INVESTING IN CLEAN HYDROGEN

by

Petya P. Miteva

Dr. Jesko von Windheim, Advisor

April 26, 2024

Master's project submitted in partial fulfillment of the requirements for the Master of Environmental Management degree in the Nicholas School of the Environment of Duke University

TABLE OF CONTENTS

TABLE OF CONTENTS 2
I. EXECUTIVE SUMMARY 4
II. PROJECT OBJECTIVES 4
III. PROJECT METHODS 5
IV. HYDROGEN BACKGROUND 6
1. Hydrogen as an important lever in global decarbonization 6
Introduction 6
Hydrogen properties 6
Clean hydrogen 8
2. Hydrogen market trends 10
Current state 10
Government support 11
Private investment in hydrogen projects 13
Innovation 14
Projected growth 15
V. INVESTMENT OPPORTUNITIES IN CLEAN HYDROGEN INNOVATION 16
1. Production 17
Electrolyzers 17
Carbon Capture, Utilization and/or Storage (CCUS) 17
Hydrogen hubs 18
2. Transportation & storage 18
Challenges for the transportation and storage of hydrogen 19
System perspective 19
3. Transformation & utilization 20
VI. FRAMEWORK FOR INVESTING IN CLEAN HYDROGEN INNOVATION 21
1. Investor Types 22
a. Catalytic capital/impact angel investors, VC funds and PE/buyout firms 23
b. Traditional VCs 24
c. Strategic corporate investors 24
d. Financial Institutions 25
2. Five-step process 25

3. Case Study 27
VI. CONCLUSION 28
VII. APPENDIX 29
Hydrogen Glossary 29
Colors of hydrogen 29
US hydrogen subsidies compared to the rest of the world in 2023 30
Country-specific government policies and subsidies in support of clean hydrogen 31
US 31
EU 31
Japan 32
Others 32
Short-Listed Hydrogen Hubs 32
Electrolyzer technologies comparison 32
Electrolyzer technologies maturity level 33
Companies innovating in clean hydrogen technology along the value chain 34
VIII. REFERENCES 35

I. EXECUTIVE SUMMARY

This paper lays out a framework and process for investors to build their investment theses in clean hydrogen innovation. This framework was developed based on conversations with industry experts and a literature review that informed an analysis of a range of investment opportunities in innovations within the hydrogen value chain. The framework functions in five steps:

- **Answer** four key questions corresponding to various investment criteria categories;
- **Refine** specific investment criteria based on these answers;
- **Rank** investment criteria from highest to lowest priority;
- **Identify** optimal investment niches by using this paper's internally developed opportunities heatmap;
- **Build** a clean hydrogen innovation investment thesis that targets the top-scoring niches.

With plentiful opportunities for innovative solutions for the production, storage, transportation, transformation, and utilization of clean hydrogen, investors are showing an appetite for tapping into this space. These innovations hold the promise of revolutionizing a variety of activities within the hydrogen value chain to enable its use in traditionally Greenhouse Gas emissions (GHG)[*] intensive sectors.[1] Yet, identifying the right opportunities within an emerging space could be challenging.

Clean[†] hydrogen is an important lever in the decarbonization of the global economy[‡], expected to account for roughly 10-12% of global annual energy use by 2050.[2,3] To meet the levels envisioned by most global decarbonization scenarios[4, 5, 6], low-carbon hydrogen production and use in applications where it replaces a higher emitting fuel or energy source needs to grow 100 times from today's levels by 2030.[7] An estimated total investment of $1 trillion[8] would be required to reach this target; yet there remains a $430 billion gap between current commitments and what's needed.[9] Stronger investment frameworks like the one put forth in this paper could help narrow this gap by enabling investors to deploy capital where it matters to usher in the ubiquitous use of clean hydrogen across the economy.

II. PROJECT OBJECTIVES

Investment opportunities to bridge the gap between the current levels of clean hydrogen use and what is estimated to be needed in a global net zero decarbonization scenario abound across the clean hydrogen value chain. However, many investors across the innovation capital stack are struggling to craft their investment thesis in this space in a way that best aligns with their investment philosophy and objectives, as it is both a fairly new space and opportunities are extremely varied. This paper aims to remedy this by providing a map of the clean hydrogen innovation space and a framework tool that can be used by investors across the innovation capital stack to better understand the range of opportunities

[*] CO_2 is the primary greenhouse gas of concern in the case of hydrogen. Therefore, the rest of this paper will focus on CO_2 emissions only.
[†] Defined as low-carbon or zero-carbon hydrogen on a life-cycle basis. (See Clean hydrogen for more information.)
[‡]According to the International Energy Agency (IEA)'s NetZero Emissions by 2050 Scenario (NZE), *a normative scenario that shows a pathway for the global energy sector to achieve net zero CO2 emissions by 2050*. Link: https://www.iea.org/reports/global-energy-and-climate-model/net-zero-emissions-by-2050-scenario-nze

and develop their clean hydrogen innovation investment theses[*] based on key investment criteria and priorities.

The three main objectives of this project can be summarized as:

1. Understanding the hydrogen market and clean hydrogen potential;
2. Conducting a landscape analysis of the investment opportunities in clean hydrogen innovation; and
3. Providing a framework tool for investors interested in making a bet on clean hydrogen innovation.

III. PROJECT METHODS

This project employed three primary methods to develop a robust framework for investing in clean hydrogen innovation.

The first step was a collaboration with an impact-driven climate tech Venture Capital (VC) fund client to develop a tailor-made clean hydrogen innovation investment thesis for them that would suit their specific needs and ambitions.

Second, this project's approach included a series of expert interviews. A spectrum of specialists across various sectors including investment firms, energy companies, startups, and governmental and academic institutions shared their knowledge in semi-structured conversations. These discussions provided diverse insights and a deep understanding of the industry's landscape. It should be noted that while the knowledge acquired through these conversations informed the development of the clean hydrogen innovation investment framework set forth in this paper, no personal interview references, direct quotes or specific data points are included in this paper. This is done at the request of the interviewees who wish to remain undisclosed.

Third, a considerable amount of time was also dedicated to a thorough of reports and papers from reputable organizations such as the Hydrogen Council, the Department of Energy (DOE), the International Energy Agency (IEA), the International Renewable Energy Agency (IRENA), and others, to ensure that this study was not only comprehensive but also grounded in current market understanding and industry benchmarks.

These methodologies made it possible to craft a detailed and actionable framework for investing in clean hydrogen innovation, aligned with the industry's growth trajectory and global net zero aspirations.

[*] Most commonly used in Venture Capital (VC) and Private Equity (PE), an *investment thesis* outlines a fund's approach to using capital to generate returns and any other desired outcomes. It could be broad, at a portfolio level, or specific to a certain sector or vertical.

IV. HYDROGEN BACKGROUND

1. Hydrogen as an important lever in global decarbonization

Introduction

In recent years and in light of global decarbonization commitments and net zero scenarios, hydrogen has gained increasing attention from both governments and the private sector as a potentially carbon-free or low-carbon alternative to fossil fuels in some of the hardest sectors to decarbonize such as heavy industry, aviation, and maritime shipping. As the International Energy Agency (IEA) put it, hydrogen "is an increasingly important piece of the net zero emissions by 2050 puzzle".[10] In their "Hydrogen for Net Zero" report[11], the Hydrogen Council and McKinsey & Company estimate that clean hydrogen can abate up to 80 gigatons of CO_2 by 2050.[*12] This is more than double what the world emits in a year – total global emissions in 2022 were 37.15 gigatons CO_2).[13]

However, many challenges remain in realizing this potential. The rest of this section dives deeper into what hydrogen is, why it is touted as a potential clean energy source, the state of the hydrogen market now, and what it is projected to be in the future.

Hydrogen properties

Hydrogen has several inherent properties that make it an efficient and potentially carbon-free energy carrier or fuel. First, it is the simplest and most abundant chemical element in the universe[14], making up approximately 75% of its mass.[15] Its molecule (H_2) is comprised of only two hydrogen atoms. On Earth, hydrogen is mostly found in its compound forms: water[16] and hydrocarbons;[17] although recent discoveries of hydrogen deposits in the Earth's crust in 2023 may suggest a paradigm shift in this matter.

Additionally, hydrogen has a very high energy content by weight (gravimetric energy density) of 120 MJ/kg[18]; in fact, the highest of any fuel (See Figure 1 below).[19] Its gravimetric energy density also competes with that of batteries, making it a prime candidate for energy storage (See Figure 2 below).[20]

---

[*] This is a cumulative number representing an 11% contribution to the annual decrease in emissions from 2021 to 2050 required for the world to remain on a path towards a 1.5-1.8C degree scenario.

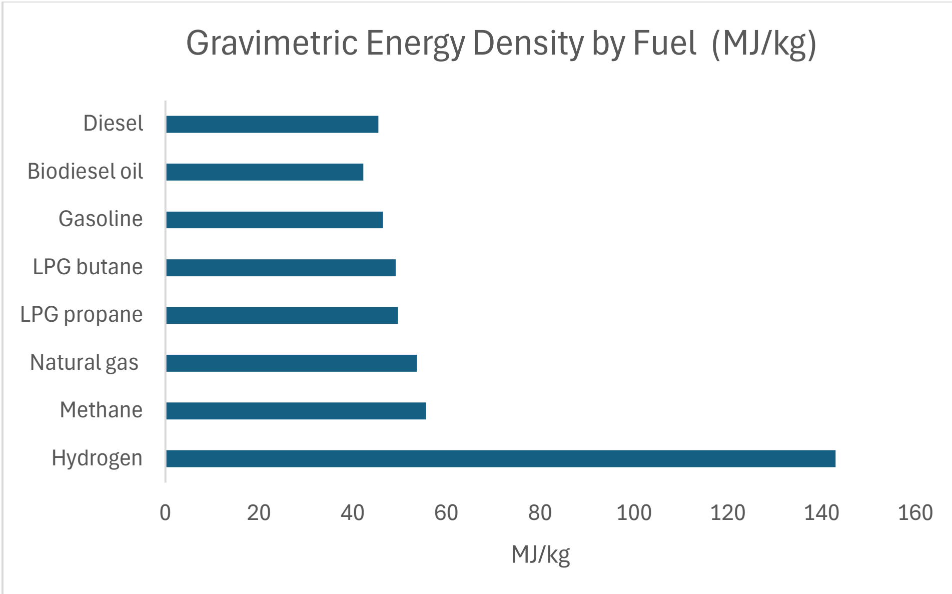


Figure 1 Gravimetric Energy Density by Fuel[21]

This is primarily due to its low density as a gas with a very small molecule and therefore, light weight, and high reactivity with oxygen.[22] In the words of Bill Gates, Founder, investor and Chair of the Board of prominent climate tech venture capital firm Breakthrough Energy Ventures, "Hydrogen is pure, reactive chemical energy."[23]

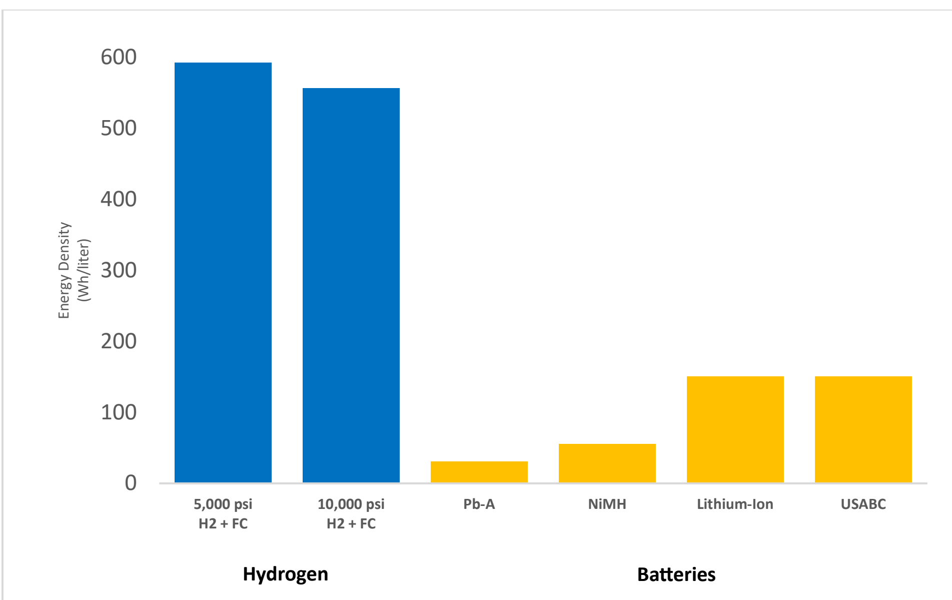


Figure 2 Energy density of hydrogen tanks and fuel cell systems compared to the energy density of batteries (2009)[24]

Because of all of its properties, hydrogen is considered a very flexible or versatile energy carrier[25] – as seen in Figure 3, it has many current and potential applications as a fuel, heat source, or feedstock.[26]

Some experts have gone as far as to call it "the Swiss army knife of decarbonization,"[27] alluding to its versatility and myriad potential uses.[28]

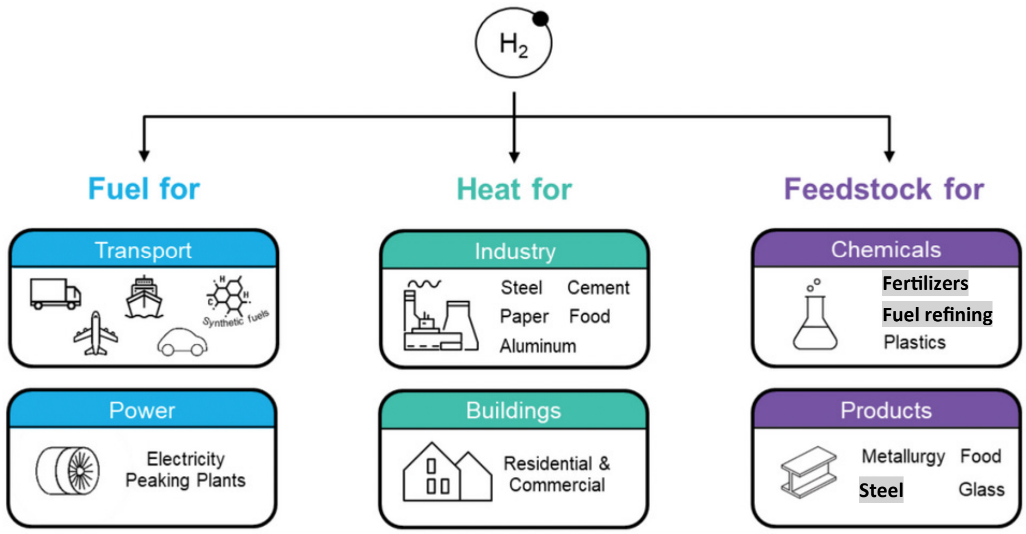


Figure 3 Summary of potential clean hydrogen applications.[29] Existing uses are highlighted in grey.

