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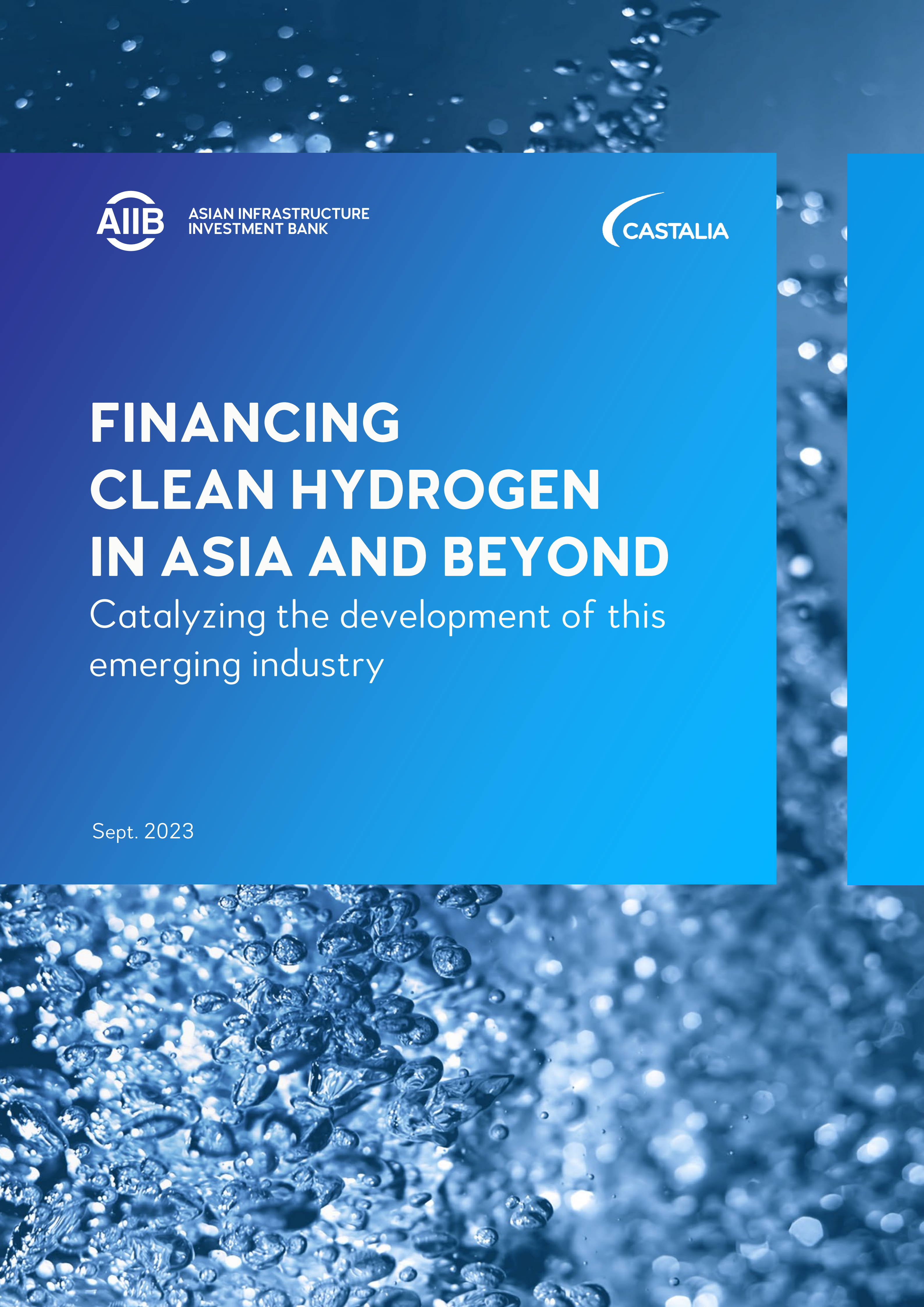
FINANCING CLEAN HYDROGEN IN ASIA AND BEYOND

Catalyzing the development of this emerging industry

Sept. 2023



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Foreword

For the world to achieve net-zero, technologies still under development will need to contribute almost half of the needed emissions reductions. Deployment of these new technologies, such as clean hydrogen, will make critical contributions to the decarbonization of hard-to-abate sectors such as heavy industries and long-haul transport. This is particularly important for countries in Asia, which are in the process of industrialization and gaining access to modern services.

Many developing countries are endowed with vast land and renewable resources and therefore have the potential to produce clean hydrogen at scale for export. Becoming leading clean hydrogen producers also offers them an opportunity to leapfrog domestic end-use infrastructure and spur economy-wide innovation and investments.

Given its transformative potential, the development of clean hydrogen needs to be accelerated if the world is to achieve its net-zero ambitions. But the development of hydrogen technologies and applications still face significant challenges – costs remain high, safety standards are still being developed, supporting infrastructure is at a nascent stage. Multilateral development banks (MDBs) have the responsibility – and the wherewithal – to support the development of the clean hydrogen sector by de-risking the hydrogen economy and catalyzing technological innovation.

Clean hydrogen fully aligns with AIIB’s Corporate Strategy through the Green Infrastructure thematic priority, further enabling the Bank to fulfil its mandate of Financing Infrastructure for Tomorrow. AIIB’s Updated Energy Sector Strategy also provides support for clean hydrogen as a transformative and innovative technology that will underpin AIIB Members’ energy transition. AIIB’s clean hydrogen investment will be guided by an identified critical pathway for clean hydrogen commercialization and pursue a practical approach taking into consideration risks and an objective to maximize impact.

Danny Alexander

Vice President, Policy and Strategy

Preface and Acknowledgements

‘Financing Clean Hydrogen in Asia and beyond: Catalyzing the development of this emerging industry’ is a report prepared by Castalia for the Asian Infrastructure Investment Bank (AIIB).

Developing a robust clean hydrogen sector will enable developing countries in Asia and beyond to decarbonize hard-to-abate sectors and accelerate their transition towards a clean energy system. International Financial Institutions (IFIs) can play an important role to de-risk and bring this promising low-carbon technology closer to commercial stage. To support the development of clean hydrogen, the report assesses the critical pathway for the commercialization of clean hydrogen value chain over a 5-, 10-, and 15-year time horizon. Recognizing the barriers to clean hydrogen development at its early stage and IFIs’ role to catalyze its commercialization, the report seeks to shed light on how IFIs can effectively deploy their financial instruments to support clean hydrogen’s critical pathway along each phase.

The study reviewed the global conditions for clean hydrogen production and use cases to identify possible engagement points for IFIs. Economic modelling identified likely least-cost hydrogen production locations and hydrogen use cases in countries with significant potential, based on short-, medium- and long-term technical and economic viability. Countries with optimal conditions for production both at large-scale and on a distributed basis were identified based on cost and capacity factor of renewable electricity, likely hydrogen demand, and availability of infrastructure that could be adapted to support hydrogen logistics. Several technically viable hydrogen use cases were compared for cost-competitiveness with alternatives. The main investment instruments were then reviewed and matched with the risk profile of identified engagement points, and how this may change overtime. The result of this study is a series of financing propositions for supporting clean hydrogen commercialization across production, use, and logistics.

The report was originated and supervised by Wei Huang (Energy officer) and finalized by Olivier Ferrage (Energy Consultant), both from the Strategy, Policy and Budget Department. We are grateful to the consultant team from Castalia, including Alex Sundakov (Executive Director), Andreas Heuser (Managing Director), Freya Tearney (Manager), Justin Chen (Analyst), who conducted extensive analysis and developed the economic model for this study. AIIB and Castalia collaborated closely to produce new insights and directions to support the practical commercialization of clean hydrogen.

