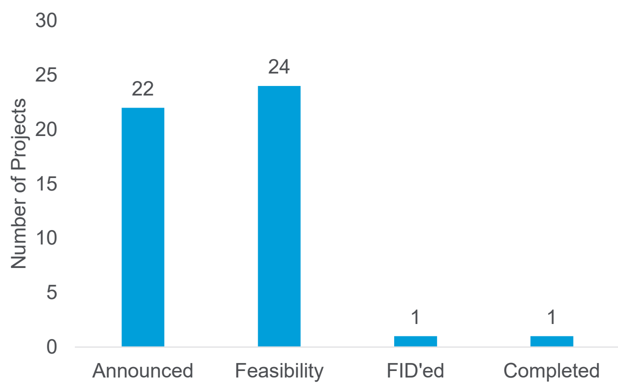
(3) Long-Distance Shipping of Hydrogen

Transporting hydrogen over long distances remains very challenging. Due to its very low boiling point, hydrogen liquefaction is extremely energy intensive. Gaseous hydrogen is liquefied by being cooled to below -253°C, which takes more than 30% of the energy content of the hydrogen using today's technology.[73] Liquid hydrogen is also very flammable, easily causing fires and explosions without proper handling. In fact, the world's first liquid hydrogen shipment from Australia to Japan suffered from gas flames shortly after the tanker was loaded.[74] The vessel in use, which later successfully delivered a cargo to Japan, could only carry about 75 metric tons of hydrogen, a fraction of the 72,000 metric tons typically carried by large liquefied natural gas vessels.

[71] Molly Walton, "Desalinated Water Affects the Energy Equation in the Middle East," IEA, January 21, 2019.
[72] Roman Goergen, "The Future of Desalination," Geographical, August 2, 2022.
[73] U.S. Department of Energy, "Liquid Hydrogen Delivery," accessed July 11, 2023.
[74] Australian Transport Safety Bureau, "Gas Control Equipment Malfunction on Board the Gas Tanker Suiso Frontier at Western Port, Hastings, Victoria on January 25, 2022," accessed July 11, 2023.

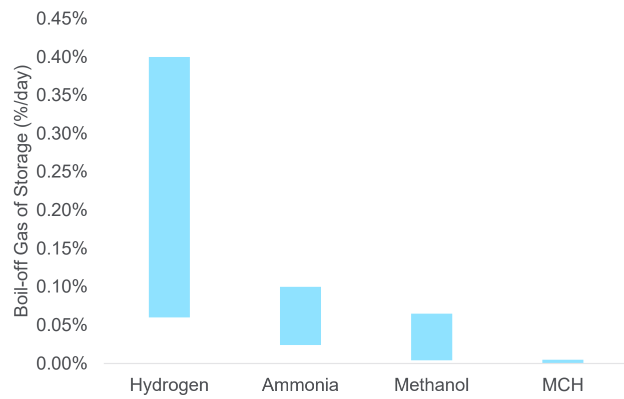
Several other fuels that can be derived from hydrogen have been put on the table as alternatives to shipping liquid hydrogen directly. These include ammonia, methanol, and methylcyclohexane (MCH), but there is no clear winner yet. On the one hand, they generally have much higher boiling points than hydrogen, and hence lower boil-off gas (BOG) losses during transportation and storage. While ammonia still requires liquefaction, this could take 50%-90% less energy than liquefying hydrogen.[75] On the other hand, depending on the end-usage, these fuels may need to be dehydrogenated upon delivery, whereby hydrogen is released for further uses. Conversion from hydrogen and reconversion back to hydrogen necessitate extra energy and costs. Finally, even if these hydrogen derivatives were to be burned directly as fuels, they could potentially cause other emission problems. For ammonia, the problem would be nitrogen oxides (NOx). For MCH and methanol, it would be carbon oxides (COx). Further, incomplete combustion of methanol could create formaldehyde, a toxic gas that can be damaging to human health even in small quantities.