What makes hydrogen attractive as a decarbonization lever, however, is the fact that unlike fossil fuels, it is a clean burning-fuel, meaning it burns without emitting CO_2 or other greenhouse gases.[*30] Therefore, it has the potential to be a clean energy source on a lifecycle basis (production, use and disposal phase[†]), especially in applications where electrification is not possible.[31] As a result, many decarbonization scenarios contemplate some participation of hydrogen in the energy mix. For example, in its Net Zero by 2050 scenario the International Energy Agency expects 10% of the energy mix by 2050 to come from hydrogen.[32]

Clean hydrogen

However, while hydrogen doesn't have emissions during its use phase,[33] this is not always the case for the rest of its value chain, and most importantly, its production phase. In other words, not all hydrogen is made equal. That is why, here we explore the most common hydrogen production approaches in more detail to better define "clean" hydrogen for the purposes of this study.

Currently, there are two main hydrogen production methods[‡]:

---

[*] This is a simplification to an extent because the high temperature, to which hydrogen heats up the surrounding air when it combusts, can generate NOx emissions higher than those of natural gas on an energy output basis. This local pollution issue is outside the scope of this study. Source: Douglas, C. et al. (2022). NOx emission impacts of hydrogen combustion in gas turbines: A short paper. Georgia Institute of Technology. Retrieved from https://research.gatech.edu/sites/default/files/inline-files/gt_epri_nox_emission_h2_short_paper.pdf

[†] Fossil fuels, for example, have emissions both in the production and use phases, but the majority is in the use phase because of their burning and releasing CO_2 in the atmosphere.

[‡] Extracting geologic hydrogen from deposits in the Earth's crust has emerged as a new potentially source of low-carbon hydrogen in the last 6 months. However, as further studies are needed to determine its technical viability, it is excluded from the present analysis.

- **Steam methane reforming** – separating the hydrogen atom from the methane molecule (CH_4). This is an example of extracting hydrogen atoms found in fossil fuel compounds.
- **Electrolysis** – splitting water (H_2O) into hydrogen and oxygen via a technology called an *electrolyzer*.

While the first process inherently emits carbon (C) as it separates the hydrogen (H) from the methane molecule (CH_4), the only by-product of electrolysis is oxygen. However, it requires large amounts of energy to overcome the strong bond between the hydrogen and oxygen atoms within the water molecule. Depending on the fuel used for generating that energy (coal, natural gas, renewables, nuclear, etc.), the resulting hydrogen could be carbon-free through the point of production (*well-to-gate*)[34] or not.

To facilitate the discussion around hydrogen and its associated production methods, there is a commonly used color-coded terminology, according to which the process type and energy source determine the "color" of hydrogen. While there are many different **hydrogen colors**, the most commonly used ones are the following (Figure 4):

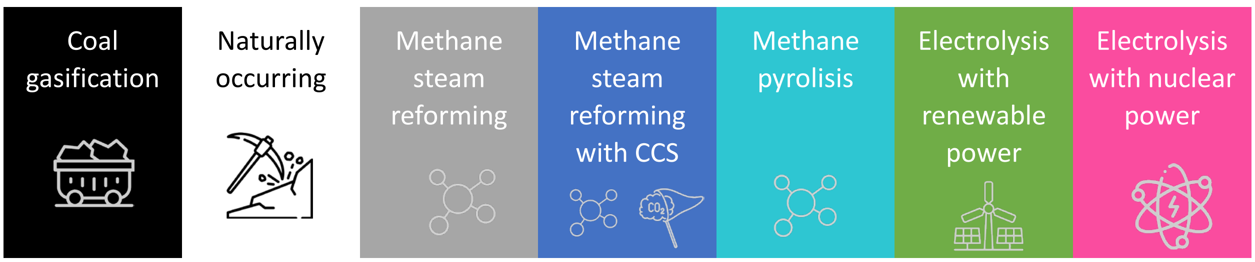


Figure 4 Hydrogen production pathways color code[35]

For more details on each type of hydrogen, see the Appendix.

The definition of "clean" hydrogen is complicated as it pertains to the intensity of carbon emissions associated with its production and could refer to any range of low carbon or carbon-free hydrogen production. Consequently, there is no clear consensus among the scientific, government, and business communities on which hydrogen production pathways are clean. While most agree that green hydrogen falls into this category, the status of blue and pink hydrogen is more debatable as carbon capture and storage (CCS) does not eliminate 100% of the CO_2 emissions and nuclear power has other potential environmental impacts. For the purposes of this study, innovations enabling both green and blue hydrogen are explored as viable low-carbon solutions of interest to climate tech investors.

For the majority of the existence of a hydrogen market, it has been primarily grey and, in many cases, derived as a by-product from different operations, such as naphtha crackers.[36] This largely remains the case with 99.3% of global hydrogen production in 2022 being grey[37] (95% in the US[38]) and only 0.1% and 0.6% blue and green respectively (Figure 5).

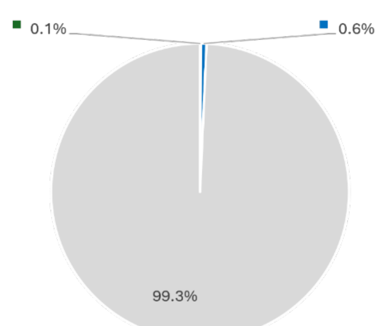


Figure 5 Global Hydrogen Production by Type (2022)

2. Hydrogen market trends

Current state

In 2022, the global hydrogen market reached 94 million metric tons* (Mt), a nearly 3% increase from 2021,[39] and was valued at $155 billion.[40]

However, despite its potential as a clean fuel, hydrogen continues to be primarily utilized as a commodity in two traditional applications: oil refining and ammonia fertilizer production. Together, these two uses account for more than 99% of the current global hydrogen demand with the remainder used in the steel industry (as a reducing agent) and for special applications in other industries (Figure 6).[41]

At the same time, the growth of the clean hydrogen economy faces some headwinds. The uptake of hydrogen in new applications such as heavy industry, fuels, and energy storage remains minimal, estimated at 0.1% of global demand by the IEA.[42]

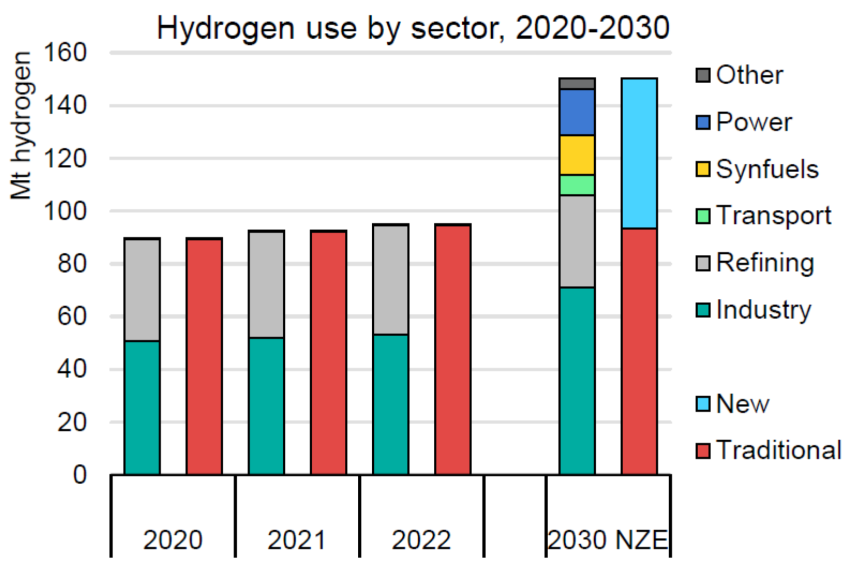
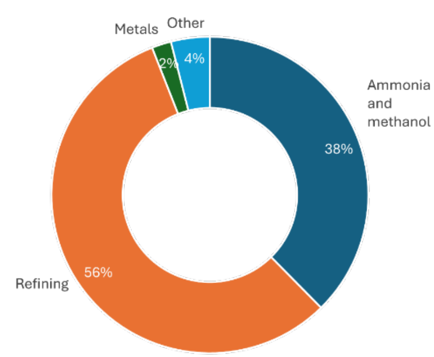


Figure 6 Hydrogen use by sector and by region, historical and in the Net Zero[43]

The US market follows a similar pattern. A total of 11.4 million metric tons of H_2 is currently consumed annually in the US, valued at approximately $17.6 billion,[44] of which 77% is served by hydrogen from steam methane reforming and the remaining 23% is a by-product from oil refining. Not only is hydrogen in the US not produced in a clean way, but the large majority is used in traditional applications (oil refining and ammonia and methanol production), which themselves are heavy CO_2 emitters (see Figure 7 for a full breakdown).[45]

Figure 7 US hydrogen market today (2020)[44]



---

* A metric ton is a measurement unit equal to 1,000 kilograms and commonly used in the metric system as a measure of weight.

Therefore, clean hydrogen adoption across the economy has a long way to go to reach its full potential as a decarbonization lever both on the supply and demand sides. The challenge to scaling green and blue hydrogen production is that both processes with existing technologies (electrolyzers and carbon capture and storage) are very energy intensive and consequently, not cost competitive with steam methane reforming. Additionally, as previously noted, hydrogen is a gas with a very small molecule, which accounts for its very low volumetric energy density, i.e. energy content by volume. These characteristics contribute to many challenges associated with its transportation and storage* and add to its overall cost.

As a result, many experts have proposed a target price for hydrogen (produced, delivered, and dispensed) of $1/kg.[46] Current price estimates as of December 2023 for green hydrogen on an LCOH (levelized cost of hydrogen) basis are about 4.5 to 6.5 USD/kg.[47] This is about 30-65% higher than previously estimated in May 2023 due to interest rate hikes affecting the capital expenditure cost of hydrogen projects.[48] According to *the DOE National Clean Hydrogen Strategy and Roadmap*, published in June 2023, demand could be expected to reach the levels illustrated in Figure 8 in each sector if clean hydrogen was available at the corresponding threshold price from the figure. That amounts to a total of between 23 million metric tons and 50 million metric tons in annual demand in the US in a base case and high demand scenario respectively if the H_2 $1/kg price target is reached.[49]

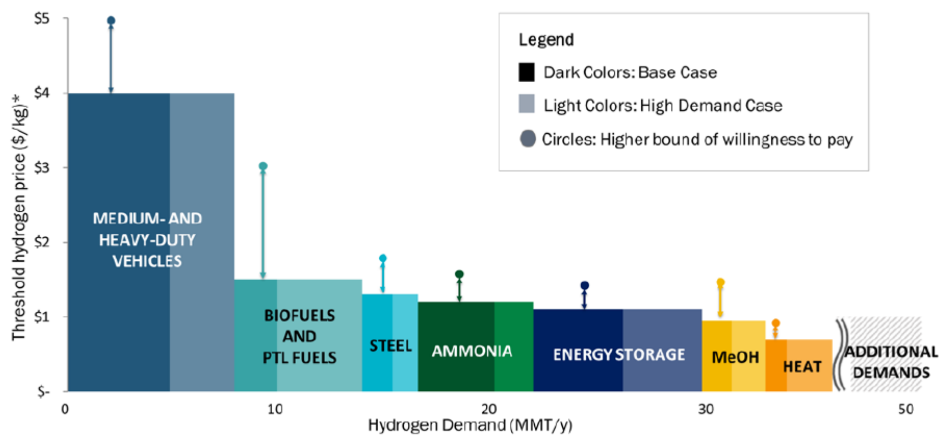


Figure 8 Expected hydrogen demand at different hydrogen price levels in the US

Given the gap between where the hydrogen market is, and where it needs to be to meet ambitious global Net Zero targets, both governments and private capital continue to invest hundreds of billions of dollars in all stages of the hydrogen production process. The following three sections discuss the investments made by governments and private industry to close the gap within the hydrogen market.

Government support

Recognizing hydrogen's potential as a clean fuel and the need to bring the cost of clean hydrogen down to compete with traditional (grey) hydrogen[50], 52 country governments have developed hydrogen strategies to boost clean hydrogen production. [51] In total, their targets would add up to between 20.4 million tons and 40 million tons by 2030† (Figure 9).[52]

* This is going to be explored in more detail in the Opportunities section of this report.

† Compared to a little over half a million tons (658,000 tons) or 0.7% of the 94 million metric tons consumed in 2022 (Source: IEA Hydrogen Insights 2023).

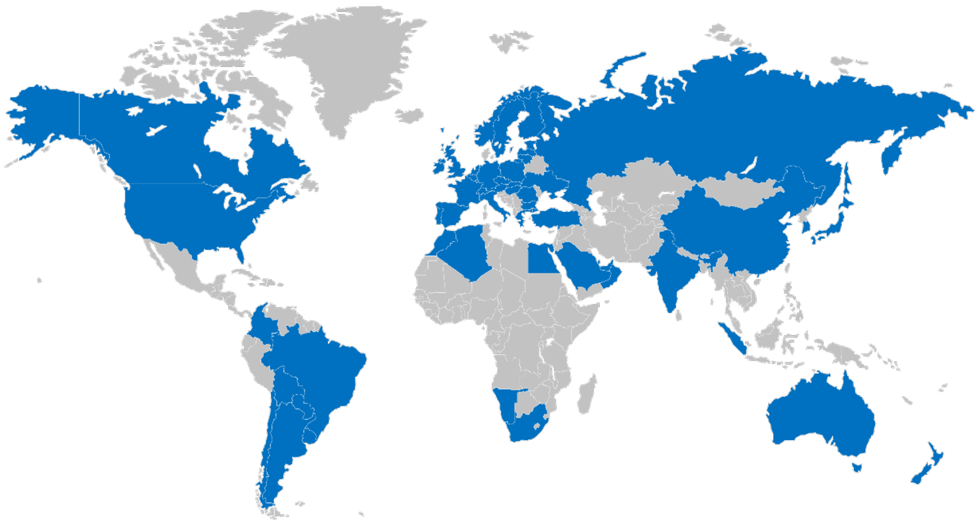


Figure 9 Countries with hydrogen policy support as of October 2022* [53]

In addition to policy support, many governments have also allocated hydrogen subsidies to jump start the hydrogen economy. In 2023, hydrogen subsidies jumped more than 43% year over year globally reaching $280B with growth in all regions' commitments (see Figure 11).[54] On a global scale, the Americas lead the charge with $155B (Figure 11) in subsidies, $137B of which are in the US (Figure in the Appendix).