Abbreviations

%	Percent
°C	Degrees Celsius
AIIB	Asian Infrastructure Investment Bank
ASEAN	Association of Southeast Asian Nations network
CCUS	Carbon capture and storage
DAC	Direct air capture
dwt	Deadweight tonnage
EBRD	European Bank for Reconstruction and Development
ESMAP	Energy Sector Management Assistance Program (ESMAP), IRENA
GMS	Greater Mekong Subregion
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
kgH2	Kilogram of hydrogen
km	Kilometer
kW_{el}	Kilowatt electric
kWh	Kilowatt hour
kWp/d	Kilowatt peak per day
LNG	Liquefied natural gas
LOHCs	Liquid organic hydrogen carriers
LRC	Linked rock cavern
MJ/L	Megajoules per liter
Mt	Million tonnes
Mtpa	Million tonnes per annum
MW	Megawatt
OEC	Observatory of Economic Complexity
OLT	Offshore LNG Toscana
PEM	Polymer electrolyte membrane
PJ	Petajoule
R&D	Research and development
t/d	Tonnes per day
TEU	Twenty-foot equivalent units
TSO	Transmission system operators
tWh/y	Terawatt-hour per year
USD	United States Dollar
W/m^2	Watts per square meter

Executive summary

International Financing Institutions (IFIs) can help catalyze the development of commercially viable clean hydrogen..[1] Given the transformative potential of clean hydrogen – but also the complexity of its value chain, it is necessary to identify where and how IFIs can engage in the hydrogen industry to be most impactful.

The report identifies engagement points to catalyze clean hydrogen use, production, and logistics in the short- to long-term as well as suitable financing instruments along each phase, with a focus on Asia and developing countries. The financing approach will evolve in relation to future commercial risks. The commercial risks vary according to the engagement point. There are different financial instruments that are targeted to those different risks. The report maps financing instruments and their risk profiles to the evolving risks of different hydrogen sector segments.

11 engagement points have been distilled based on extensive research and analysis

The report identifies 11 key engagement points across the hydrogen value chain—four in end-use applications, three in production, and four in logistics. The 11 engagement points were identified through extensive research and analysis by taking the following steps:

- First, the most promising technologies and business models for end-use, production, and logistics were identified using extensive primary and secondary research and analysis
- Second, the promising technologies identified in the first step were examined for viability in various countries (with a focus on Asia and developing countries).[2]
- Third, the readiness of technologies was examined from the short- to long-term in light of barriers and risks that could limit the commercial uptake of hydrogen.

The report matches financial instruments to commercial risks of each engagement point

The available financial instruments are matched to the risk profiles of the 11 identified engagement points, which all have commercial risks. Some of the risks are high because some segments are in the early stage of development, and the market niche is not yet established. In other cases, commercial risks are lower because the technology is established, and the risk relates to other more conventional market factors.

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[1] This report focusses on hydrogen production from electrolysis (green hydrogen). Both green and blue hydrogen are considered for hydrogen end-use applications and hydrogen transport and transmission. These segments are agnostic to the origin of the hydrogen and could serve as a basis for ecosystem development and green hydrogen deployment. The report also assesses liquid and compressed hydrogen, as well as ammonia and as liquid organic hydrogen carriers (LOHCs).

[2] These country analytical frameworks can be taken forward to examine hydrogen investment projects in other countries, not just the countries analyzed in this report.

Different financial instruments can be deployed to support clean hydrogen development across the spectrum of risks. The report assesses the engagement points' key risks. It then matches financial instruments to those risks on the short- to long-term considering the changes to the commercial risk profile of each engagement point over time:

- Project finance was matched against engagement points where the relevant technology is mature, and hydrogen technology is likely to be competitive. Furthermore, commercial risks can be managed within a project's contractual arrangements (for example, cash flows in a take-or-pay contract to supply hydrogen)
- Corporate finance was matched against engagement points where the relevant technology is mature, and the investment target companies are likely to have a wider corporate balance sheet to support repayment of the lending
- Equity investment was matched against engagement points where the technology is likely to be established, but there is sufficient risk for the company to develop a market or gain market share to make debt financing unviable
- Venture capital investment was matched against long-range engagement points in companies with higher technological risk, and where companies are at the leading edge of hydrogen economy development.

Table 0.1 provides a summary of engagement points and investment approach across the hydrogen value chain, including countries with significant potential.

Table 0.1: Summary of engagement points and financing approach across the hydrogen value chain

Value chain	Engagement point	Timeframe and financing instrument[3]			High-potential countries/regions
		Short-term	Medium-term	Long-term	
End-use	**Conversion of truck and bus fleets, and later specialized vehicle fleets**	Corporate finance	Corporate finance	Corporate finance	Bangladesh, Cambodia, Indonesia, Kyrgyzstan, Myanmar, Nepal, Lao PDR, Tajikistan, Uzbekistan
	Clean ammonia and methanol production	Corporate finance	Corporate finance	Corporate finance	China, Egypt, India, Indonesia, Malaysia, Pakistan, Qatar, Saudi Arabia
	Technologies for hydrogen-based long-haul aviation	Venture capital	Venture capital	Venture capital	Australia, China, Germany, Japan, Korea, Netherlands, Singapore, United Kingdom
	Ammonia-powered ships	Venture capital	Corporate finance	Corporate finance	Bangladesh, China, Germany, Indonesia, Japan, Norway, Pakistan
Production	**Large-scale hydrogen production projects**	Project finance	Project finance	Project finance	Australia, Canada, Chile, China, Egypt, Lao PDR, Norway, Oman, Portugal, Saudi Arabia, Spain, United Arab Emirates
	Distributed hydrogen production projects	Corporate finance	Corporate finance	Project finance	China, Indonesia, Kyrgyzstan, Lao PDR, Nepal, Tajikistan, Uzbekistan
	Technologies to improve hydrogen production efficiency	Venture capital	Venture capital	Ordinary equity	China, Europe, New Zealand
Logistics	**Hydrogen refueling facilities**	Corporate finance	Corporate finance	Project finance	China, Indonesia, Kyrgyzstan, Lao PDR, Nepal, Tajikistan, Uzbekistan

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[3] Concessional financing and technical assistance may be deployed all along the hydrogen value chain.

	Ammonia production and storage technologies	Corporate finance	Corporate finance	Project finance	Australia, Canada, China, India, Indonesia, Middle East and North Africa, Pakistan, Uzbekistan
	Conversion of pipelines for hydrogen transmission	Corporate finance	Corporate finance	Corporate finance	China, Egypt, Europe, Georgia, Indonesia
	Technologies to scale up large-scale compressed hydrogen storage	Venture capital	Venture capital	Venture capital	China, Indonesia, Sweden, Tajikistan, United Kingdom

Source: Castalia analysis

Introduction

Clean hydrogen[4] has a critical role to play in the decarbonization of hard-to-abate sectors such as heavy industries and long-haul transport. While the momentum behind hydrogen is growing, investment is hindered by a combination of risks and challenges. Notably, the hydrogen value chain is long and complex both horizontally and vertically (Figure 0.1), with significant investment needed in each value chain segment to bring hydrogen to a commercial scale. Given its transformative potential, investment in clean hydrogen needs to ramp up if the world is to achieve its net-zero ambitions.

International financial institutions (IFIs) can help catalyze the development of commercially viable clean hydrogen. Concessional finance and technical assistance provided by IFIs have been instrumental for mainstreaming clean technologies such as solar and wind energy over the last decade and will continue to play a critical role in supporting hydrogen development. But for clean hydrogen to reach the required scale at a pace aligned with the climate goals, IFIs must also leverage other available financial instruments such as equity and debt. The report provides recommendations on how IFIs can deploy these instruments to support the development of clean hydrogen by identifying feasible engagement points along the clean hydrogen value chain and matching their risk profiles with appropriate financial instruments. It also identifies countries with the most conducive market conditions and highlights key technological barriers and risks to each engagement point, and details how these barriers and risks might be overcome.

The main body of the report is divided into 4 sections. Section 1 sets out the analytical framework and identifies how each financial instrument in the scope of this report can support emerging technologies at various stages of development. Sections 2, 3, and 4 detail the engagement points for catalyzing end-use applications, production, and logistics, respectively. This includes discussion on the most appropriate financing instrument over time, countries with high potential to lead segment development, and key barriers and risks for each engagement point. The appendices provide detailed research and analysis that inform the financing approach for engagement points in end-use (Appendix A), production (Appendix B), and logistics (Appendix C).