Figure 30. Boiling Points of Potential Hydrogen Carriers



Source: Citi GPS

Figure 31. Boil-Off Gas (BOG) Losses of Potential Hydrogen Carriers During Storage on Cryogenic Shipping Tanks (%/day)

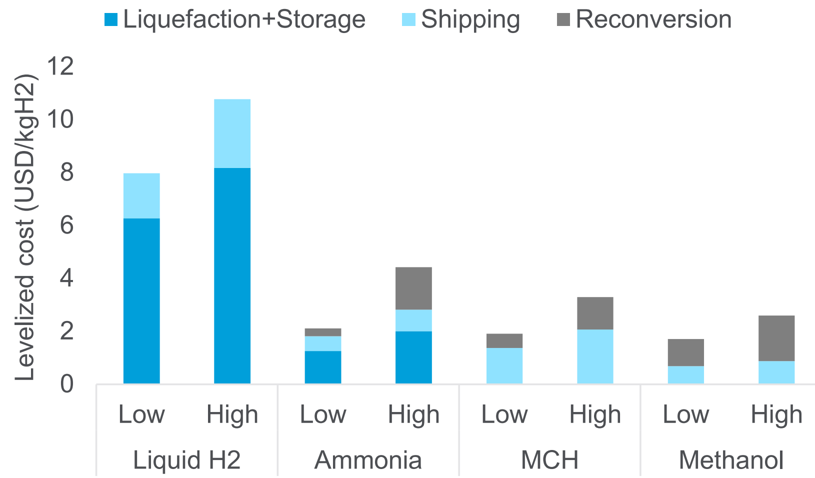


Source: Citi GPS, Oxford Institute for Energy Studies

Long-distance shipping of hydrogen, whatever the form of carrier, is very costly today, representing a major component of the total costs along the hydrogen supply chain. Estimated shipping costs range widely, as the technologies used in shipping are still immature. Nonetheless, one study that summarized multiple studies found that shipping in the form of liquid hydrogen could costs between $8/kg hydrogen and $10.80/kg hydrogen, the highest cost among the four carriers considered.[76] Even the cheaper options like ammonia or methanol could still see delivered costs of hydrogen double or triple its production costs. Therefore, many hydrogen projects today focus on creating hubs or valleys that pool together hydrogen production sites and end-users to avoid significant pipeline or shipping haul.

[75] Oxford Institute for Energy Studies, *Global Trade of Hydrogen: What Is the Best Way to Transfer Hydrogen Over Long Distances?* September 2022.
[76] Ibid.

Figure 32. Approximate Levelized Hydrogen Shipping Costs in Different Forms of Carriers



Source: Oxford Institute for Energy Studies, Citi GPS

The difficulty of long-distance shipping of hydrogen highlights the potentially long and winding road toward a globally traded and liquid hydrogen market. While the LNG industry certainly offers valuable lessons, hydrogen also faces some unique challenges.[77] For example, unlike LNG, hydrogen will be shipped and traded in multiple forms, so there may not be a unified hydrogen market. Further, the various production pathways of hydrogen and their associated carbon emissions mean that measuring and tracking hydrogen's carbon intensity is critical from the onset, which calls for greater international cooperation in setting up rules and standards.

(4) Hydrogen Blending in Existing Natural Gas Pipelines

A promising emerging demand application is blending hydrogen into existing natural gas pipelines, which could potentially speed up its deployment by reducing infrastructure costs. Demonstration projects have mushroomed, mostly testing up to 20% hydrogen by volume.[78] For example, the HyDeploy project in the UK has successfully tested a blended hydrogen content of up to 20% by volume in two separate trials, demonstrating safe operation without having to change existing home appliances.[79] In the U.S., Hawaii's Oahu island has been using an average of around a 12% blend of hydrogen in its gas network since the 1970s, mainly for cooking or water-heating purposes.