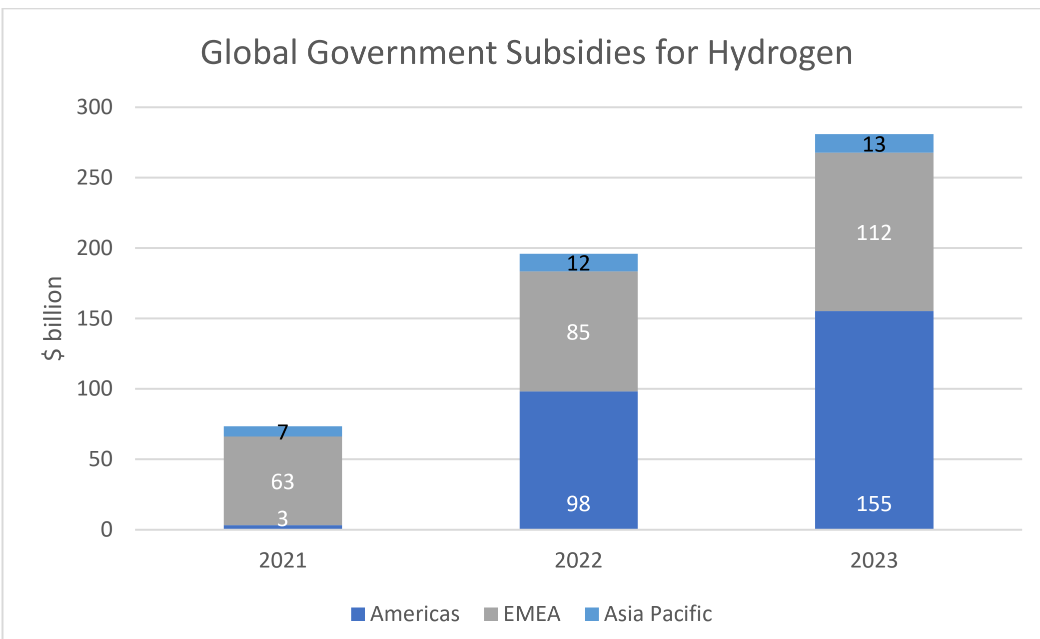


Figure 10 Funding for hydrogen† by announcement year and region, as of August 2023[55]

---

* Considers policies in place, in preparation and initial policy discussions.

† Includes funding schemes that are announced and in force. Includes tax credits, grants, research and development funding, contracts for difference and fixed premium subsidy mechanisms. Excludes loans, loan guarantees and funding for fuel-cell passenger vehicles. Funding from US Inflation Reduction Act tax credits for

Most available subsidies are in the form of tax credits, followed by grant programs and R&D funding. Fixed premiums and contracts for difference that guarantee a set additional payment to producers or suppliers of clean hydrogen, over and above the market price, thereby ensuring a consistent revenue stream, are another two mechanisms used by some countries, but are very infrequent (see Figure 11).

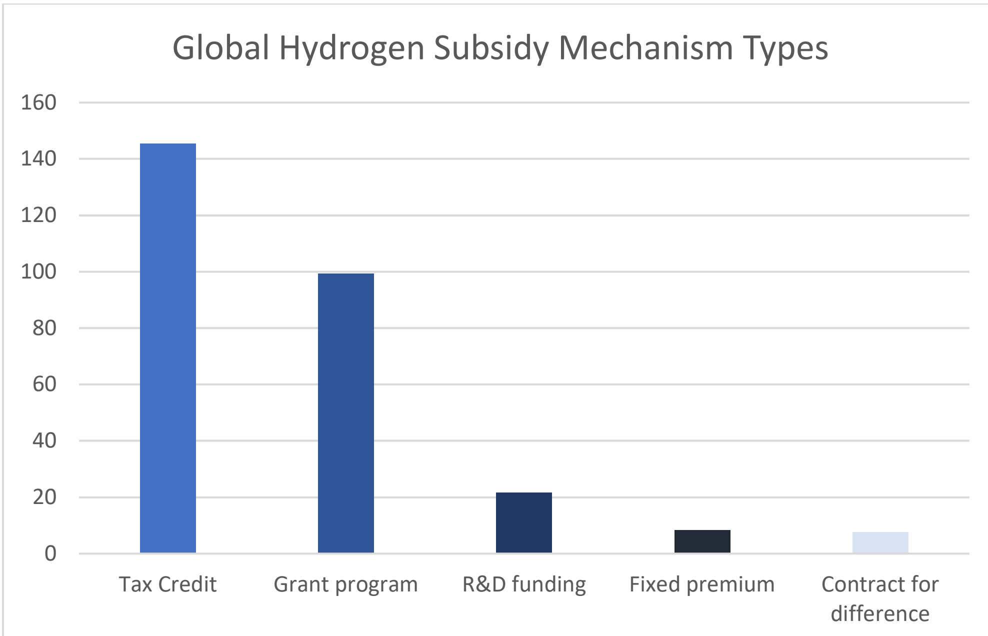


Figure 11 Global Hydrogen Subsidy Mechanism Types (As of August 2023)[56]

More information on the different policies and subsidies employed by countries around the world can be found in the Appendix.

Private investment in hydrogen projects

These programs and incentives have helped derisk some clean hydrogen technology and value chain activities and attract attention from several classes of private investors. Most notably, technologies such as electrolyzers have reached a level of maturity that allows their commercial-scale adoption.[57] Additionally, many industry players have been pursuing the build-out of infrastructure for the production, storage and transportation of hydrogen. For example, companies that have synergies with hydrogen such as utilities, independent power producers, developers, and oil & gas majors (e.g. Dominion, AES, Nextera, ExxonMobil), among others, have announced investments in hydrogen projects that span the value chain from production to distribution and delivery. There was a pipeline of projects for 174 million tons of H_2 annual production by 2050 (as of September 22, 2023).[58] More detail can be found in Figure 12 below.

hydrogen and carbon capture and storage estimated based on the announced hydrogen project pipeline as of August 14, 2023.

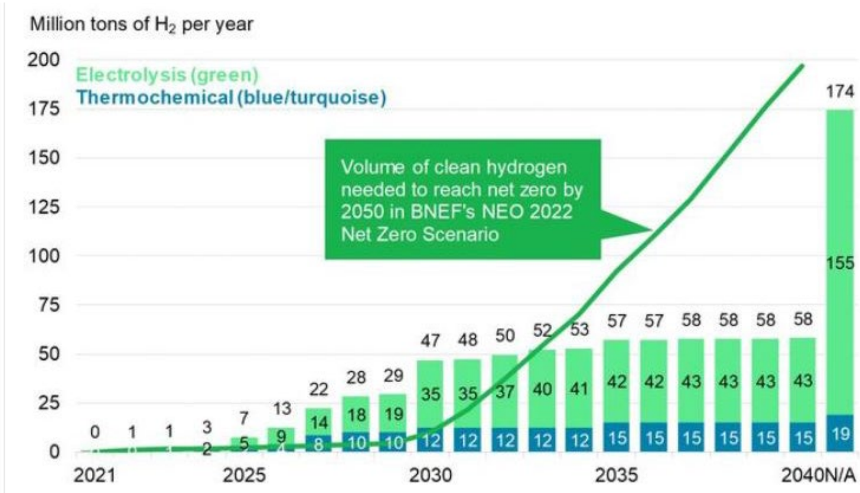


Figure 12 Cumulative clean hydrogen supply pipeline of proposed by developers as of September 22, 2023[59]

However, production capacity and infrastructure build-out projects are usually financed through project finance vehicles such as debt and use existing technologies. Therefore, they are outside the scope of this study and its intended target audience, innovation investors.

Innovation

Significant amounts of private capital have been flowing into hydrogen technology innovation as well.

For example, hydrogen was the second largest clean tech sector by total cumulative deal amount in 2022, according to a PitchBook report.[60] There were 148 Venture Capital (VC) deals for a total deal value of $3.2 billion.[61] Companies that received funding included Monolith, Sunfire, Electric Hydrogen, TES, Guofuhee, Universal Hydrogen, Amogee, FE Fuel, and Syzygy Plasmonics.[62]

When it comes to clean hydrogen innovation, making the production of clean hydrogen more efficient and cost effective has received by far the most attention from governments and investors alike. Electrolyzer investment has been significant and growing since 2018 (see Figure 13). As a result, there has been a proliferation of electrolyzer innovations over the past decade.

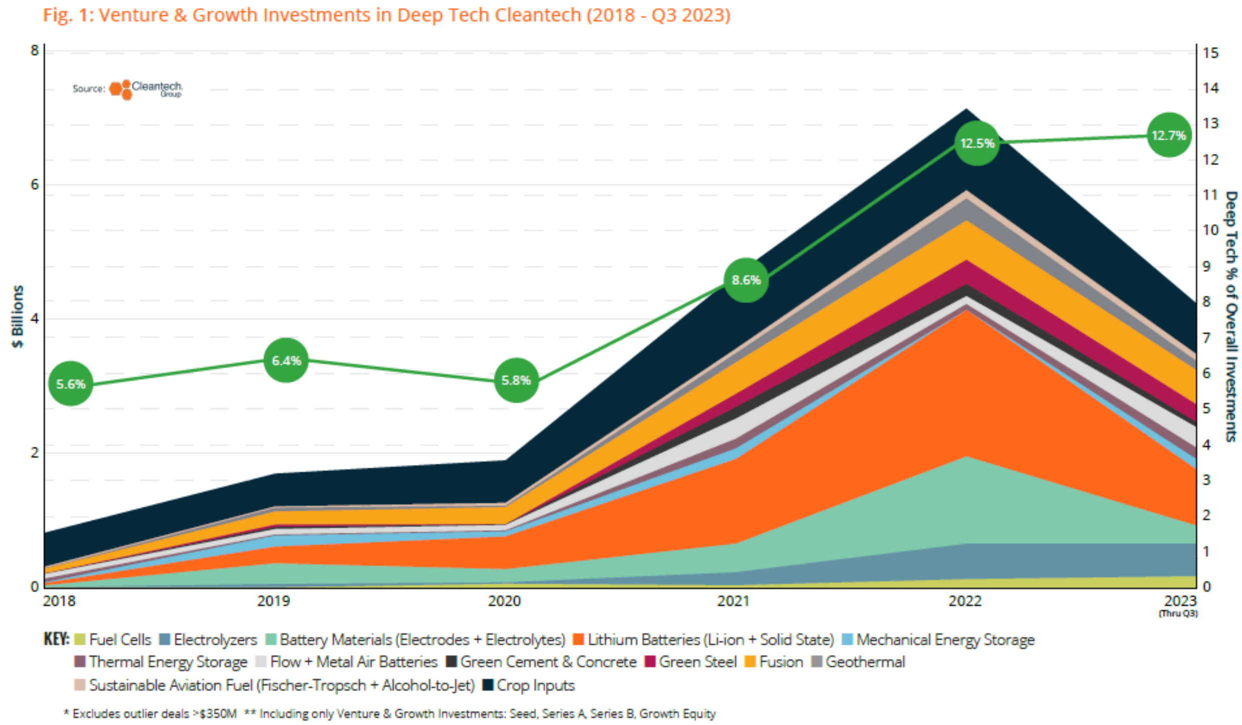


Figure 13 Venture and Growth Investments in Deep Tech (2018-Q3 2023)[63]

Additionally, there is also ongoing innovation work in all parts of the hydrogen value chain to enable a fully robust, safe, and cheap hydrogen economy at scale. This creates many opportunities for investors to get involved.

Projected growth

The global hydrogen market is expected to increase significantly in the coming years driven by decarbonization targets and political support spurring a surge in its use in new applications. According to the 2023 edition of IEA's Net Zero Emissions by 2050 Scenario (NZE Scenario), the global demand for hydrogen for new applications is expected to grow by 6% annually until the end of the decade.[64] This would entail reaching more than 150 Mt of hydrogen use by 2030, of which at least 40% will be for new applications,[65] and 500[*] million metric tons by 2050.[66]

This projected demand for hydrogen is illustrated in Figure 14 below.

[*] Other estimates go as high as 615 million metric tons. Source: International Renewable Energy Agency (IRENA). (2022). Global hydrogen trade to meet the 1.5°C climate goal: Part I - Trade outlook for 2050 and way forward. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/Jul/IRENA_Global_hydrogen_trade_part_1_2022_.pdf

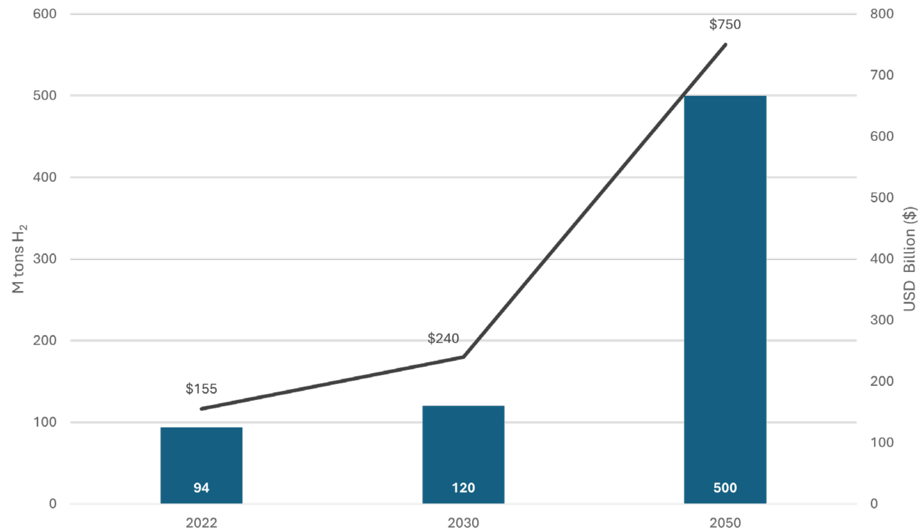


Figure 14 Projected Hydrogen Market Growth*

V. INVESTMENT OPPORTUNITIES IN CLEAN HYDROGEN INNOVATION

To capitalize on this enormous opportunity to bridge the gap between the current state of the hydrogen market and its projected 2030 and 2050 levels, investors can consider backing innovations along the entire clean hydrogen value chain. Each phase of the clean hydrogen value chain faces its own set of unique challenges and consequently, presents a variety of investment opportunities to tackle them (see Figure 15). This section examines the challenges and potential for innovation within each stage of the value chain.