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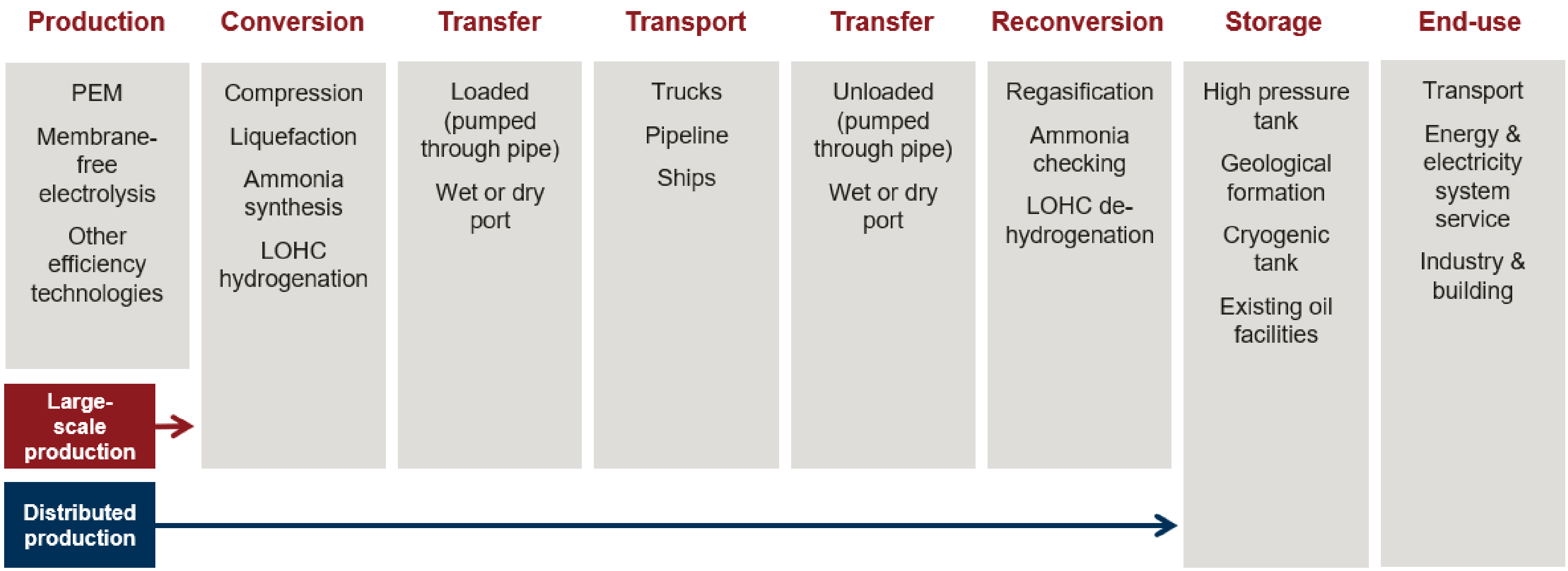
[4] This report focusses on hydrogen production from electrolysis (green hydrogen). Both green and blue hydrogen are considered for hydrogen end-use applications and hydrogen transport and transmission. These segments are agnostic to the origin of the hydrogen and could serve as a basis for ecosystem development and green hydrogen deployment. The report also assesses liquid and compressed hydrogen, as well as ammonia and as liquid organic hydrogen carriers (LOHCs).

Figure 0.1: Overview of the hydrogen value chain



Source: Castalia; Abbreviations: PEM, Polymer electrolyte membrane; LOHC, Liquid organic hydrogen carrier

1 Analytical framework

This section aims to lay out the analytical framework which identifies when, where, and how IFIs can utilize the financial instruments included in the scope of this report to best support the commercialization of clean hydrogen. The outline to the analytical framework is described below:

- How engagement points are shortlisted (Section 1.1)
- How high-potential countries are identified (Section 1.2)
- How risks are assessed (Section 1.3)
- How financing instruments are matched to the engagement points (Section 1.4).

1.1 Identification of engagement points to catalyze clean hydrogen commercialization

An extensive analysis of technological and commercial developments in the hydrogen sector was carried out to identify feasible engagement points throughout the clean hydrogen value chain along different time horizons. For each identified value chain segment, viable business models and barriers and risks were also analyzed:

- Technologies in hydrogen use are assessed in Appendix A for technological readiness and economic viability, relative to other use cases and energy sources. Through the analysis, four engagement points were identified.
- Clean hydrogen production modalities are assessed in Appendix B for technological readiness and economic viability. This analysis resulted in three engagement points.
- Different logistics approaches for hydrogen are assessed in Appendix C for technological readiness and economic viability in context of wider development of the hydrogen sector and other options to transmit energy. This analysis resulted in the identification of four engagement points.

1.2 Identification of high-potential countries

Focusing on Asia and developing countries, high-potential countries were identified using the analytical framework described below.

Countries with high potential for hydrogen use

Taking the analysis of end-use applications from Section 1 as the basis, the identified segments were then examined for viability across different countries with a focus on least developed countries. To do this, key research questions and thresholds are applied to assess if there is potential that significant demand will develop for each end-use application across countries in the mid-term. Research questions and qualifications are detailed in Table A.2. A range of public and proprietary data sources have been used to answer the questions.[5]

Countries with high potential for hydrogen production

Countries that have high potential to produce hydrogen at scale were identified based on two criteria:

- Ability to produce hydrogen (capacity factors), renewable energy (solar and wind) potential, likelihood of excess power, and connectivity to potential demand sources (domestic and foreign).
- Willingness to produce hydrogen (priority factors), availability of renewable electricity for hydrogen production vis-à-vis other electricity needs and policy environment.

Countries with high potential for hydrogen logistics

Countries with high potential in hydrogen logistics were identified based on their likeliness to:

- Export (or transport large volumes of hydrogen domestically) hydrogen.
- Produce and be able to export/transport hydrogen at a competitive price.

It is important to note that a global hydrogen market does not yet exist, and several technical and economic limitations could mean that it will not develop. Specifically, hydrogen cannot yet be stored and transported in large volumes, and it is not clear that the costs of transporting hydrogen over large distances will be low enough to be economical compared to hydrogen production closer to the point of use (even if the electricity and other production input costs are higher).[6] Therefore, the report also identified countries that have:

- Access to the infrastructure needed for hydrogen export (such as ports or pipelines).
- Existing experience in exporting hydrogen-like commodities.
- High domestic demand for hydrogen.

1.3 Assessment of risks and barriers

Hydrogen is an emerging clean energy technology and energy vector with many proposed use cases. There will be uncertainties as regard to whether hydrogen will be the most economical clean energy solution for each of the proposed sectors and use cases considered in the analysis. Commercial risks also need to be taken into considerations. Accordingly, a risk assessment was carried out with two elements:

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[5] Some data was limited due to being out of date, missing, or not comparable across countries. A mix of international organization (for example, the World Bank, ADB, and government documents), private firm, and media reporting data was used, with a preference for data from credible sources.

[6] It is far cheaper to transport electricity than it is to transport large volumes of hydrogen.

- First, the competitiveness and economic viability of the hydrogen use case, production technology, or logistics engagement point was assessed in the short- to long-term.
- Second, the commercial risk of the engagement point was assessed in the short- to long-term.

Competitiveness and economic viability risks

The competitiveness and economic viability of each engagement point was assessed (hydrogen use case, the production modalities, and each hydrogen logistics method). The analysis focused on how each engagement point is likely to develop in the short- to long-term. The whole clean hydrogen value chain faces some degree of barriers and risks to full, mainstream commercialization. There will continue to be uncertainties as to whether hydrogen will emerge as the most economical clean energy solution all along the value chain. There are competing technologies and energy vectors that are also being steadily improved upon. For instance, competing battery electric technology, and battery size/weight is improving. In hydrogen storage, developments in long-distance electricity transmission from low-cost renewable energy regions to high-cost regions could change the economics of storing and transporting hydrogen. In the appendices, the key competitive threats to hydrogen were identified and discussed. These are related to physical limits to clean hydrogen technologies, including:

- End-use—on-board storage constraints and the requirement for carbon feedstock.
- Logistics—low purity, low hydrogen content, and the involvement of fossil fuels.

Commercial risks

Even if hydrogen technology becomes economically competitive in the respective sectors and use cases, commercial risks will continue to be an important consideration. For some segments, the commercial risk will decline over time, as the particular use case, production modality, and logistic modality matures. The commercial risks, the mitigating factors, and the risk management approaches were identified.

1.4 Matching financial instruments to identified engagement points

Finally, financial instruments were matched to the engagement points according to their risk profiles. IFIs' available financial instruments were determined (Section 1.4.1). Then the conceptual framework for how the financing instruments can be deployed towards the identified engagement points is explained (Section 1.4.2).