[77] International Energy Forum, "What the Hydrogen Economy Can Learn From LNG," February 1, 2023.
[78] California Public Utilities Commission, "Hydrogen Blending Impacts Study," July 18, 2022.
[79] HyDeploy, "Pioneering the Safe Use of Blended Hydrogen in Gas Networks to Reduce Carbon Emissions," accessed July 11, 2023.

Yet, there is some uncertainty around equipment performance and safety, particularly at higher hydrogen concentrations. It has long been known that hydrogen can cause metals to become brittle, a phenomenon called "hydrogen embrittlement." This could increase fatigue crack growth rates in commonly used pipeline steels.[80] Further, the low molecular weight and volumetric energy density of hydrogen could lead to pressure de-rating of existing pipelines. Since transporting hydrogen along pipelines requires higher compression energy, some existing natural gas pipelines may hit technical limits during retrofit and therefore not be able to increase the share of hydrogen to 100%. End-use appliances may also be a limiting factor, as higher combustion temperatures with hydrogen-natural gas blends could potentially lead to local overheating of components, driving increased emissions of NOx. There is also a higher chance of flashbacks in household appliances, where the gas flame moves into hoses or even gas cylinders.

(5) Public Perception of Hydrogen Safety

Hydrogen is highly flammable and explosive, and its leaks and flames can be hard to detect, posing safety hazards. Like natural gas and propane, hydrogen is odorless and colorless. However, the current practice of adding an odorant (Mercaptan) to propane and natural gas for leak identification does not apply to hydrogen. This is because no known odorants that can be added to hydrogen can diffuse at the same rate as hydrogen.[81] What is more, hydrogen has a very broad flammability range and only needs minimal energy to ignite, while its flame is nearly invisible during daylight hours.[82] All of these factors suggest that we ought to be very careful when handling hydrogen.

Therefore, public concerns around hydrogen safety could delay or challenge new projects, similar to how natural gas pipelines and renewables projects have had to overcome NIMBY objections. In November 2022, the pilot project to blend 5% of hydrogen in existing natural gas pipelines in the U.S. state of Oregon was canceled due to objections from local residents and environmental groups, who cited concerns over costs and safety.[83] Around the same time, a Swiss project to produce renewable hydrogen for road transportation was called off after the court ruled in favor of private citizens' appeal.[84]

[80] Kevin Topolski et al., "Hydrogen Blending into Natural Gas Pipeline Infrastructure: Review of the State of Technology," NREL, October 2022.
[81] Occupational Safety and Health Administration of U.S. Department of Labor, "Green Job Hazards: Hydrogen Fuel Cells, Fire and Explosion," accessed July 11, 2023.
[82] Hydrogen's flammability range: 4% to 74% concentration in air and 4% to 94% in oxygen. It requires only 0.02 millijoules of energy to ignite the hydrogen-air mixture, which is less than 7% of the energy needed to ignite natural gas.
[83] Steve Ernst, "NW Natural Pulls Plug on Hydrogen Pilot Over Local Objections," Clearing Up, November 4, 2022; Adam Duvernay, "Groups Oppose NW Natural Plan to Blend Hydrogen with Eugene Natural Gas," *The Register-Guard*," October 27, 2022.
[84] Hydrogen Central, "Axpo Halts Green Hydrogen Project in Switzerland in Face of Local Opposition," October 10, 2022.

Financing Low Carbon/Green Hydrogen

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Financing green hydrogen projects is a new frontier that requires a diverse approach, leveraging experience from various sectors like LNG, power, oil and gas, and mining. Given the value-chain integration and scalability risks associated with green hydrogen projects, financing large-scale projects will need ad hoc risk management frameworks and financing structures that are familiar to infrastructure lenders and investors.