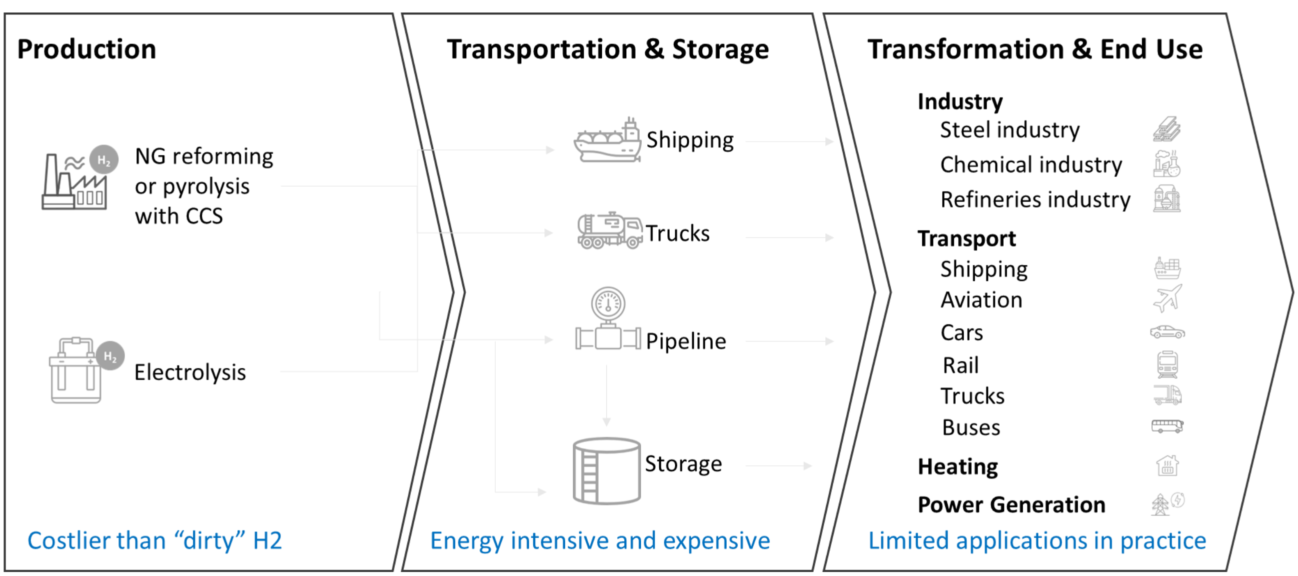


Figure 15 The clean hydrogen value chain

* The 2030 hydrogen market value of $240 billion assumes global hydrogen consumption slightly below the projected, at 120 Mt by 2030, split up into 2/3 grey hydrogen and 1/3 green with an average price of $3/kg. In 2050, that figure could reach $750 billion with 500 Mt green hydrogen production at $1.50/kg.

1. Production

Making the production of clean hydrogen cost competitive with traditional grey hydrogen was the first big hurdle to the commercial lift-off of clean hydrogen[67] that many entrepreneurs and investors alike flocked to solve. As a by-product and a commodity, the cost of grey hydrogen has traditionally been very low ($0.98-$2.93 per kilogram H_2),[68] while blue hydrogen costs $1.8-$4.7 per kilogram and green $4.5-$12 per kilogram (as of August 2023).[69] Both green and blue hydrogen have therefore been selling at a premium.

That is why, for a long time, the focus was entirely on bringing the levelized cost of hydrogen (LCOH) down by innovating around the two technologies for clean hydrogen production: electrolyzers and carbon capture and storage (CCS).

Electrolyzers

Electrolyzers are the main technology used to produce green and pink hydrogen.

Electrolyzers work by splitting the water molecule, which is comprised of two hydrogen atoms and one oxygen atom (H_2O), into its building blocks. This produces hydrogen and releases oxygen as a byproduct. There are three common types of electrolyzers:

- Alkaline water – longest history, cheaper catalysts, most commonly used;
- PEM (Proton exchange membrane) – distinguished by its ability to operate at high current densities, which makes it uniquely suitable for some applications. For example, when coupled with renewables, it can utilize any sudden spikes of energy input;
- Solid oxide – most recent tech, uses less electricity but is further from maturity.

Each electrolyzer type is most suitable for slightly different applications. More details on electrolyzer types are provided in the Appendix.

Alkaline electrolyzers have existed for ammonia production with hydropower since the 1920s.[70] While some companies continue working on electrolyzer improvements such as scale (capacity), different membrane materials, and anodes, among others, companies such as AirLiquide, Nel, and others have almost reached maturity.[71] Innovation investment opportunities in this space have therefore shifted from early-stage VC to late-stage VC, PE and industry players.[72]

Four devices and materials companies that produce green hydrogen (b.spkl, Evoloh, QD-Sol, Sungreen H2) and five alternative fuel companies (Dimensional Energy, Koko, Networks, Metafuels, Nium) were included in the October 2023 edition of the “Cleantech 50 to Watch” by Cleantech Group, making a significant percentage of the overall growth in cleantech for the year.[73]

Carbon Capture, Utilization and/or Storage (CCUS)

Carbon capture and storage/sequestration (CCS) or carbon capture, utilization and storage (CCUS) is required for low carbon blue hydrogen production. There is an opportunity to invest in innovations in efficient carbon capture technology development as a result. Innovations in this space are particularly attractive to oil and gas majors and traditional energy companies because it would allow them to capitalize on their retired oil and gas wells as storage for the captured CO_2, in addition to being able to continue producing hydrogen as a byproduct of natural gas. Notably, companies like Exxon Mobil are already developing this approach both for their own operations and as a service to heavy industry customers.[74] They have the advantage of the already existing extensive CO_2 pipeline network of over 1,500 miles and 15 onshore storage sites[75] [76] along the Gulf Coast including in Louisiana, Texas and Mississippi, originally designed to move CO_2 for enhanced oil recovery, and can now be utilized for carbon capture and storage in these largest U.S. markets for CO_2 emissions[77]. The Gulf Coast is made even more attractive for blue hydrogen production by the presence of more than 1,000 miles of dedicated hydrogen pipelines.[78]

Some prominent carbon capture, use and storage companies to watch (from Cleantech 50 to Watch October 2023)[79] include bluemethane, blusink, Mission Zero, Octavia Carbon, Arca and Vesta.

Hydrogen hubs

Another avenue for bringing down the cost of produced and delivered clean hydrogen is innovating on the business model by co-locating production facilities with cheap renewable energy generation sources. This concept of hydrogen hubs, with the support it has received from government funding, has boosted the pipeline for clean hydrogen production by 2040 to 174 million tons (see Figure 12).[80] These hub can boost the demand for technologies such as electrolyzer and carbon capture and storage, but do not directly attract innovation investors.

Overall, the production of hydrogen is the most mature segment within the clean hydrogen value chain with government backing and interest from large corporations.

2. Transportation & storage

While the cost-effective production of clean hydrogen may be reaching a tipping point, important challenges in the storage and transportation of hydrogen remain. What is more, there is less of a consensus among the scientific and business communities on the most promising route to solving them. As a result, there are a range of opportunities for investment in finding solutions to these challenges (see Figure 16 for the range of opportunities).

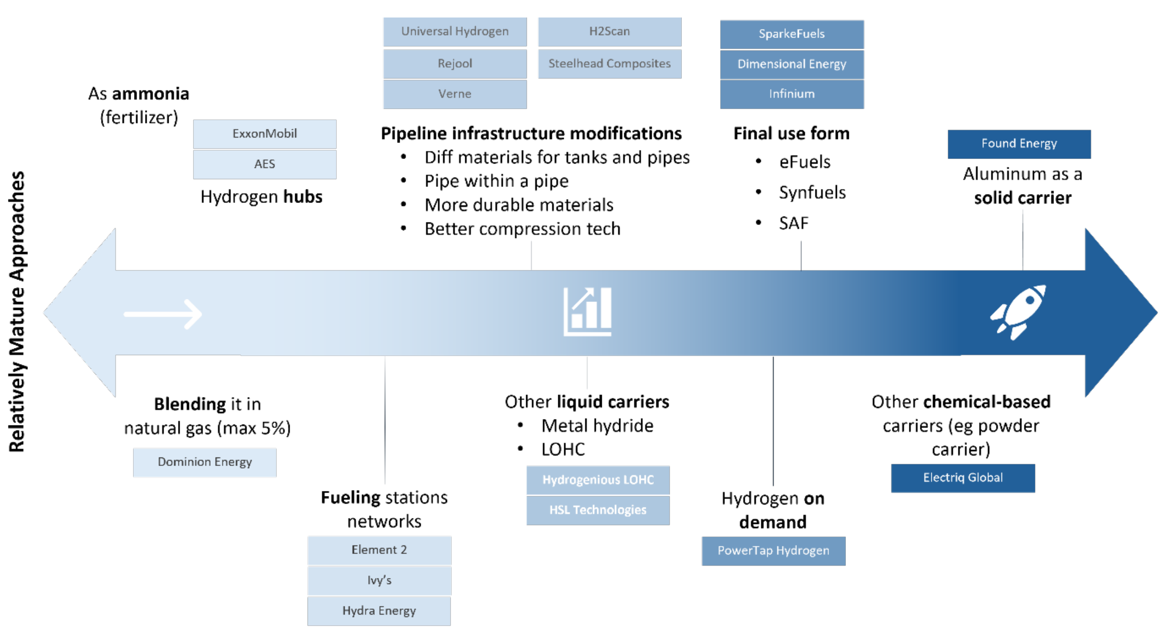


Figure 16 Different opportunities in the transportation and storage ecosystem

Challenges for the transportation and storage of hydrogen

Importantly, challenges related to the storage and transportation of hydrogen stem from its inherent properties as a chemical element.

First, because of hydrogen's low volumetric energy density at atmospheric pressures and temperatures, it requires a significant amount of physical space to store and transport in its gaseous form. That means that it requires a larger storage and transportation network to move an amount of energy comparable to that of the existing natural gas network. Alternatively, it could be compressed or liquified to be able to transport it by specialized trucks, storage tanks, pipelines and ships. However, this requires large amounts of energy to create high pressure and/or very low temperatures. Finally, it could be transformed chemically into other materials such as ammonia (which has its own challenges) or ethanol[81] before transportation.

Second, due to the small size of its molecule and how reactive it is with oxygen, leakages and safety are also major concerns in handling hydrogen. Special storage and transportation vessels or pipelines and sensors are needed to ensure safety at all times and avoid hydrogen embrittlement[*].

For all of these reasons, currently, it is very costly to store and transport hydrogen, and, therefore, it is only transported over short distances or produced on-site for use in niche applications. Transportation via pipelines and tankers, while theoretically possible, has rarely been put into practice. Innovations that provide a solution to these challenges are a great potential investment opportunity.

System perspective

From a system perspective, this energy-intensive and expensive solution to the transportation and storage of hydrogen is only possible because grey hydrogen is a cheap commodity.

That is why building infrastructure for the transportation and distribution of hydrogen, and developing new technologies that could potentially reduce the associated cost, are key levers for the wide-spread commercialization of clean hydrogen.

The Hydrogen Council and McKinsey estimate that a total of $430 billion in infrastructure investment are required to meet the IEA Net Zero scenario hydrogen participation. Based on the announced projects, there is a gap of $210 billion in infrastructure funding – the largest gap between required and committed investments within the clean hydrogen value chain.[82]

This is a tremendous opportunity for several different types of investors:

- Adapting existing natural gas transportation and storage infrastructure, building out hydrogen infrastructure, and collocating hydrogen production with renewable resources and off takers in the short to medium term – best suited for infrastructure and scale investors, often project investors like banks, O&G majors, and energy companies, and government funding;

[*] Making metal pipes and vessels brittle by infiltrating their pores thanks to the extremely small size of hydrogen molecules. Source: Dwivedi, S. (2018). Hydrogen embrittlement in different materials: A review. Retrieved from https://www.researchgate.net/profile/Sandeep-Dwivedi-4/publication/328526701_Hydrogen_embrittlement_in_different_materials_A_review/links/5c406482458515a4c72c36e3/Hydrogen-embrittlement-in-different-materials-A-review.pdf

- Technologies that will revolutionize the safer and cheaper handling of hydrogen in the medium-to-long term – most attractive to early-stage to late-stage VC investors, angel investors and impact investors.

3. Transformation & utilization

Despite the countless potential applications of clean hydrogen, as already mentioned, 99% of the existing market in 2022 globally and in the US remains from traditional users, namely oil refining and ammonia production (see Figure 6 and Figure 7). Enabling the demand side for clean hydrogen is a significant factor in aiding it to reach its full potential.

Opportunities in the transformation and utilization of clean hydrogen are as many as its practical and theoretical applications. For a more structured approach to exploring these opportunities, this research focused on the three avenues by which hydrogen can be utilized as a clean energy source*:

1. Direct combustion – as a substitute (or blended with) natural gas and other fossil fuels directly. Applications include industrial processes that require high heat such as cement, steel, aluminum, etc.

2. Fuel cells – to generate an electric current from the energy stored in hydrogen. This can function as energy storage, for power generation, or in fuel-cell vehicles (passenger and light- and heavy-duty trucks)

3. Power-to-X – hydrogen can be used as an input to produce e-fuels or synthetic fuels that can also act as drop-in fuels to replace fossil fuels such as gasoline, diesel, etc.