1.4.1 IFIs can help catalyze investment by taking early-stage risks and investments

IFIs could help catalyze the development and scale-up of clean hydrogen technologies. This can be done by providing early-stage capital and expertise, crowd in private capital, and de-risk investment. This in turn will support sustainable businesses (especially ones with high economic, social, and environmental benefits but limited financial returns), build credibility, and guide industry development in a sustainable direction.

Financial instruments to support the development and uptake of emerging technologies
IFIs offer a variety of financial instruments. In addition to concessional finance, technical assistance, and policy dialogue that are traditionally provided by IFIs to support the early-stage development of clean technologies, Table 2.1 outlines the most relevant financial tools to support the development and commercialization of emerging technologies. Table 1.1 below compares these instruments' key characteristics.

Table 1.1: Summary of identified financial instruments relevant for emerging technologies

Category	Product	Source of returns	Required conditions		
			Certain project cash flow	Strong corporate balance sheet	Sound underlying business activity
Equity	Venture capital	Dividends and equity appreciation, through uncertain business activities with high upside return	✗	✗	✗
	Ordinary equity	Dividends and equity appreciation, through well understood business activities	✗	✗	✓
Debt	Corporate finance	Repayment, backed by the borrower's balance sheet	✗	✓	✓
	Project finance	Repayment, through the project's future cash flow	✓	✗	✓

Source: Castalia analysis

1.4.2 Framework for matching financial instruments to clean hydrogen engagement points

Venture capital
Venture capital is used for long-range opportunities where there is high risk of failure, but where large payoffs are possible if the business opportunity succeeds. Investors require a high-risk tolerance, and typically invest in a portfolio of opportunities. Venture capital can provide capital for relatively immature businesses engaging in high-risk

business activities.[7] Any one business is likely to fail, but successful businesses should provide returns high enough to make the overall venture capital portfolio profitable.

Venture capital in clean hydrogen will be most appropriate for overcoming risks and barriers associated with highly immature and unproven technologies. For clean hydrogen, these are all technological barriers where venture capital can fund research and development to potentially overcome these barriers:

- Immature technology (end-use and logistics).
- Alternative clean competitors (end-use and logistics).
- Large conversion, storage, or transport losses (logistics).

Ordinary equity

Ordinary equity exposes investors to higher risk. It can be used to support emerging opportunities in most locations. Ordinary equity can provide capital for relatively mature businesses that do not have a strong balance sheet. However, the underlying business activity should be well understood and sound in principle.

Ordinary equity is most suitable for overcoming risks and barriers associated with technologically proven but commercially unproven business models. For clean hydrogen, these include:

- Limited commercial models or projects (end-use and logistics)—funding development and manufacturing of new commercial models (that may or may not be successful on the market)
- High regulatory barriers or standards (end-use and logistics)—funding efforts to comply with the standard by going through certification process, and providing operational runway while certification is underway.

Corporate finance

Corporate finance exposes investors to lower risk. It can be used to support emerging opportunities in most locations, backed by a firm’s balance sheet. Corporate finance can provide capital to mature companies that wish to invest in risky technologies. The strength of the corporate balance sheet will enable repayment, should the project cash flows prove insufficient.

Corporate finance is most suitable for overcoming risks and barriers associated with technologically mature but commercially unproven business models. For clean hydrogen, these include:

- Off-take uncertainty (production)—betting on sufficient off-take demand, assuming that it is at least somewhat likely that future cash flows will be sufficient to cover repayment

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[7] The high level of risk should stem from reasonable risk-taking actions that provide high upside, not from poor governance or planning processes. If a business has poor governance or planning processes, it should not be eligible for any type of finance.

- High cost of hydrogen fuel (end-use and production)—absorbing the extra costs of hydrogen fuel, assuming the cost is unlikely to shortly decrease to a viable level.

Project finance

Project finance exposes investors to lower risks, provided the appropriate structuring is adopted with sufficient certainty about cash flows. It can be used to support mature opportunities in certain locations where there are significant non-technological barriers to adoption. Project finance can provide capital for mature projects that can provide certain future cash flows, which will help repay the loan.

Project finance is most suitable for overcoming risks and barriers associated with commercially mature technologies and business models. For clean hydrogen, these include:

- Limited supporting infrastructure (end-use)—financing the supporting infrastructure to strengthen the ecosystem as a whole
- Long asset replacement cycles (end-use)—enabling replacement prior to typical replacement cycles, assuming there are economic, social, or environmental benefits associated
- High capital cost (end-use and logistics)—providing initial funding for capital expenditure for businesses with limited liquidity
- High cost of hydrogen fuel (end-use and production)—absorbing the extra costs of hydrogen fuel, assuming the cost is likely to shortly decrease to a viable level
- Slow scale up of renewable electricity (production)—providing project finance to renewable electricity projects.

2 Engagement points for catalyzing hydrogen end-use

Four key engagement points were identified in hydrogen end-use. These are the result of extensive research and analysis on technological readiness, country potential, key technological and commercial barriers and risks, and mapping identified financing instruments to evolving risks (as outlined in Section 1). The analysis is contained in Appendix A. Table 2.1 below summarizes the conclusions.

Table 2.1: Summary of engagement points in hydrogen end-use

Engagement point	Timeframe and financing structure			High-potential countries
	Short-term	Medium-term	Long-term	
Conversion of truck and bus fleets, and later specialized vehicle fleets	Corporate finance	Corporate finance	Corporate finance	Bangladesh, Cambodia, Indonesia, Kyrgyzstan, Myanmar, Nepal, Lao PDR, Tajikistan, Uzbekistan
Clean ammonia and methanol production	Corporate finance	Corporate finance	Project finance	China, Egypt, India, Indonesia, Malaysia, Pakistan, Qatar, Saudi Arabia
Technologies for hydrogen-based long-haul aviation	Venture capital	Venture capital	Venture capital	Australia, China, Germany, Japan, Korea, Netherlands, Singapore, United Kingdom
Ammonia-powered ships	Venture capital	Corporate finance	Corporate finance	Bangladesh, China, Germany, Indonesia, Japan, Norway, Pakistan

Source: Castalia analysis

2.1 Conversion of truck and bus fleets, and later specialized vehicle fleets

Firms that want to convert existing fossil-fuel heavy vehicle fleets (trucks, buses, and specialized vehicles) into heavy hydrogen fuel cell electric vehicles (HFC-EVs) could need corporate finance. Compared to others, this segment is lower risk because:

- HFC-EVs are technologically and commercially mature.
- HFC-EV buses and trucks exist and are in production by major vehicle manufacturers.
- Industrial and specialized vehicle manufacturers are developing HFC-powered specialized vehicles.

Commercial risks in this segment are low and will remain low in the long-term—at the point where firms want to convert fleets, the technology will likely be proven. The scale of financing will grow throughout the period, and the pace will depend on demand from fleet owners. The key commercial risk is the repayment of corporate debt, which can be managed by ensuring the borrower has a strong balance sheet. The recommendations that follow assume that HFC-EV heavy vehicles maintain the technical and economic advantage of alternative heavy vehicle options.[8]

Providing corporate finance in the short- to long-term

In the short-term, IFIs could provide corporate finance to established transport or industrial firms with heavy vehicles. IFIs should prioritize identifying firms with existing freight transport operations (particularly with a significant market share) and where heavy goods vehicles have long distances to travel.[9]

In the medium-term, needs for specialized vehicle are also likely to emerge, particularly in mining and ports—in situations where operational demand is high, and vehicle range is important.

Transport sector demand is most likely to emerge as large fleets are renewed. HFC-Evs have higher capital costs than conventional trucks, and fleet owners will need to finance the more capital-intensive fleet renewal. Fleet owners should be renewing heavy vehicle fleets from around 5 years.

The commercial risks of fleet upgrades and renewals are linked to the corporate balance sheet of the fleet-owning firm. The utilization of the HFC-EV trucks and specialized vehicles depends on the corporate performance of the owner, and its balance sheet utilization. Therefore, corporate finance (debt) is the most appropriate form of financing.

2.2 Clean ammonia and methanol production

Hydrogen from fossil fuels (gray hydrogen) is currently a critical feedstock in industrial chemical production, especially in ammonia and methanol production. Green hydrogen production to replace grey hydrogen represents significant potential given the large amounts of hydrogen required. Firms seeking to switch to clean feedstock will need corporate finance and, later, project finance needs for new green ammonia production, storage, and shipping infrastructure will appear.