Green hydrogen projects have many parallels to offshore wind and LNG projects — technologically complex, large-scale, capital-intensive energy businesses. Therefore, we expect the commercial and financing models for green hydrogen to draw from the relevant parts of offshore wind and LNG. The initial LNG projects developed in 1960s and 1970s were mostly financed on balance sheet by project sponsors' equity. As the spot market for LNG developed in the 1980s and Export Credit Agencies (ECAs) began playing a prominent role in the 1990s, LNG project financing structures emerged and evolved into a combination of commercial bank loans, ECA financing, project bonds, and equity investments from diverse sources.

Green hydrogen is still finding its footing in the market. Until demand grows, investors are likely to focus on projects serving industries with existing uses for hydrogen, such as fertilizers, refineries, and specialty vehicle fuel. Project co-location with such end-users would be beneficial and minimize the need for new infrastructure, shorten timelines, and reduce overall capital requirements. Decarbonizing these sectors should pave the way for other applications of hydrogen and its derivatives. Governments are also promoting and funding new uses of green hydrogen, such as hydrogen-powered public transport and power plants.

While it is still in the early stages, we are witnessing the initial development of project financing for clean hydrogen. Earlier this year, the NEOM Green Hydrogen Company (NGHC), a joint venture between ACWA Power, Air Products, and NEOM, announced that NGHC had achieved financial close on the world's largest green hydrogen production facility, with a final total investment value of $8.4 billion (an increase relative to the original $5 billion budget that was driven by inflation, updated land fees, scope changes, and debt financing costs). The plant is currently being constructed in Oxagon, located in Saudi Arabia's NEOM region, and funded through a $6.1 billion non-recourse financing package from 23 local, regional, and international banks and financial institutions. S&P Global has certified that the NGHC facilities are aligned with the green loan principles, making this financing one of the largest project financings ever established under the green loan framework. The project financing is supported by an exclusive 30-year offtake agreement for 100% of the green ammonia produced at the facility with Air Products, which is also acting as the primary contractor and system integrator for the project via a $6.7 billion EPC contract. The NGHC's plant aims to integrate up to 4GW of solar and wind energy and produce approximately 600 metric tons of carbon-free hydrogen per day by the end of 2026, in the form of green ammonia. The project's total financing includes an ECA facility and commercial and mezzanine debt facilities, both arranged on a non-recourse project finance basis, as well as the participation of the National Development Fund (NDF) on behalf of the National Infrastructure Fund (NIF) as well as of the Saudi Industrial Development Fund (SIDF).

ECAs are expected to play a crucial role in financing low carbon and green hydrogen projects by providing direct loans, loan guarantees, or insurance products, as well as offering political risk insurance, credit guarantees, or risk-sharing arrangements. ECAs can also facilitate market access for new hydrogen projects by supporting the export of goods and services related to project development. This includes equipment, technologies, and expertise necessary for the production, storage, and transportation of green hydrogen. ECAs' support will help attract private sector investment and enable project developers to secure necessary funding.

Producing green hydrogen on a large scale is a complex process with evolving technology. It requires local sources of water and renewable energy, as well as facilities for liquefaction, reconversion, and transportation, which are currently limited. As with other emerging technologies, green hydrogen's scalability faces uncertainty, including lack of performance benchmarks, as well as potential equipment, materials, and infrastructure development delays. Investors will need to ensure that all components required to produce and deliver hydrogen, or its derivatives, are de-risked as customary for asset-level financings.

Large-scale hydrogen projects need reliable offtake arrangements. Despite the buzz around green and blue hydrogen, large financings have been lagging, with very few closed. One feature that is holding back projects achieving bankability is the absence of a hydrogen market. This makes it challenging for investors to assess prospects of future revenue, which depends — to a material extent — on customers' willingness to pay initially higher prices relative to fossil fuel-based alternatives. The ideal scenario for project financing is a long-term, fixed-price contract with a creditworthy purchaser. One alternative solution could be a long-term contract-for-difference (CfD), supported by the public sector, that provides long-term visibility into the price of green hydrogen. For instance, the European Commission plans to introduce carbon CfDs to encourage hydrogen use and electrification in industries.

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