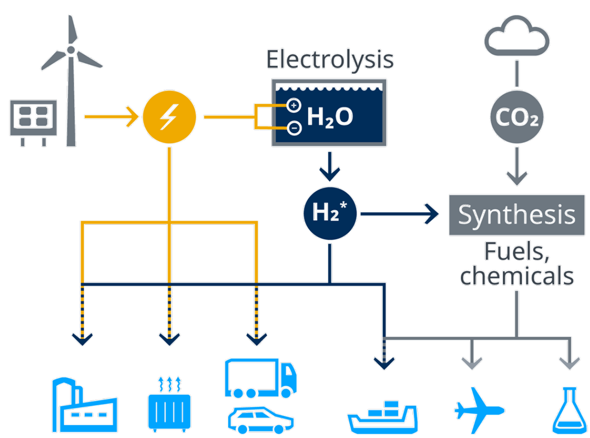


Figure 17 Power-to-X: Carbon neutral fuels[83]

As seen in Figure 18 below, the most promising applications of clean hydrogen, are in heavy industry where it can be used to generate high heat via combustion, and as a fuel or as a feedstock to other

* Additionally, hydrogen can be used as an input to the chemical and pharmaceutical industries for many non-energy applications. These are outside of the scope of this study.

sustainable fuels (Sustainable Aviation Fuel (SAF), green ammonia, etc.) for long-haul trucking, maritime shipping and aviation.

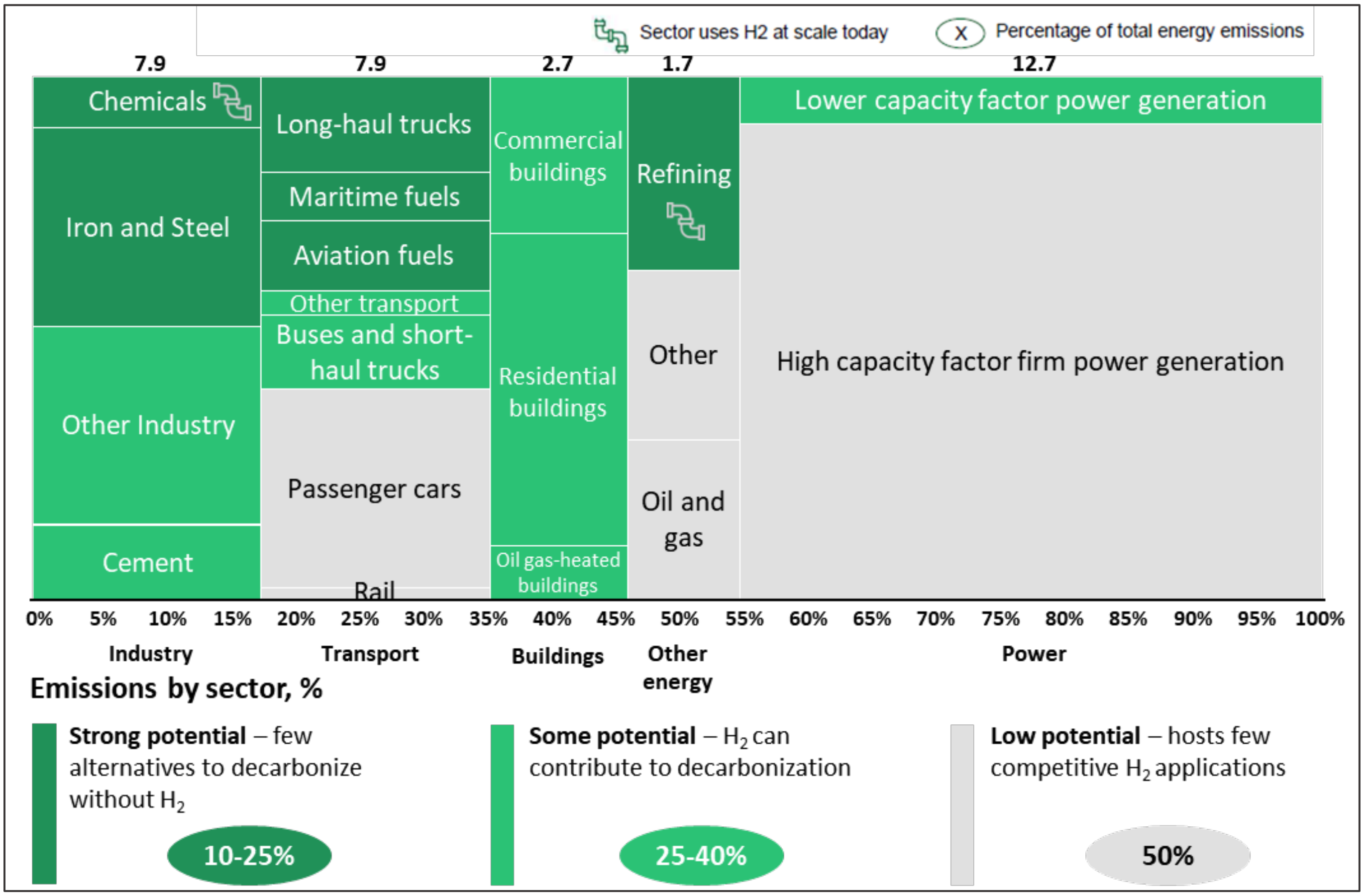


Figure 18 Potential hydrogen application and decarbonization potential.[84]

VI. FRAMEWORK FOR INVESTING IN CLEAN HYDROGEN INNOVATION

This section seeks to provide specific guidance to investors who are looking to finance clean hydrogen innovation based on their profile and priorities such as risk appetite, return expectations, and other investment objectives. The framework and process are designed to help investors develop their individual clean hydrogen investment theses according to their unique profile and needs.

The capital stack for clean hydrogen technology varies depending on the development stage of the technology (R&D, Pilot or FOAK, Scale-Up or NOAK, and Growth). Figure 19 below illustrates a hypothetical capital stack, which would not be atypical for technology innovation in a space such as clean hydrogen with all its complexities and challenges as discussed in previous sections.

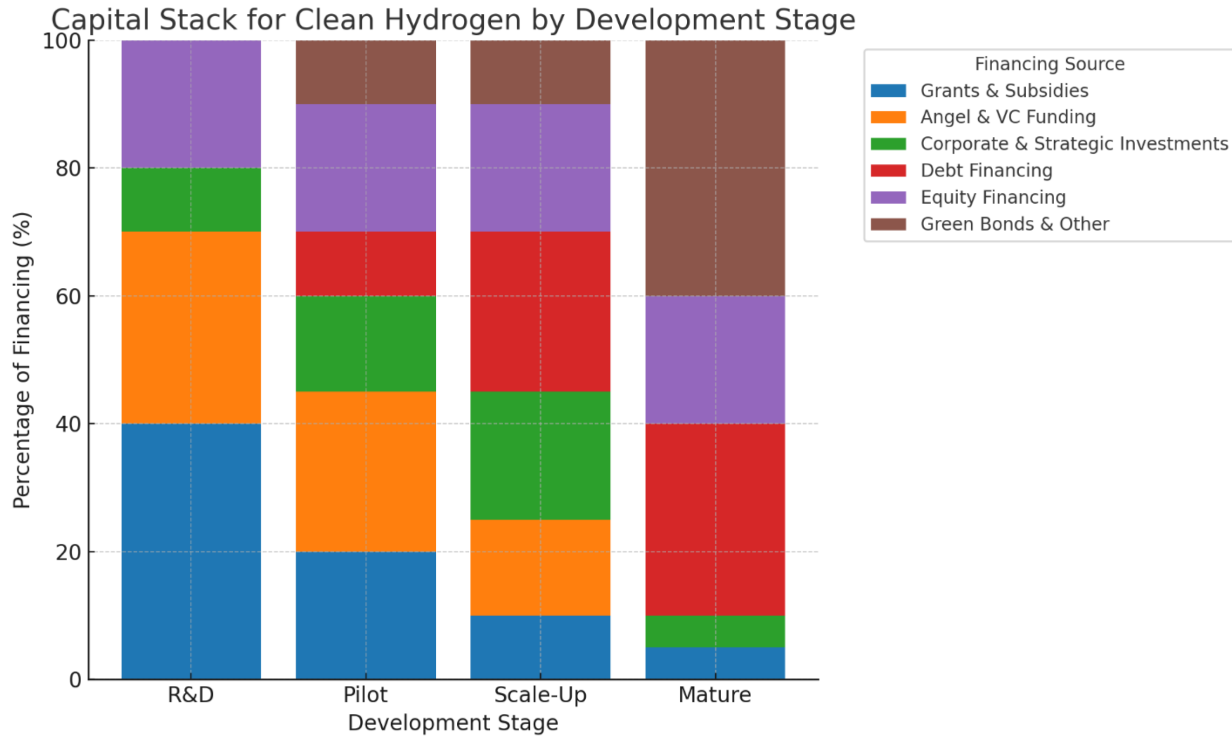


Figure 19 Hypothetical Capital Stack for Clean Hydrogen Innovation by Development Stage (Generated with the help of AI)

This framework is relevant for innovation investors across the capital stack up to FOAK, potentially excluding grants and subsidies providers.

1. Investor Types

Investors across the capital stack for clean hydrogen innovation and in particular, early-stage innovation, or pre commercial scale-up, can benefit from this framework. This development phase was chosen as the focus of this study because it is the most crucial and unique to climate tech. Many of the technologies addressing challenges in the clean hydrogen value chain can be considered “tough tech”, a term popularized by The Engine[85], a venture capital firm founded by MIT in 2016. It refers to technologies that address significant global challenges, often requiring long-term development and substantial capital, involving advanced scientific and engineering innovations. The most challenging development stage for those is in-between testing a lab-scale pilot and installing a first-of-a-kind (FOAK) commercial scale pilot before fully derisking the technology at scale.

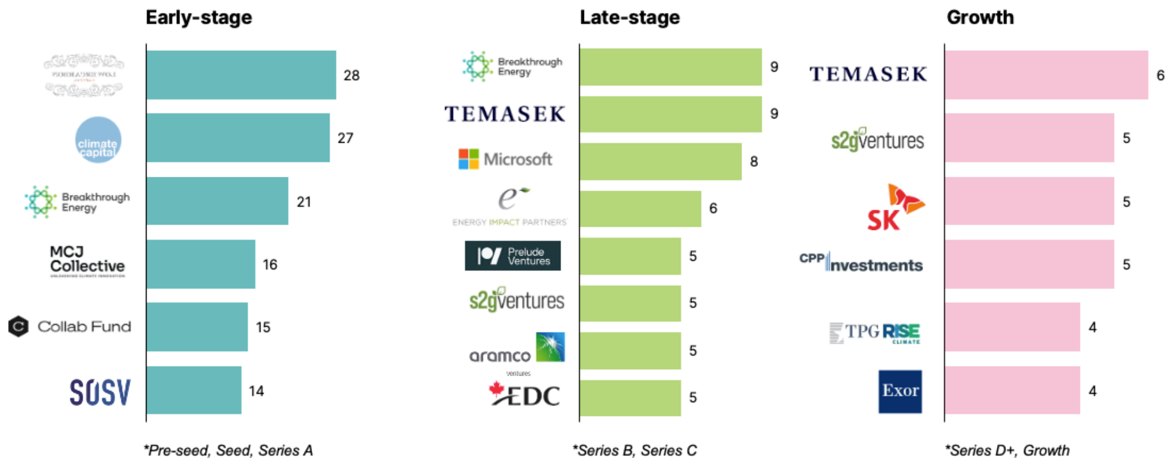


Figure 20 Distribution of some climate tech investors' participation across financing rounds in H1 2023[86]

The four main categories of investors who would find this framework useful include: catalytic capital/impact VC funds, traditional early and late-stage VC funds, strategic corporate investors, and, to a lesser extent, financial institutions. The framework reflects the different interests and approaches that these investors could have. Based on 25 personal semi-structured interviews with representatives from each group and a literature review, below are summaries of each group's interests and how they might align with innovation investment stages in climate tech and clean hydrogen technologies.

a. Catalytic capital/impact angel investors, VC funds and PE/buyout firms

These investors (e.g. Breakthrough Energy Ventures, Autodesk Foundation) often prioritize investment opportunities in new technologies based on their potential to abate/avoid emissions in hard to abate sectors where it truly counts (see Figure 18). Their main objective is to achieve a very high positive impact on climate commitments, usually are open to a longer time horizon, and projected returns are a secondary consideration. In climate tech, these investors often back companies to achieve milestones such as initial lab tests and first-of-a-kind (FOAK) commercial-scale facility or project.

PE or buyout firms provide private equity capital, which usually comes in during growth financing rounds. However, because of tough tech's heavy capital requirements and longer development cycles, which include the FOAK to NOAK phase or the so-called "valley of death"[87], there could be space for more impact-focused PE firms to come in pre growth. An example is Core Sustainability Capital, Danish firm founded in 2022. It seeks to make impact investments in renewable energy and other climate technology sectors.[88]

These investors would want to focus on disruptive technologies for clean hydrogen that have the potential to accomplish a paradigm shift in hard-to-abate industries such as steel, cement, and aviation.

Case Study: H2 Green Steel
H2 Green Steel is a Swedish hydrogen steelmaker working toward building the world's first large-scale green steel plant (use of hydrogen). Their capital raised since 2021 includes both debt and equity for close to $11 billion across 35 investors (as of January 22, 2024). Investors span the whole gamut of investor types: impact and traditional venture capital, PE, government, angel, corporate VC funds and strategic investors, asset managers, sovereign wealth funds, infrastructure fund, and a lender. For example, their most recent round was co-led by Altor, GIC, Hy24, and Just Climate.

Figure 21 H2 Green Steel Case Study[89]

b. Traditional VCs

More traditional VCs normally look for technologies that are on the brink of commercial-scale deployment and can be expected to make returns within 10 years (usually through an exit such as an Initial Public Offering (IPO) or an acquisition).[90] Within the clean hydrogen innovation space, opportunities that fit this profile support improvements in the cost competitiveness of electrolyzer technology and improvements to existing methods for the transportation and use of hydrogen such as sensors, better storage tank materials, and software for monitoring and tracking. These technologies have been developing over the past decade and are about to reach a tipping point for commercial-scale adoption with growing government support.