This engagement point has moderate commercial risks but will become less risky once the technology is proven. The main commercial risk is associated with the future cost of green hydrogen and clean chemicals. Production of ammonia and methanol with gray hydrogen is currently much cheaper than with green hydrogen. Therefore, policies that reduce the cost of green hydrogen or penalize gray hydrogen (penalizing fossil fuel derived hydrogen use), or major step changes in green hydrogen production costs, or

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[8] One should still be cautious and monitor the development of battery EVs and charging technology for heavy vehicles. Hydrogen fuel cell electric vehicles (HFC-Evs) can be more economical than battery electric (EV) heavy vehicles because of the latter's constraints on payload and utilization. However, HFC-Evs' future economic and financial viability depends on maintaining or growing the (current) superior distance and payload capacity compared to battery Evs. This is developing rapidly. Battery Evs may develop superior energy efficiency (so-called "well to wheel" efficiency), making them more economic. Several technologies could drive battery Evs to be more economical, including rapid charging, overhead catenary wires, or better batteries.

[9] HFC-EV heavy vehicles are most viable on long routes with the heaviest cargo.

willingness of users to pay higher prices for clean chemicals, will be required for clean chemicals to be competitive with alternatives.

General repayment risks associated with corporate finance and project finance investments are also relevant. These risks can be managed by ensuring the borrower has a strong balance sheet under corporate finance arrangements, and also establishing off-take agreements for the chemical output where project finance is used.

Corporate finance for chemical firms seeking to switch to clean feedstock

Firms that currently produce ammonia or methanol will require significant capital investment to convert production to utilize green hydrogen. This can be through conversions of existing conventional ammonia and/or methanol production plants, or newly built plants in new locations.

Ammonia and methanol production facilities are typically located in places close to natural gas sources (on pipelines or near gas wells), near industrial areas, or on global shipping routes. Future new ammonia or methanol production plants using green hydrogen will be located where low-cost electricity is available near ports. In some cases, this may coincide with the location of conventional ammonia production.

In any case, significant financing will be required for the production plants. The following financing needs will present themselves:

- Corporate finance—existing ammonia or methanol production plants are typically owned by large firms. Balance sheet financing would be appropriate in those cases.
- Project finance—where conversions or new plant construction financing can be backed by off-take contracts for the chemical output, project finance is appropriate. The risks of the project will be linked to the cash flows from off-takers (typically the downstream chemical firms).[10]

2.3 Technologies for hydrogen-based long-haul aviation

Hydrogen use in aviation is in very early stages of development. Three possible uses of hydrogen exist—green hydrogen could power turboprop engines via a fuel cell, it could be combusted in a jet engine, and finally, when combined with carbon dioxide (CO_2), it could be a constituent element in synthetic fuels. Providing venture capital to firms developing this technology could be explored.

This engagement point has high commercial risks because the underlying technologies will remain uncertain in the medium-term, and therefore commercial returns are uncertain. The future economic viability of hydrogen in aviation will depend on how alternative sustainable fuels develop. Sustainable aviation fuel sourced from organic feedstocks and waste vegetable oils is already available as a 100 percent drop-in

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[10] For example, Germany recently announced a subsidy for green ammonia imports. Secure off-take could emerge for ammonia and justify investment through project finance. https://www.hydrogeninsight.com/policy/germanys-h2global-kicks-off-world-s-first-green-hydrogen-subsidy-scheme-with-ammonia-import-tender/2-1-1369442

replacement for conventional jet fuel. It is not clear which technologies will 'win.' These risks can be managed by using a portfolio-based approach.

Venture capital investment in firms developing technology for hydrogen-fueled long-haul aviation

The early stage of hydrogen-based technologies in aviation means that investments will be high-risk. In some cases, major aviation firms are directly investing in pure science and research and development (R&D) emerging from universities and research institutions. Early-stage technology companies are also securing investment from venture capital investors.

Risks are high because the technology is in early stages of development and the field is also opaque as firms are protective of their intellectual property, so limited information is available publicly. Depending on one's risk appetite, one could identify and support early-stage venture capital investment in hydrogen-based technology firms. Taking a portfolio-based approach to venture capital investment is recommended—that is, any one business will not fully succeed, but some of the portfolio businesses should provide returns high enough to make the overall venture capital portfolio profitable. Given the expected increase in global hydrogen demand in aviation end-use, projects and firms that do succeed are likely to create significant value for both investors and the hydrogen ecosystem.

2.4 Ammonia-powered ships

Marine engine technology fueled by hydrogen-derived fuels, most likely ammonia, is being developed. It appears to be the most likely low-carbon fuel for transoceanic or long-distance shipping. Investment needs will emerge as vessel owners renew their fleets and will require financing. Furthermore, there will be needs to finance the firms developing the technology to build new power plants or convert existing ships. IFIs could explore providing venture capital for firms developing ammonia-powered vessels and later provide corporate finance to fleet owners that want to retrofit or replace fossil-fueled vessels.

Commercial risks are high because technology is still developing and alternative low carbon technologies may 'win,' and therefore, returns are uncertain. It is likely to become less risky in the medium- to long-term once the technology is proven. Economic viability will depend on global agreements and national policies on fossil fuels. In addition, the long-life cycle and relatively slow fleet turnover rate of vessels will affect the future viability of ammonia-powered vessels.

General repayment risks associated with venture capital investments and corporate finance are also relevant but exacerbated by the technological risks outlined. These risks can be managed by taking a portfolio-based approach where venture capital is deployed and, once a technology is proven and support to fleet owners is provided, ensuring the borrower has a strong balance sheet.

Venture capital and then corporate finance for firms developing ammonia-powered vessels

The development of ammonia-powered ship engines is still in early stages of development. Start-up companies are developing engines that can be retrofitted, but several different ammonia technologies remain in consideration. Therefore, IFIs could consider venture capital financing for such early-stage projects. Companies in Norway, Germany, Japan, and China are developing such engines. This is a high-risk investment because technology is still developing and the field is also opaque as firms are protective of their intellectual property, so limited information is available publicly. IFIs could consider taking a portfolio-based approach, to spread risks across several technologies.

If ammonia-powered ships become established, fleet owners will require financing to retrofit, or replace fossil-fueled vessels. Corporate finance lending to shipping fleet companies would enable them to finance the switch to ammonia vessels. The commercial risks of fleet retrofits or replacements are linked to the corporate balance sheet of the fleet-owning firm. The utilization of the hydrogen vessels depends on the corporate performance of the owner and its balance sheet utilization.

3 Engagement points for catalyzing clean hydrogen production

There are three key engagement points identified in hydrogen production. These are the result of exhaustive research and analysis on technological readiness, country analysis, key technological and commercial barriers and risks, and mapping of financing instruments to evolving risks (as outlined in Section 1). The analysis is contained in Appendix B. Table 3.1 below summarizes these:

Table 3.1: Summary of engagement points in clean hydrogen production

Engagement point	Timeframe and financing structure			High-potential countries/regions
	Short-term	Medium-term	Long-term	
Large-scale hydrogen production projects	Project finance	Project finance	Project finance	Australia, Canada, Chile, China, Egypt, Lao PDR, Norway, Oman, Portugal, Saudi Arabia, Spain, United Arab Emirates
Distributed hydrogen production projects	Corporate finance	Corporate finance	Project finance	China, Indonesia, Kyrgyzstan, Lao PDR, Nepal, Tajikistan, Uzbekistan
Technologies to improve hydrogen production efficiency	Venture capital	Venture capital	Ordinary equity	China, Europe, New Zealand

Source: Castalia analysis

3.1 Large-scale hydrogen production projects

IFIs could explore providing project finance to large-scale clean hydrogen production plants by existing renewable energy firms that have secured an off-take agreement for clean hydrogen.

Commercial risks will most likely be low in the short- to long-term, provided an off-take agreement is secured. However, given project finance is typically provided as no recourse financing tied to project cash flows, project losses could still occur. Losses could arise for three main reasons. Firstly, large-scale electrolysis technologies do not bring expected improvements in efficiency and cost, then the cost of green hydrogen could exceed the price specified in the off-take agreement. Secondly, improved performance of distributed sub-scale production could also render large-scale production plants less competitive. Finally, in the long-term, the case for large-scale clean hydrogen production close to low-cost renewable electricity generation is uncertain. If long-distance trans-oceanic transmission lines are built, it is likely to be cheaper to transmit renewable electricity and produce hydrogen closer to the point of use than to produce hydrogen and transport it by land or sea. This risk can be managed by ensuring the firm has an adequate injection of equity and strong off-take agreements are established.

Project finance investments in large-scale hydrogen production projects

Few large-scale hydrogen production plants exist today but as the demand for clean hydrogen grows, more firms are seeking to build large-scale hydrogen production plants. The hydrogen produced will be sold to hydrogen end users to make a profit. Such projects have two key benefits:

- Catalyze local hydrogen value chains by providing an affordable source of green hydrogen.
- Drive down the cost of green hydrogen by scaling up technologies and accelerating the learning curve.

Projects could be found in locations that can provide plentiful and cheap renewable energy at a high-capacity factor. This would help reduce the cost of green hydrogen and improve the viability of the project. Electrolysis technology is improving and green hydrogen production cost in some locations is forecasted to drop to USD2 per kilogram.

An off-take agreement is critical to the success of project finance because the future demand for hydrogen remains uncertain. Without an off-take agreement, providing any form of financing would make the risks prohibitive. An off-take agreement will require some domestic hydrogen demand to absorb the hydrogen produced. This could come in the form of a firm both producing and consuming hydrogen—some of the hydrogen produced is used on-site (such as for ammonia production) while the remainder is sold. IFIs can leverage their technical expertise and convening power to support firms in securing off-take agreements.

3.2 Distributed hydrogen production projects

Firms that wish to build subscale distributed hydrogen production projects could require corporate finance. Distributed production could be least-cost as hydrogen transport is not needed if the hydrogen produced is consumed onsite. This is most likely promising for some hydrogen refueling stations, which is discussed in Section 4.1.

Commercial risks are moderate in the short- to medium-term, but risk is likely to reduce as projects become more mainstream. Risks are predominantly associated with the economic viability of distributed production, which will depend on the relative costs of sub-scale distributed production, and large-scale production combined with hydrogen transport costs. Distributed production could become less competitive if large-scale production achieves enough efficiency savings to overcome the costs associated with hydrogen transport. This could occur in locations with legacy gas pipelines, which could be converted to provide a cheap form of hydrogen transport (Section 4.3). General commercial risks associated with corporate finance investments are also relevant.

Corporate finance to support firms building distributed hydrogen production plants

This engagement point utilizes the same financing structure approach as outlined in Section 4.1, as it will most likely be undertaken by the same firms as those rolling out refueling facilities. Corporate finance is appropriate because the balance sheets of the incumbent fuel companies provide security.

3.3 Technologies to improve hydrogen production efficiency

Firms developing technologies to improve hydrogen production efficiency and decrease the cost of green hydrogen might need venture capital financing. Firms innovating in hydrogen electrolyzer technologies are the most promising. Alongside reducing the cost of electricity, reducing the cost and efficiencies of electrolyzers can decrease the cost of green hydrogen by up to 85 percent by 2050.[11] Like many other renewable energy technologies, hydrogen electrolyzers are likely to benefit from learning and scale as they are mass-produced instruments.[12]

There are high commercial risks in the short- to medium-term, because many efficiency-improving technologies are still in development and remain unproven, both technically and commercially, and it is unclear which technologies will be successful. For example, electrolyzers may continue to require large amounts of rare earth metals, increasing their capital costs, while renewable energy prices may not decrease enough for green hydrogen to be an economic substitute for gray hydrogen and other fossil fuels. Investment into R&D is also inherently risky—desired outcomes may not occur on time, on budget, or at all. This segment is likely to become less risky once technologies are more mature.

Equity investment into firms improving hydrogen production efficiency

The number of firms developing green hydrogen production technologies is growing. Firms innovate both on the electrolyzer stack level (relevant for both large-scale and sub-scale production) and the systems level (more relevant for large-scale production). Broadly, four types of electrolyzer technologies exist, each with pros and cons. Alkaline and polymer electrolyte membrane (PEM) electrolyzers are widely used today. Anion exchange membrane (AEM) and solid oxide electrolyzers are less mature but may be cheaper or more efficient.

Associated risks are very high because the underlying technologies remain uncertain. The field is also opaque as firms are protective of their intellectual property, so limited information is available publicly. Like all R&D projects, the payoff is highly uncertain. However, given the expected increase in global hydrogen demand, projects and firms that do succeed are likely to create significant value for both investors and the hydrogen ecosystem. Therefore, venture capital is the most appropriate form of financing in the medium-term. In the long-term, equity financing may become more suitable as winners emerge and seek finance for expansion.

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[11] IRENA (2020), Green Hydrogen Cost Reduction, available: https://www.irena.org/publications/2020/Dec/Green-hydrogen-cost-reduction

[12] K. Surana, C. Doblinger, L. D. Anadon, N. Hultman (2022), Effects of technology complexity on the emergence and evolution of wind industry manufacturing locations along global value chains, Nature Energy, Vol 5, 821–821, https://doi.org/10.1038/s41560-020-00685-6

4 Engagement points for catalyzing hydrogen logistics

There are four key engagement points in hydrogen logistics. These are the result of exhaustive research and analysis on technological readiness, country analysis, key technological and commercial barriers and risks, and mapping of financing instruments to evolving risks (as outlined in Section 1). The analysis is contained in Appendix C. Table 4.1 below summarizes these.

Table 4.1: Summary of engagement points in hydrogen logistics

Engagement point	Timeframe and financing			High-potential countries
	Short-term	Medium-term	Long-term	
Hydrogen refueling facilities	Corporate finance	Corporate finance	Project finance	China, Indonesia, Kyrgyzstan, Lao PDR, Nepal, Tajikistan, Uzbekistan
Ammonia production and storage technologies	Corporate finance	Corporate finance	Project finance	Australia, Canada, China, India, Indonesia, Middle East and North Africa, Pakistan, Uzbekistan
Conversion of pipelines for hydrogen transmission	No investment recommended	Corporate finance	Corporate finance	China, Egypt, Europe, Georgia, Indonesia
Technologies to scale up large-scale compressed hydrogen storage	Venture capital	Venture capital	Venture capital	China, Indonesia, Sweden, Tajikistan, United Kingdom

4.1 Hydrogen refueling facilities

Financing firms that wish to expand into hydrogen refueling services for heavy HFC-EVs could be explored. Incumbent fuel companies that want to transition into new fuels are especially promising. Corporate finance is the most appropriate financing tool. In some cases, market entrants may emerge, in which case project finance or equity is more appropriate.

The potential commercial risks are linked to the uptake of heavy HFC-EVs, which provide the demand for hydrogen refueling services. Refueling facilities could be built, but no (or low) demand emerges, for example, because battery EVs become more competitive. Risks are likely to decrease as projects become more mainstream, however, the scale of financing will grow throughout the period, and the pace will depend on demand from fleet owners.

General repayment risks associated with corporate finance and project finance and equity are also relevant. These can be managed by ensuring the borrower has a strong balance sheet (corporate finance) or has established off-take agreements or the refueling facility is almost certain to provide sufficient future cash flows (project finance and equity).

Corporate finance to support firms rolling out hydrogen refueling facilities

Corporate finance would help incumbent fuel companies finance the capital costs of the refueling infrastructure. As more heavy vehicle users switch to HFC-EVs, they will require refueling facilities. These new facilities will require financing, and in some countries, the incumbent fuel companies may be wary of the additional risk (demand and technology) associated with hydrogen refueling infrastructure. The barriers to entering the hydrogen refueling market are around securing key sites to ensure network effects and scale economies. The key locations for hydrogen refueling will be at depots, key locations on highway networks, and at logistics hubs such as ports, inland ports, or railway terminus. Such locations are typically owned by logistics firms or infrastructure companies. Incumbent fuel companies typically already have the sites secured, although relatively few agreements would be needed to secure sufficient market scale.

Corporate finance is appropriate in this case because the balance sheets of the incumbent fuel companies provide security. As the use of fossil-fuel vehicles declines, incumbent firms will need to diversify into clean fuels such as hydrogen. Incumbent firms already own or lease land at the likely refueling stops. Existing fuel companies are recognized brands and have expertise in secondary businesses (such as repair services, retail, and food). However, hydrogen refueling facilities remain untested. The existing balance sheets are likely to be strong, which helps de-risk the investment.

The timeline of HFC-EV uptake remains somewhat uncertain, but uptake is likely to begin in the short-term in developed countries. Therefore, investment into refueling facilities could be paired with that of HFC-EVs (Section 2.1). Refueling facilities can also help secure long-term off-take agreements for hydrogen production, which can complement large-scale hydrogen production (Section 3.1).