Case Study: TDK Ventures
TDK Ventures, the venture arm of industrials company TDK, invested in Verdagy in 2022 for their "scalable, low-cost approach to hydrogen electrolysis." Verdagy is a developer of electrolyzer technology that can reach 200 MW scale with patents pending on improvements of various electrolyzer components and aspects. As of April 2024, Verdagy already has secured a contract for the supply of electrolyzers to Doral Renewables to be used by the developer in commercial-scale projects through 2030. This investment falls within the Production phase of the hydrogen value chain as discussed in the Investment opportunities in clean hydrogen innovation section of this report. Despite TDK Ventures participating in a Series A funding round, the technology was already close enough to maturity to be deployed commercially only a couple of years later.

Figure 22 TDK Ventures Case Study[91,92, 93]

c. Strategic corporate investors

This category of investors encompasses companies whose business models could have synergies with hydrogen, such as a distributor, OEM, off-taker, or end user, for example. By investing in clean hydrogen technology innovation, these investors typically aim to ensure access to it once it's been sufficiently derisked. Strategic corporate investors could be energy companies in different parts of the energy ecosystem, such as developers, owner operators, or traditional vertically integrated utilities (e.g. AES, NextEra, and Dominion Energy), oil & gas majors (e.g. Shell, ExxonMobil), automotive and aerospace manufacturers, airlines, cement, steel, and aluminum producers, and others.

For example, the venture arm of an aviation company would want to bet on technologies or infrastructure that would enable cheap and accessible hydrogen-based sustainable aviation fuel such as by Air Company and Universal Hydrogen.

Case Study: ExxonMobil and blue hydrogen production and distribution in Texas
Oil and gas major ExxonMobil can sell its natural gas to blue hydrogen production facilities and, at the same time, use existing CO_2 pipeline infrastructure and retired oil or natural gas wells to transport and store CO_2 captured from the same facilities. That is why the proposed Hydrogen Hub in Texas (HyVelocity Hub) relies primarily on blue hydrogen generation (80%) and only 20% green hydrogen.

Figure 23 Case Study ExxonMobil and blue hydrogen production and distribution in Texas[94]

Some of these investments could potentially have a limited climate impact if innovations target only existing non-decarbonized users of hydrogen (oil refineries and ammonia producers) and prefer low-carbon (but not carbon-free) options for their compatibility with existing infrastructure. Nonetheless, projects that are built with these types of technologies, may still be eligible for government incentives in the US, which are based on the level of CO_2/kg of hydrogen produced.[95]

Most corporate investors, however, would fall outside of the innovation funding realm that is the central focus of this study and invest instead in large-scale projects with proven technologies from companies like Nel Hydrogen, Plug Power, and BLOOM. For that reason, many of the short-listed Hydrogen Hub proposals slated to receive DOE funding are an attractive opportunity for this type of investor.[96]

d. Financial Institutions

Financial institutions could include lenders and debt providers, asset managers, institutional investors such as pension funds, sovereign wealth funds, and others. These organizations will typically provide loans or other debt financing instruments to specific projects that can show evidence of future cash flows. For this type of investor, mature technology with commercial scale and an experienced project developer and operator in charge are key. That is why they represent a very small share of the clean hydrogen innovation capital stack but can participate in it albeit in rarer instances.

While not the focus of this study, for a quick comparison's sake, these are the important metrics for investors in hydrogen projects identified via an analysis of large-scale green hydrogen projects that have successfully secured financial commitments conducted by Liz Mullen[97]:

- Levelized Cost of Hydrogen (LCOH) – includes electrolyzer CAPEX, renewable electricity OPEX, utilization rate, and financial considerations such as the discount rate and debt to equity ratio of the project[98]
- Strong public sector support – national hydrogen strategies and market incentives (low-cost loans, tax credits, or grant programs)[99]
- Access to renewable energy resources, geologic storage, and access to water and raw materials[100]
- Guaranteed off-taker[101]
- Experienced developer[102]

Government grants and infrastructure investors are not included for various reasons.

2. Five-step process

Developed using the information collected throughout this study, this tool can help investors develop their investment theses for clean hydrogen innovation. The five-step process to using this framework is summarized in Figure 24.

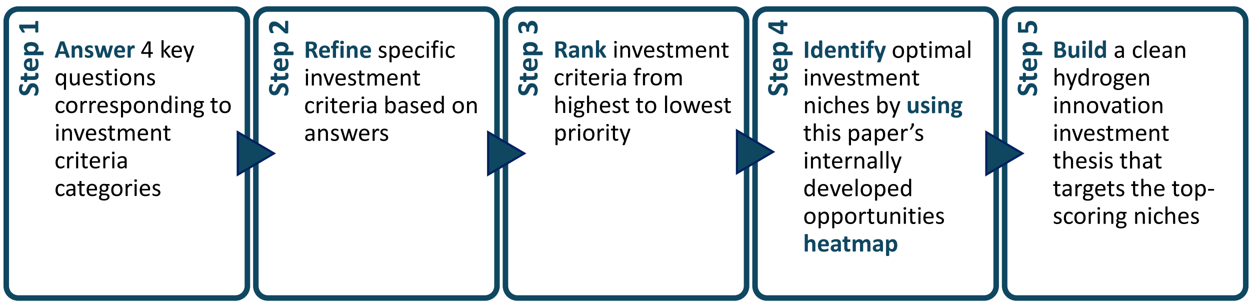


Figure 24 Process for utilizing the framework to build an investment thesis for clean hydrogen innovation

The first and second steps require investors to answer four key questions and refine the underlying specific investment criteria (summarized in Table 1) to ascertain their strategic investment approach. Category question number 1 pertains to the desired attributes of a technology in which to invest. Considerations include the technological maturity and its capital intensity —essentially, the extent of financial resources required for its development. For instance, software solutions generally demand minimal capital investment, while the development of a novel power generation technology such as a fusion nuclear reactor entails a significantly higher financial commitment. Subsequently, the investor must assess their investment profile in relation to their desired clean hydrogen innovation bet (question 2). This includes the investment horizon or the timeframe within which a return is anticipated; the expected magnitude of the return; and the check size that the investor is prepared to allocate to each investment venture. Moreover, the investor ought to deliberate on the desired degree of climate impact of their investments, ranging from a substantial to a moderate contribution towards decarbonization. The final consideration in this step involves identifying specific challenges (if any) within the hydrogen sector that the investor is particularly keen to address. This question is optional and could be informed by insights from the three previous ones.

The questions and criteria are summarized in Table 1 below:

	Category	Criteria
1	What tech characteristics are they looking for in an investment?	• Maturity • Capital requirements
2	What is their overall investment philosophy and profile?	• Investment horizon • Expected returns • Check size
3	What level of climate impact are they looking for?	• Decarbonization potential (CO2)
4	What hydrogen-related challenge are they trying to solve?	• Lowering the cost of production • Scaling production • Enabling transportation/storage • Enabling utilization

Table 1 Four category questions that investors need to answer in step 1 of the process

Once the investor has defined their criteria list, they can proceed to organize the list in order of priority from highest to lowest. This step ensures that if two or more criteria point to conflicting investment niches, they can easily be resolved.

These criteria across four dimensions translate directly to the heatmap of clean hydrogen innovation opportunities developed as part of this project (Figure 25). The heatmap scores prospects across the hydrogen value chain on their alignment with these criteria. Step four entails utilizing this heatmap to identify the specific hydrogen niches that best match the investor's priority criteria.

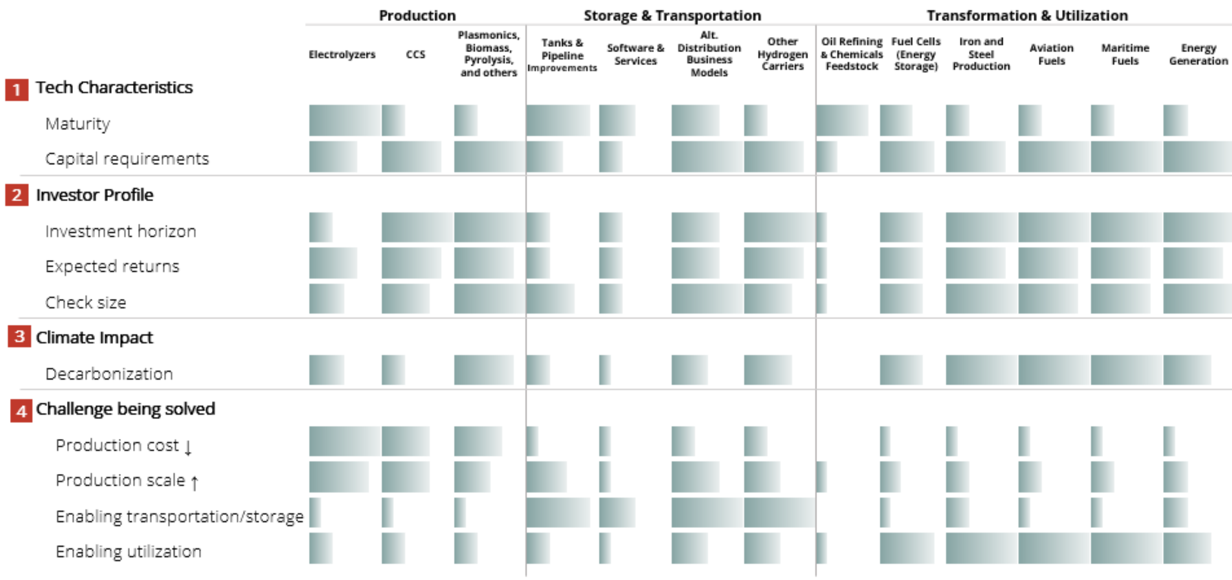


Figure 25 Opportunity heatmap – investment thesis building tool

Finally, based on these results, the investor can build their investment thesis for clean hydrogen innovation that targets the identified niches. The complete five-step process for using the framework is illustrated in Figure 24 and the heatmap – in Figure 25.

3. Case Study

To help illustrate the practical application of this framework, we consider the following case study.

Case Study: Corporate Impact Climate Tech VC Fund
A philanthropic corporate climate tech VC fund interested in deploying catalytic capital in clean hydrogen innovation was the client at the start of this project that was able to use this framework to build their investment thesis in this space.

First, based on their primary objective as a philanthropic fund, they recognized that climate impact takes precedence. Using the hydrogen innovation's capacity for decarbonization as the principal criterion of significance, the heatmap revealed that the most substantial potential lies in the transformation and utilization of hydrogen, alongside certain storage and transportation innovations, and less so in nascent production technologies. In second place, in terms of maturity, their investment interest gravitates towards early-stage technologies, which dovetails with their overarching impact thesis and therefore points to similar opportunities when using the heatmap. These results crystalized in a pronounced interest in solving certain challenges in the clean hydrogen value chain such as enabling its transportation and storage, and utilization.

This evaluation allowed for a concise articulation of the fund's investment thesis. Given the significant existing investment in production, and the maturity that such technologies have already achieved, it would be strategic for them to pivot away from investing in production technologies. When considering transportation and storage, numerous innovations appear to offer only incremental enhancements over existing technologies, which do not align with the fund's vision. Their focus should, therefore, be directed towards pioneering innovations that have the potential to substantially impact decarbonization efforts and scalability. Furthermore, in the sphere of hydrogen applications, emphasis should be placed on transformative uses beyond ammonia production and oil refining. In summary, this fund should target groundbreaking innovations in hydrogen transportation and storage, as well as technologies that enable clean hydrogen's application across various industries.

Figure 26 Case Study on the use of the framework for investing in clean hydrogen

This case study serves as an example of how a company might employ this analytical framework. However, in practice, any fund or investor can adapt it to their unique priorities. By answering the initial set of strategic questions, they can formulate a tailored investment thesis.

VI. CONCLUSION

Driven by the key role it is expected to play in global decarbonization and government support around the world, clean hydrogen presents many opportunities for a variety of investors. Clean hydrogen innovation investors across the capital stack can utilize the opportunity heatmap and investment thesis building process in this paper to identify specific value chain phases or technologies that they are best suited to support. With this framework at their disposal, investors can both capitalize on the clean hydrogen technology innovation opportunities and at the same time contribute to building and scaling the hydrogen economy of the future to reach our societal net zero target of 2050.

VII. APPENDIX

Hydrogen Glossary

Term	Definition
Energy content by weight	highest energy content of any common fuel by weight (about three times more than gasoline).
Energy density	Energy content by volume.
Energy carrier	Energy carriers are different from energy sources. They transport energy in a usable form from one place to another but need to be produced (or separated). Can be used as a source of energy or fuel.
Flexible (energy carrier)	An energy carrier that can be used in a variety of ways for many different applications. Synonym: versatile.
Drop-in fuel	A substitute to traditional fossil fuels that does not require infrastructure modifications.
Synthetic fuel/E-fuel	Identical to fossil fuels but chemically manufactured from inputs such as methanol, hydrogen, etc.
Power-to-X	Converting power (electricity) to an energy carrier, for example Power-to-Liquid is using electric power to produce a liquid fuel.

Table 2 Hydrogen Glossary

Colors of hydrogen

Production Technology	Color	Definition	Carbon Intensity
Methane steam reforming	Grey	Produced through methane steam reforming without carbon capture or storage (CCS). Sometimes coal gasification is also called grey, but in this report, we are using "brown" to refer to coal gasification.	High
	Blue	Same as grey hydrogen but the carbon dioxide is captured and stored through carbon capture and storage (CCS) technology.	Moderate
Electrolysis	Green	Produced through splitting water with an electrolyzer technology while using renewable energy (solar, wind, hydro) to power the electrolyzer	Low

	Pink	Produced through splitting water with an electrolyzer technology while using nuclear energy to power the electrolyzer	Low
	Yellow	A subtype of green hydrogen marked by the use of solar power exclusively for the electrolyzer's energy needs	Low
Coal Gasification	Black[103]	Coal gasification which uses bituminous coal as the input and inherently emits CO2.	High
	Brown[104]	Coal gasification which uses lignite as the input and inherently emits CO2.	High
Other	White (sometimes Gold)	Naturally occurring hydrogen extracted from the Earth's crust. Historically considered limited. Recently discovered deposits of potentially "billions to quadrillions of metric tons of hydrogen trapped in rocks underground." By some estimates, this could meet humanity's needs for 200 years.[105]	Low
	Turquoise[106, 107]	Made using a process called methane pyrolysis to produce hydrogen and solid carbon. This is a new production method, which hasn't been proven at scale yet.	Low

Table 3 Selected commonly used color-code typology for hydrogen production

US hydrogen subsidies compared to the rest of the world in 2023

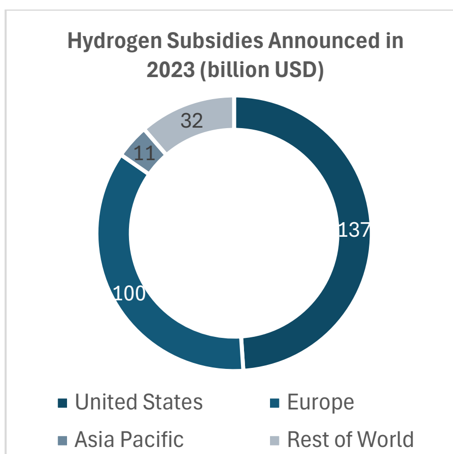


Figure 27 *Hydrogen subsidies US vs world as of August 2023*[108]

Country-specific government policies and subsidies in support of clean hydrogen

US

The US has been one of the starkest proponents of a hydrogen economy starting with a hydrogen strategy, followed by a series of funding and incentive schemes:

1. Hydrogen Shot

The "Hydrogen Shot" is an initiative by the U.S. Department of Energy (DOE) as part of its Energy Earthshots program, aimed at accelerating the development of abundant, affordable, and reliable clean energy solutions. Launched on June 7, 2021, the Hydrogen Shot specifically targets the reduction of the cost of clean hydrogen by 80% to $1 per kilogram within a decade, an ambitious goal referred to as "1 1 1" — $1 for 1 kilogram in 1 decade.[109] The DOE's approach involves engaging stakeholders, supporting relevant research and development, and providing incentives that promote regional diversity in clean hydrogen applications.

This initiative also lays a foundation for clean hydrogen deployment within the American Jobs Plan[110], supporting demonstration projects and potentially unlocking new markets for hydrogen in various industries, such as steel manufacturing and energy storage.

2. IRA Production Tax Credit 45V

In 2022, Congress passed the landmark Inflation Reduction Act (IRA). It offered, among other things, a hydrogen incentive provision in the form of a production tax credit (PTC), which created a 10-year incentive for clean hydrogen of up to $3.00/kilogram called the "45V production tax credit". These credits are estimated to amount to $137 billion disbursed over the next 10 years[111], making it "the world's most lucrative incentive for making clean hydrogen."[112] A guidance proposal on what projects would qualify for the $3/kg PTC was issued in December 2023[113] and is still under consideration.

3. Hydrogen Hubs

Government funding is also available for the development of large-scale clean hydrogen manufacturing and consumption clusters, the so-called *Hydrogen Hubs*. Negotiations are ongoing with the seven proposed hubs that were short-listed by the DOE. The finalist hubs are poised to receive $7 billion in Federal Investment[114] and span the entirety of the United States, varying in production method and end-use hydrogen applications.[115] (A full list of the seven finalist hydrogen hub proposals can be found in the Appendix)

EU

The next largest government incentive program for hydrogen deployment is in the EU, where the committed funds are only about 27% less than in the US.[116] The EU and country governments are using a variety of mechanisms from grants to loans and venture capital and R&D funds.

Institution	Mechanism	Amount	Detail
EU Hydrogen Bank	Fixed premium per kilogram of hydrogen produced	€3 billion	EU Hydrogen Bank €3 billion. EU trade bank for funding hydrogen production through "pilot auctions for renewable hydrogen production"

	for a maximum of 10 years of operation		https://www.euinnovationfund.eu/ . It offers a fixed premium per kilogram of hydrogen produced for a maximum of 10 years of operation. The bank has €800 million available for the first auction slated to launch in the autumn of 2023.[117]
Germany		€3.6 billion	H2Global plan €3.6 billion (disbursed over 10 years)
	Contract for difference	€50 billion	15-year-contract for-difference plan for industrial decarbonization (WIP)
EU		€100 billion	Earmarked
UK		£900 million ($1.1 billion)	Earmarked

Table 4 EU hydrogen funding mechanisms

Japan

Japan is planning to spend ¥7 trillion ($47 billion).[118]

Others

China has committed $10 billion.[119]

India has announced $2 billion.[120]

Short-Listed Hydrogen Hubs

- **Appalachian Hydrogen Hub** (Appalachian Regional Clean Hydrogen Hub (ARCH2); West Virginia, Ohio, Pennsylvania)
- **California Hydrogen Hub** (Alliance for Renewable Clean Hydrogen Energy Systems (ARCHES); California)
- **Gulf Coast Hydrogen Hub** (HyVelocity H2Hub; Texas)
- **Heartland Hydrogen Hub** (Minnesota, North Dakota, South Dakota)
- **Mid-Atlantic Hydrogen Hub** (Mid-Atlantic Clean Hydrogen Hub (MACH2); Pennsylvania, Delaware, New Jersey)
- **Midwest Hydrogen Hub** (Midwest Alliance for Clean Hydrogen (MachH2); Illinois, Indiana, Michigan)
- **Pacific Northwest Hydrogen Hub** (PNW H2; Washington, Oregon, Montana)

Electrolyzer technologies comparison

Type	Commercial Status	Considerations

Alkaline	Mature	• Slower dynamic response; less suited for variable renewable energy (VRE) support.
Proton exchange membrane (PEM)	Commercial, fast growth	• Platinum and iridium are required. Current global iridium production could support annual deployment of up to 3-7.5 GW a year. • Faster dynamic response; well suited to VRE and voltage regulation.
Solid oxide electrolyzer cells (SOEC)	Demonstration plants	• No cycling (ramp up or down); well suited for constant base load hydrogen production.
Anion exchange membrane (AEM)	Limited deployment	• Does not use any precious metals. • Membrane is less expensive than that used for PEM.

Table 5 Main electrolyzer technology comparison[121]

Electrolyzer technologies maturity level

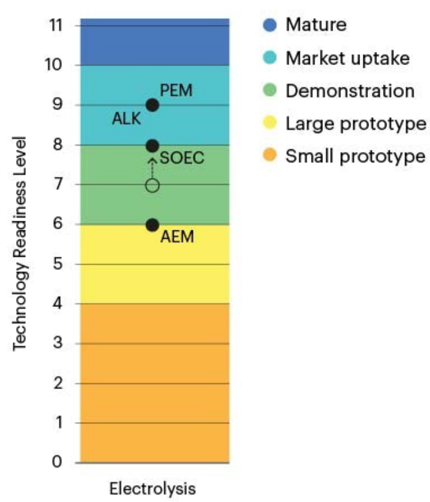
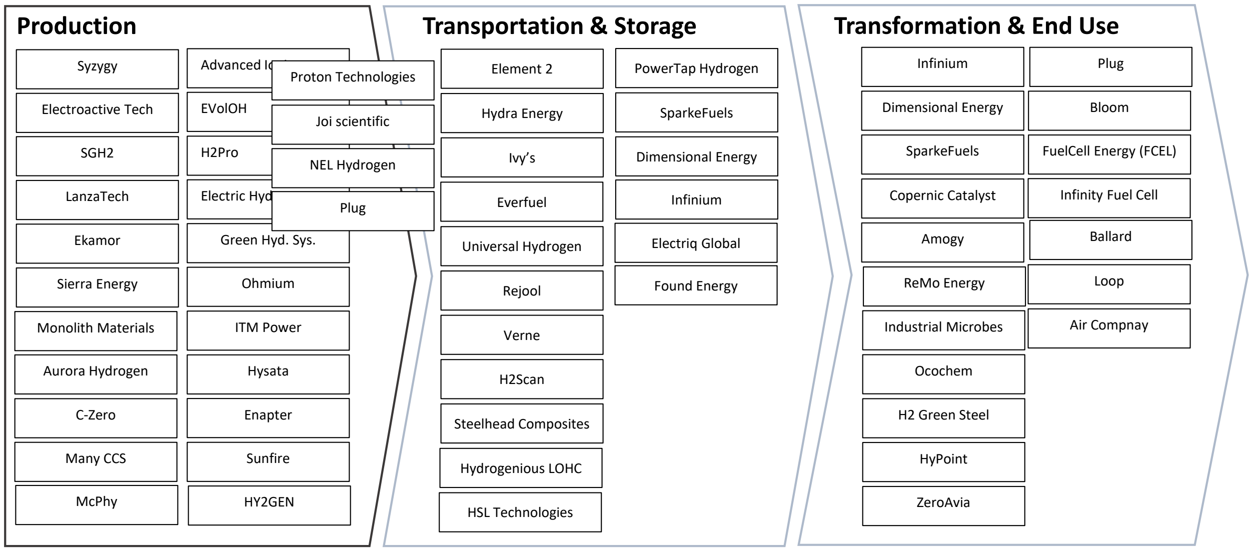


Figure 28 Electrolyzer technologies maturity level[122]

Companies innovating in clean hydrogen technology along the value chain



VIII. REFERENCES

[1] International Energy Agency. (2023). Hydrogen [Web page]. https://www.iea.org/energy-system/low-emission-fuels/hydrogen

[2] International Energy Agency. (2021). Executive summary. In Global hydrogen review 2021. Retrieved from https://www.iea.org/reports/global-hydrogen-review-2021/executive-summary

[3] International Renewable Energy Agency. (2022, January 1). Geopolitics of the energy transformation: Hydrogen. Retrieved February 16, 2024, from https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/Jan/IRENA_Geopolitics_Hydrogen_2022.pdf

[4] IEA (2022), World Energy Outlook 2022, IEA, Paris https://www.iea.org/reports/world-energy-outlook-2022 , Licence: CC BY 4.0 (report); CC BY NC SA 4.0 (Annex A)

[5] IRENA (2023), World Energy Transitions Outlook 2023: 1.5°C Pathway, Volume 1, International Renewable Energy Agency, Abu Dhabi.

[6] International Renewable Energy Agency. (2022, January 1). Geopolitics of the energy transformation: Hydrogen. Retrieved February 16, 2024, from https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/Jan/IRENA_Geopolitics_Hydrogen_2022.pdf

[7] International Energy Agency. (2023). Executive summary. In Global hydrogen review 2023. Retrieved from https://www.iea.org/reports/global-hydrogen-review-2023/executive-summary

[8] Hydrogen Council & McKinsey & Company. (2023, December). Hydrogen Insights December 2023 Update. Retrieved from https://hydrogencouncil.com/wp-content/uploads/2023/12/Hydrogen-Insights-Dec-2023-Update.pdf

[9] Ibid.

[10] International Energy Agency. (2023). Hydrogen [Web page]. https://www.iea.org/energy-system/low-emission-fuels

[11] Hydrogen Council & McKinsey & Company. (2021, November). Hydrogen for Net-Zero: A critical cost-competitive energy vector. https://hydrogencouncil.com/en/hydrogen-for-net-zero/

[12] Ibid.

[13] Ritchie, H., & Roser, M. (2023). CO2 and greenhouse gas emissions. Our World in Data. Retrieved from https://ourworldindata.org/co2-emissions

[14] Hydrogen is the simplest in terms of atomic complexity, consisting of one proton and one electron. Jolly, William Lee. "hydrogen". Encyclopedia Britannica, 22 Apr. 2022, https://www.britannica.com/science/hydrogen

[15] U.S. Department of Energy. (2022, September 1). DOE National Clean Hydrogen Roadmap (Draft). Retrieved February 16, 2024, from https://hydrogen.energy.gov/pdfs/clean-hydrogen-strategy-roadmap.pdf

[16] Jolly, William Lee, supra note 7

[17] Abrajano et al., High-Molecular-Weight Petrogenic and Pyrogenic Hydrocarbons in Aquatic Environments, Treatise on Geochemistry, Vol. 9 (2007), https://doi.org/10.1016/B0-08-043751-6/09055-1

[18] Molloy, P. (2019, October 2). Run on less with hydrogen fuel cells. Rocky Mountain Institute. Retrieved from https://rmi.org/run-on-less-with-hydrogen-fuel-cells/

[19] U.S. Department of Energy. (2024, February 16). Hydrogen Storage. Office of Energy Efficiency & Renewable Energy. https://www.energy.gov/eere/fuelcells/hydrogen-storage

[20] Thomas, C. E. (n.d.). Fuel cell electric vehicles (FCEVs) vs. battery electric vehicles (BEVs). U.S. Department of Energy. Retrieved from https://www.energy.gov/sites/default/files/2014/03/f9/thomas_fcev_vs_battery_evs.pdf

[21] Mazloomi, K., & Gomes, C. (2012). Hydrogen as an energy carrier: Prospects and challenges. Renewable and Sustainable Energy Reviews, 16(5), 3024-3033. https://doi.org/10.1016/j.rser.2012.02.028

[22] Ibid.