Project finance or equity investment appropriate for new market entrants

New market entrants may also emerge and seek financing. These entrants will not have the same corporate balance sheet as incumbent fuel companies. Cases of new market entry should be relatively few, compared to incumbent fuel companies converting all or part of a refueling facility to hydrogen. In these cases, two pathways are possible:

- Project finance, secured against cashflows from refueling off-take agreements with key customers.
- Equity investment in the market entering refueling company, provided that contracts with key customers are in place.

4.2 Ammonia production and storage technologies

Providing corporate finance to firms that are developing technologies to scale up ammonia production and storage could be explored. Ammonia is likely to play a critical role in the development of the global hydrogen ecosystem, but the current scale of green ammonia production is tiny compared to the volumes required to meet global ammonia demand. Ammonia is currently widely traded, and ammonia production is a key end-use of hydrogen—these make ammonia an attractive medium for global hydrogen trade.

Commercial risks are moderate in the short- to medium-term, which are likely to reduce as the market becomes more mainstream. Ammonia supply chains already exist today, meaning that if decarbonization is to occur, large quantities of green hydrogen will be required for ammonia production. A key risk is around competitiveness of alternatives, which could make investments in ammonia production and storage technologies redundant. For example, carbon capture technology for gray ammonia production could advance to become technically and economically viable, and other forms of hydrogen (such as liquid hydrogen or LOHCs) may become the preferred hydrogen carrier. However, advances in these technologies are somewhat unexpected. Another key risk is that the cost of green hydrogen may not decrease enough to make green ammonia as cheap as gray ammonia, which could reduce demand from end-users.[13] General repayment risks associated with corporate finance are also relevant. These risks can be managed by ensuring the borrower has a strong balance sheet.

Corporate finance to scale up ammonia production and storage; project finance in the future

Green ammonia production and storage will probably be done by existing fossil-fuel ammonia producing firms. These are typically industrial chemical firms. Expanding into green ammonia production and storage will require a re-alignment of supply chains. Current gray ammonia supply chains follow natural gas supply chains, with production occurring adjacent to natural gas fields or on major gas pipelines. In the switch to green ammonia production and storage, production will occur close to low-cost renewable energy sources (whether production locations or close to transmission lines).

Corporate finance lending will enable incumbent ammonia production firms to make the capital investments for the switch to green hydrogen feedstock. Project finance may be provided for new green ammonia production, storage, and shipping infrastructure, once technologies and supply chain are proven.

4.3 Conversion of pipelines for hydrogen transmission

Firms that seek to convert existing fossil fuel pipelines into hydrogen pipelines could require financing. Where available, converted hydrogen pipelines are the cheapest way to transport hydrogen over short to medium distances, driving down the delivered cost of green hydrogen.

Commercial risks are likely to be high initially as the technology is still being proven. However, risk is likely to reduce to moderate or low risks in the medium-term. A key risk is that electricity transmission may be more economic, which would make investments in pipeline conversions redundant. Hydrogen conversion involves large energy losses,

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[13] However, this risk is somewhat mitigated because ammonia production and storage technologies are the same independent of the hydrogen source (green or gray).

and it is also more expensive than transport of electricity. Where electricity transmission is possible, transmitting electricity followed by on-site hydrogen production could be cheaper. Where electricity transmission is challenging (such as for transoceanic routes), hydrogen pipelines are also challenging. Therefore, the number of pipeline conversion opportunities is likely limited and may arise on a case-by-case basis. Some technical uncertainty also remains regarding the compatibility of pure hydrogen with high grade steel over time, with corresponding policy and regulatory risks.

Corporate finance for firms converting existing pipelines into hydrogen pipelines

Repurposed natural gas pipelines are among the cheapest way to transport large volumes of hydrogen. Many countries have extensive natural gas transmission networks. Existing gas pipeline businesses may wish to expand into hydrogen transmission as demand for natural gas falls. The construction of new hydrogen pipelines is relatively mature, but conversion remains unproven outside a few isolated systems. However, this is expected to change in the short-term.

Investment needs are likely to rise once repurposed pipelines are proven as economic solutions, which is when gas pipeline businesses are likely to scale up pipeline conversion with rising hydrogen demand. IFIs can provide corporate finance to existing infrastructure firms that require additional capital for converting pipelines, and where either due to country risk or sector risk, they have a particular advantage. Hydrogen pipelines still have an unproven business model subject to considerable regulatory risk, so they are too risky for project finance. However, since gas pipeline businesses tend to have large asset bases and strong corporate balance sheets, corporate finance is appropriate to support pipeline conversion.

Gas networks are complex; different systems may require different conversion strategies. Generally, the highest potential exists where natural gas is already transported through pipelines to existing petrochemical facilities, which reduces off-take risk. Promising locations should have high hydrogen production costs due to high electricity prices and limited electricity transmission capacity. Conversion is most likely to start in countries with high and firm renewable energy capacity. Countries that rely on natural gas (or other fossil fuels) to provide firming capacity or heating are likely to be late adopters because they may take longer to phase out natural gas.

4.4 Technologies to scale up large-scale compressed hydrogen storage

Providing venture capital would be adequate for firms developing technologies that can support the scale-up of compressed hydrogen storage. Where available, large-scale geological formations are the cheapest way to store large amounts of hydrogen over time. Hydrogen can be produced when electricity is cheap and plentiful; hydrogen can be released when electricity supply is limited and prices are high to make a profit and ensure energy security.

Commercial risks are high in the short- to long-term because the underlying technologies remain uncertain, and therefore, commercial returns are uncertain. It is not clear whether the technology will be proven viable or be the most economic storage option. The development of large-scale energy storage technologies remains at an early stage, with many options in development for large-scale application, such as pumped hydro, pumped heat, and advanced batteries. This risk can be managed by using a portfolio-based approach.

Venture capital for firms scaling up large-scale compressed hydrogen storage

Venture capital financing is appropriate for scaling up compressed hydrogen storage technologies. This is because large-scale storage of compressed hydrogen remains in R&D and pilot phases. Small-scale storage is more mature but is not viable for energy security.[14]

Hydrogen storage is likely to have a niche in certain locations with favorable geological conditions and where other technologies are not viable.

Large-scale storage has high barriers to entry due to the need to secure geological formations, comply with safety requirements, and build supporting infrastructure (that are often themselves unproven). These barriers to entry have limited the number of firms innovating in large-scale hydrogen storage. Other external barriers must also be overcome, such as limited renewable energy generation capacity (which means that electricity may not be available or cheap enough to produce excess hydrogen) and immature hydrogen transport infrastructure (which could increase the cost of hydrogen transport between production and storage sites).

In future, if the technology matures, and the risks consequently reduce, IFIs could explore other forms of investment.

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[14] Small-scale storage is also important as it can buffer against inconsistent hydrogen production for uses where a steady supply of hydrogen is important, such as ammonia production.

Appendix A: Detailed assessment of hydrogen end-use

This Appendix provides a detailed assessment of promising engagement points in hydrogen end-use applications. It outlines the analytical frameworks and analyses used to assess potential in hydrogen end-use applications. The analysis was undertaken in three main parts:

- Determining promising end-use applications across a range of sectors in the short-to-medium term (A.1)
- Assessing potential for large-scale development of demand for hydrogen across countries (A.2)
- Analyzing technology readiness of hydrogen end-use applications and examining barriers and risks in hydrogen end-use applications (A.3).

A.1 Determining engagement points for end-use applications

Potential engagement points for end-use applications across a range of sectors in the short-to-medium term were identified using extensive primary and secondary research and analysis. This research and analysis indicated that in the short-to-medium-term, hydrogen is likely to be:

- Economically feasible and competitive in heavy land vehicles (including specialty vehicles) and as an industrial feedstock
- Economically feasible, but not competitive for high temperature heat
- A viable business model for demand response for hydrogen producing firms in locations where hydrogen production starts, and there is domestic demand elsewhere in the economy[15]
- A viable business model for long-term energy security in locations that are producing hydrogen and have appropriate storage options.[16]

In the medium-to-long term, hydrogen maybe used in:

- Maritime and rail transport applications[17]

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[15] Demand response is not an end-use application. Instead, it is viable as a complementary business model for a hydrogen producing firm if there is domestic demand for the hydrogen from end-use applications. Demand response has been grouped under end-use applications in this report.