[23] Gates, B. (2022). To cut emissions, use this Swiss army knife. Breakthrough Energy. Retrieved from https://breakthroughenergy.org/news/to-cut-emissions-use-this-swiss-army-knife/

[24] Thomas, C. E. (n.d.). Fuel cell electric vehicles (FCEVs) vs. battery electric vehicles (BEVs). U.S. Department of Energy. Retrieved from https://www.energy.gov/sites/default/files/2014/03/f9/thomas_fcev_vs_battery_evs.pdf

[25] International Renewable Energy Agency. (2022, January 1). Geopolitics of the energy transformation: Hydrogen. Retrieved February 16, 2024, from https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/Jan/IRENA_Geopolitics_Hydrogen_2022.pdf
[26] Ibid.
[27] Roberts, D. (2018, February 16). HyTech Power may have solved hydrogen, one of the hardest problems in clean energy. Vox. Retrieved from https://www.vox.com/energy-and-environment/2018/2/16/16926950/hydrogen-fuel-technology-economy-hytech-storage.
[28] U.S. Department of Energy. (2023, October 26). Hydrogen Fuel Basics. https://www.energy.gov/eere/fuelcells/hydrogen-fuel-basics
[29] The Gigaton [Substack pseudonym]. (2023, October 26). The Bottom Line. https://thegigaton.substack.com/i/44838809/the-bottom-line
[30] National Renewable Energy Laboratory. (n.d.). Hydrogen research. Retrieved from https://www.nrel.gov/research/eds-hydrogen.html
[31] Meidl, R. A. (2023). U.S. can lead hydrogen economy if treasury encourages lifecycle thinking and diverse. Baker Institute for Public Policy. Retrieved from https://www.bakerinstitute.org/research/us-can-lead-hydrogen-economy-if-treasury-encourages-lifecycle-thinking-and-diverse
[32] International Energy Agency. (2021). Executive summary. In Global hydrogen review 2021. Retrieved from https://www.iea.org/reports/global-hydrogen-review-2021/executive-summary
[33] Douglas, C., et al. (2022). NOx emission impacts of hydrogen combustion in gas turbines: A short paper. Georgia Institute of Technology. Retrieved from https://research.gatech.edu/sites/default/files/inline-files/gt_epri_nox_emission_h2_short_paper.pdf
[34] Staiger, C. F., Moran, S., & Hurst, H. (2023). In-depth understanding: New proposed regulations for clean hydrogen. Buchanan Ingersoll & Rooney PC. Retrieved from https://www.bipc.com/in-depth-understanding-new-proposed-regulations-for-clean-hydrogen
[35] Arcos, J. M. M., & Santos, D. M. F. (2023). The hydrogen color spectrum: Techno-economic analysis of the available technologies for hydrogen production. Gases, 3(1), 25-46. https://doi.org/10.3390/gases3010002
[36] International Energy Agency. (2023). Global Hydrogen Review 2023. Page 22. https://www.iea.org/reports/global-hydrogen-review-2023
[37] Ibid.
[38] U.S. Department of Energy. (n.d.). Hydrogen resources. Retrieved from https://www.energy.gov/eere/fuelcells/hydrogen-resources
[39] International Energy Agency. (2023). Global Hydrogen Review 2023. https://www.iea.org/reports/global-hydrogen-review-2023
[40] International Renewable Energy Agency. (2022). Geopolitics of hydrogen. IRENA. Retrieved from https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/Jan/IRENA_Geopolitics_Hydrogen_2022.pdf
[41] International Energy Agency. (2023). Global Hydrogen Review 2023. https://www.iea.org/reports/global-hydrogen-review-2023
[42] Ibid.
[43] Ibid.
[44] Greentech Media. (n.d.). Can the U.S. catch up in the green hydrogen economy? Retrieved from https://www.greentechmedia.com/articles/read/can-the-us-catch-up-in-the-green-hydrogen-economy
[45] Fuel Cell and Hydrogen Energy Association. (n.d.). Hydrogen in industrial applications. Retrieved from https://www.fchea.org/hydrogen-in-industrial-applications
[46] U.S. Department of Energy. (n.d.). Hydrogen Shot. Retrieved from https://www.energy.gov/eere/fuelcells/hydrogen-shot
[47] Hydrogen Council in collaboration with McKinsey & Company. (2023, December). Hydrogen Insights December 2023 Update. [PDF] Retrieved from https://hydrogencouncil.com/wp-content/uploads/2023/12/Hydrogen-Insights-Dec-2023-Update.pdf
[48] Ibid.
[49] U.S. Department of Energy. (2023, September). U.S. National Clean Hydrogen Strategy and Roadmap. https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/us-national-clean-hydrogen-strategy-roadmap.pdf

[50] U.S. Department of Energy. (2022, September 1). DOE National Clean Hydrogen Roadmap (Draft). Retrieved February 16, 2024, from https://hydrogen.energy.gov/pdfs/clean-hydrogen-strategy-roadmap.pdf
[51] Liebreich, M. (2023, October 26). Liebreich: Clean hydrogen's missing trillions. https://about.bnef.com/blog/liebreich-clean-hydrogens-missing-trillions/
[52] Ibid.
[53] Hydrogen for Net-Zero. Hydrogen Council, McKinsey & Company. November 2021 + BNEF + Liebreich Associates
[54] BloombergNEF. (2023, February 22). Hydrogen subsidies skyrocket to $280 billion with US in the lead. https://about.bnef.com/blog/hydrogen-subsidies-skyrocket-to-280-billion-with-us-in-the-lead/
[55] Ibid.
[56] Ibid.
[57] IEA [International Energy Agency]. (n.d.). Electrolysers - Energy System [online]. Retrieved [date accessed] from https://www.iea.org/reports/electrolysers
[58] BloombergNEF Hydrogen Project Database. Bloomberg New Energy Finance. (2023). BloombergNEF Hydrogen Project Database. Retrieved from https://about.bnef.com/blog/2h-2023-hydrogen-market-outlook-the-demand-question/
[59] Ibid.
[60] PitchBook Data, Inc. (2023). Q4 2022 Clean Energy Report: VC trends and emerging opportunities.
[61] Ibid.
[62] Ibid.
[63] Cleantech Group. (2023). Cleantech 50TW 2023 Report. Cleantech Group.
[64] International Energy Agency. (2023). Net Zero Emissions by 2050 Scenario. Retrieved from https://www.iea.org/reports/global-energy-and-climate-model/net-zero-emissions-by-2050-scenario-nze
[65] Fuel Cell and Hydrogen Energy Association. (n.d.). Hydrogen in industrial applications. Retrieved from https://www.fchea.org/hydrogen-in-industrial-applications
[66] BloombergNEF. (2022). New Energy Outlook 2022. https://about.bnef.com/new-energy-outlook/
[67] U.S. Department of Energy. (2023). Pathways to commercial liftoff: Clean hydrogen. U.S. Department of Energy.
[68] Bhashyam, V. (2023, October 27). Green hydrogen to undercut gray sibling by end of decade. https://about.bnef.com/blog/green-hydrogen-to-undercut-gray-sibling-by-end-of-decade/
[69] Ibid.
[70] IRENA. (2022). Innovation outlook: Green ammonia. Retrieved from https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/May/IRENA_Innovation_Outlook_Ammonia_2022.pdf
[71] From personal interviews.
[72] BloombergNEF. (2023, January 18). 2023 hydrogen levelized cost update: Green beats gray. https://about.bnef.com/blog/2023-hydrogen-levelized-cost-update-green-beats-gray/
[73] Cleantech Group. (2023). Cleantech 50TW 2023 Report. Cleantech Group.
[74] Exxon Mobil Corporation. (n.d.). Low Carbon. Retrieved from https://lowcarbon.exxonmobil.com/
[75] U.S. Department of Energy. (n.d.). Review of CO2 pipeline infrastructure in the US. Retrieved from https://www.energy.gov/policy/articles/review-co2-pipeline-infrastructure-us
[76] ExxonMobil. (n.d.). Carbon capture and storage. Retrieved from https://corporate.exxonmobil.com/what-we-do/delivering-industrial-solutions/carbon-capture-and-storage#Denbury
[77] ExxonMobil. (2023, November 2). ExxonMobil completes acquisition of Denbury. Retrieved from https://corporate.exxonmobil.com/news/news-releases/2023/1102_exxonmobil-completes-acquisition-of-denbury
[78] HyVelocity Hub. (n.d.). Home page. Retrieved from https://www.hyvelocityhub.com
[79] Cleantech Group. (2023). Cleantech 50TW 2023 Report. Cleantech Group.
[80] BloombergNEF Hydrogen Project Database. Bloomberg New Energy Finance. (2023). BloombergNEF Hydrogen Project Database. Retrieved from https://about.bnef.com/blog/2h-2023-hydrogen-market-outlook-the-demand-question/
[81] "Geopolitics of the Energy Transformation: Hydrogen." IRENA, 1 Jan. 2022, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/Jan/IRENA_Geopolitics_Hydrogen_2022.pdf. Accessed 16 Feb. 2024.
[82] The Hydrogen Council and McKinsey & Company. Hydrogen Insights Dec 2023 Update. https://hydrogencouncil.com/wp-content/uploads/2023/12/Hydrogen-Insights-Dec-2023-Update.pdf

[83] DW. (2019). Power-to-X: The secret to a 100% renewable energy system. Retrieved from https://www.dw.com/en/power-to-x-the-secret-to-a-100-renewable-energy-system/a-51662014
[84] U.S. Department of Energy. (2023). Pathways to commercial liftoff: Clean hydrogen. U.S. Department of Energy.
[85] The Engine. (n.d.). What is tough tech? Retrieved from https://engine.xyz/what-is-tough-tech
[86] Climate Tech VC. (2023). Climate tech H1 2023 venture funding. Retrieved from https://www.ctvc.co/climate-tech-h1-2023-venture-funding/
[87] Clean Energy Finance Forum. (2022, March 28). Explainer: The valley of death and the challenges of scaling climate tech. Retrieved from https://www.cleanenergyfinanceforum.com/2022/03/28/explainer-the-valley-of-death-and-the-challenges-of-scaling-climate-tech
[88] PitchBook. (n.d.). Market data on venture capital investments. Retrieved from https://my.pitchbook.com/profile/515433-52/investor/profile#general-info
[89] PitchBook. (n.d.). Market data on venture capital investments. Retrieved from https://my.pitchbook.com/profile/461901-61/company/profile#investors
[90] Harvard Business School Online. (2021). Investment time horizon. Retrieved from https://online.hbs.edu/blog/post/investment-time-horizon
[91]TDK Ventures. (2022). TDK Ventures invests in green hydrogen electrolysis startup Verdagy. Retrieved from https://tdk-ventures.com/tdk-ventures-invests-in-green-hydrogen-electrolysis-startup-verdagy/
[92] PitchBook. (n.d.). Market data on venture capital investments. Retrieved from https://my.pitchbook.com/profile/482764-33/company/profile#investors
[93] Global Hydrogen Review. (2024, April 10). Doral announces agreement with Verdagy. Retrieved from https://www.globalhydrogenreview.com/hydrogen/10042024/doral-announces-agreement-with-verdagy/
[94] HyVelocity Hub. (2023, April). HyVelocity H2Hub FAQs. Retrieved from https://www.hyvelocityhub.com/wp-content/uploads/2023/04/HyVelocity-H2Hub-FAQs-4_23.pdf
[95] U.S. Department of Energy. (2023). DOE pathways to commercial liftoff: Clean hydrogen. Retrieved from https://liftoff.energy.gov/clean-hydrogen/
[96] U.S. Department of Energy. (n.d.). Funding notice: Regional Clean Hydrogen Hubs. Retrieved from https://www.energy.gov/oced/funding-notice-regional-clean-hydrogen-hubs
[97] Mullen, Elizabeth (2023). Financing the Green Hydrogen Economy. Master's project, Duke University. Retrieved from https://hdl.handle.net/10161/27178.
[98] Ibid.
[99] Ibid.
[100] Ibid.
[101] U.S. Department of Energy. (n.d.). Funding notice: Regional Clean Hydrogen Hubs. Retrieved from https://www.energy.gov/oced/funding-notice-regional-clean-hydrogen-hubs
[102] Ibid.
[103] National Grid Group. (n.d.). Hydrogen Colour Spectrum. https://www.nationalgrid.com/stories/energy-explained/hydrogen-colour-spectrum
[104] Ibid.
[105] Cipher News. (n.d.). A treasure hunt for underground hydrogen is on. Cipher News. Retrieved from https://ciphernews.com/articles/a-treasure-hunt-for-underground-hydrogen-is-on
[106] National Grid Group. (n.d.). Hydrogen Colour Spectrum. https://www.nationalgrid.com/stories/energy-explained/hydrogen-colour-spectrum
[107] Pacific Northwest National Laboratory. (2021, March 18). New clean energy process converts methane to hydrogen with zero carbon dioxide emissions. Retrieved from https://www.pnnl.gov/news-media/new-clean-energy-process-converts-methane-hydrogen-zero-carbon-dioxide-emissions
[108] BloombergNEF. (2023, February 22). Hydrogen subsidies skyrocket to $280 billion with US in the lead. https://about.bnef.com/blog/hydrogen-subsidies-skyrocket-to-280-billion-with-us-in-the-lead/
[109] Energy.gov. (2021). Hydrogen Shot. Retrieved from https://www.energy.gov/eere/fuelcells/hydrogen-shot
[110] U.S. Department of Energy. (n.d.). Hydrogen Shot. Retrieved from https://www.energy.gov/eere/fuelcells/hydrogen-shot
[111] Bloomberg New Energy Finance. (2023). Hydrogen subsidies skyrocket to $280 billion with US in the lead. BloombergNEF. Retrieved from https://about.bnef.com/blog/hydrogen-subsidies-skyrocket-to-280-billion-with-us-in-the-lead/

[112] McKay, D. (2023, October 20). Clean hydrogen has a serious demand problem. Canary Media. https://www.canarymedia.com/articles/hydrogen/clean-hydrogen-has-a-serious-demand-problem

[113] U.S. Department of the Treasury. (2023, December 26). Section 45V credit for production of clean hydrogen; Section 48(a)(15) election to treat clean hydrogen production property as energy property. Federal Register. Retrieved from https://www.federalregister.gov/documents/2023/12/26/2023-28359/section-45v-credit-for-production-of-clean-hydrogen-section-48a15-election-to-treat-clean-hydrogen

[114] U.S. Department of Energy. (2024, January). OECD Hydrogen Hubs: Building the foundation for global clean hydrogen trade. https://www.energy.gov/sites/default/files/2024-01/OCED_H2Hubs.pdf

[115] Ibid.

[116] BloombergNEF. (2023, February 22). Hydrogen subsidies skyrocket to $280 billion with US in the lead. https://about.bnef.com/blog/hydrogen-subsidies-skyrocket-to-280-billion-with-us-in-the-lead/

[117] U.S. International Trade Administration. (2023, March 16). EU Launches Hydrogen Bank. https://www.trade.gov/market-intelligence/eu-launches-hydrogen-bank

[118] Liebreich, M. (2023). Clean hydrogen's missing trillions. BloombergNEF. Retrieved from https://about.bnef.com/blog/liebreich-clean-hydrogens-missing-trillions/

[119] Ibid.

[120] Ibid.

[121] International Renewable Energy Agency (IRENA). (2022). Geopolitics of the energy transformation: The hydrogen factor. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/Jan/IRENA_Geopolitics_Hydrogen_2022.pdf

[122] https://www.iea.org/energy-system/low-emission-fuels/electrolysers
IEA [International Energy Agency]. (n.d.). Electrolysers - Energy System [online]. Retrieved [date accessed] from https://www.iea.org/reports/electrolysers