[16] Energy security is not an end-use application. Instead, it is viable as a complementary business model for a hydrogen producing firm if there are viable domestic long-term storage options. Energy security has been grouped under end-use applications in this report.

[17] The use of clean hydrogen, or clean hydrogen derived fuels (ammonia), in maritime applications is less certain than other end-use applications because the technology is still developing and potential competing clean technologies are also being advanced.

- Aviation applications.

This initial analysis is displayed in Table A.1. End-use applications that are likely to be only feasible over the very long-term (beyond 15 years) are not included in this analysis.

Table A.1: Hydrogen end-use applications and future developments

Sector	End-use	Maturity				Demand			
		Now	Short-term	Medium-term	Long-term	Now	Short-term	Medium-term	Long-term
Transport	Heavy land vehicles.[18]	Medium	High	High	High	Low	Medium	High	High
	Maritime and rail	Low	Medium	Medium	High	None	Low	Low	Medium
	Long-haul aviation	Very low	Low	Low	Medium	None	None	Low	Low
Industry and buildings	Industrial feedstock	Medium	Medium	High	High	Low	Medium	High	High
	High temperature heat	High	High	High	High	Low	Medium	Medium	Medium
Energy and electricity system services	Demand response	High	High	High	High	Low	Medium	Medium	High
	Energy security	Medium	Medium	High	High	Low	Low	Medium	Medium

Source: Castalia (2022), New Zealand Hydrogen Scenarios; IEA (2019), The Future of Hydrogen; IRENA (2022), Green Hydrogen in Industry; IRENA (2022), Global Hydrogen Trade to Meet the 1.5C Climate Goal

A.2 Assessing hydrogen demand

Promising end-use applications identified in A.1 were then examined for viability across countries.

Assessing potential for large-scale development of demand for hydrogen

Promising end-use applications were then analyzed for viability across countries. To do this, key research questions and thresholds to qualify (likely to have demand or may have demand) are applied to countries for each end-use application. Research questions and qualifications are detailed in Table A.2. A range of public and proprietary data sources have been used to answer the questions.[19]

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[18] Heavy land vehicles, or heavy vehicles, refer to vehicles with a gross vehicle mass of more than 3,500 kilograms. Some examples are freight trucks, tractor-trailers, certain off-road vehicles, coach buses, mining excavators, forklifts, cranes, and straddle carriers.

[19] Some data was limited due to being out of date, missing, or not comparable across countries. A mix of international organization (for example, the World Bank, ADB, and government documents), private firm, and media reporting data was used, with a preference for data from credible sources.

Table A.2: Research questions and qualifications used in end-use application analysis

End-use case	Questions	Information captured	Qualification
Heavy vehicles	Is the country reliant on road or rail for freight?	▪ Yes or no ▪ % of total transported freight by road	If the majority of freight is transported by road, then move onto following heavy vehicle questions
	Is the road network extensive and relatively developed (e.g., paved)?	▪ Yes or no ▪ Length of the road network and % of road that is paved	If the road network is extensive, developed, and provides access, then move onto the following heavy-vehicle question
	Does it provide access to towns, cities, and transport hubs (such as ports and airports)?	▪ Yes or no	
	What is the size of the heavy vehicle fleet?	▪ % of land vehicle fleet that is heavy-duty vehicle ▪ % of heavy-duty vehicles that are the heaviest (i.e., exceeding 12 tonnes)	If the size of the fleet is around 4 percent or more of the total land vehicle fleet, then this is a possible end-use application for the country.[20]
Specialty vehicles	Does the country have a major mining sector or other extractive sectors needing industrial vehicles?	▪ Yes or no ▪ Record industries	If yes, then this is a possible end-use application for the country
Maritime	Does the country have a port?	▪ Yes or no	If yes, then move onto the following maritime questions
	Is the country's port(s) ranked in the Lloyds List Top 100 ports 2021 list?	▪ Yes or no	If yes, then this port is a large international trade hub, which is also likely to have sophisticated ships and logistics, meaning this is a possible end-use application for the country.[21]
	How much freight is transported domestically via vessel?	▪ % of total freight transported domestically	If this is more than 40 percent, then this is a possible end-use application for the country
	Does the country mainly utilize maritime transport for long-distance travel (e.g., inter-island transport)?	▪ Yes or no	If yes, then this is a possible end-use application for the country

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[20] Percentage based off previous Castalia analysis.

[21] Ports without these characteristics are unlikely to be at the leading edge of hydrogen use in maritime applications (unless they have significant freight transported domestically via vessel or use maritime transport for long-distance travel—see following questions)

End-use case	Questions	Information captured	Qualification
Industrial feedstock	Does the country have a large industrial sector that utilizes a carbon-intensive feedstock (e.g., ammonia, urea, methanol, and petrochemicals)?	▪ Yes or no ▪ Record industries ▪ Record volume of natural gas, fossil fuels, or gray hydrogen used for industrial processes (PJ)	If yes, then this is a possible end-use application for the country
Heating	Does the country undertake industrial processes using high heat (such as wood, pulp, and paper; petroleum; chemical; cement; rubber product manufacturing; dairy manufacturing)?	▪ Yes or no ▪ Record industries	If yes, then this is a possible end-use application for the country
Demand response	Is the country likely to produce hydrogen domestically?[22]	▪ Yes or no	If the answer is yes to both questions, then demand response might emerge as a complementary business model for a hydrogen producing firm
	Will the country likely have hydrogen demand from other areas of the economy?	▪ Yes or no ▪ Record end-use applications	
Energy security	Is the country likely to produce hydrogen domestically?[23]	▪ Yes or no	If the answer is yes to both questions, then energy security might emerge as a complementary business model
	Does the country have geological characteristics that could store H2?	▪ Yes or no ▪ Record characteristics	
Overarching	Is at least somewhat likely to produce clean hydrogen	▪ Yes or no	If the answer is yes to any of the questions, the country is generally more likely to develop end-use applications for clean hydrogen
	Intends to supply, use, or export clean hydrogen or develop hydrogen technologies[24]	▪ Yes or no	
	Has climate change policies that incentivize low-carbon options, as indicated by the presence of or intent to adopt a carbon tax or emissions trading scheme (ETS)	▪ Yes or no	

Note: Aviation was not included in the research because all countries will have hydrogen aviation technology if hydrogen emerges as the preferred way to decarbonize air travel.
Source: Castalia

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[22] Answer from hydrogen production analysis, discussed in Appendix B.

[23] Answer from hydrogen production analysis, discussed in Appendix B.

[25] TRL are a type of measurement system used to assess the maturity level of a particular technology.

A.3 Analyzing technology readiness and barriers and risks to investable hydrogen end-use applications

Analyzing the technology readiness level (TRL)[25] and barriers and risks to investable hydrogen end-use applications informed the financing approach discussed in Section 2.

Determining technology readiness of investable hydrogen end-use applications

The readiness of technologies over the short-to-medium term was analyzed after the analysis of promising end-use technologies and demand from countries had been undertaken. Table A.3 outlines the TRL scale used. The results of this analysis are provided in Table A.4.

Table A.3: Methodology to assess commercialization of technology

Technology readiness level[26]	Description	Example now
1	Basic research	Hydrogen aircraft
2	Applied research	
3	Critical function of proof of concept	
4	Testing and validation of components	
5	Testing and validation of system	Green steel
6	Prototype system verified	
7	Integrated pilot system demonstration	Ammonia ships
8	System incorporated in commercial designs	
9	System proven and ready for full commercial deployment	Hydrogen trucks

Source: NASA, Technology Readiness Level (TRLs)

Table A.4: Technology readiness timeline of promising end-use applications

Category	End-use	Now	Short-term	Medium-term	Long-term
Heavy land vehicle	Trucks and buses	9	9	9	9
	Specialized vehicles	7	8	9	9
Aviation[27]	Long-haul aviation	2	4	6	8

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[25] TRL are a type of measurement system used to assess the maturity level of a particular technology.

[26] Adopted from NASA's TRL, available at: https://www.nasa.gov/directorates/heo/scan/engineering/technology/technology_readiness_level

[27] Aviation was included in this analysis because investment might support the commercialization of the technology.

Category	End-use	Now	Short-term	Medium-term	Long-term
Maritime	Ammonia ships (long haul)	7	8	9	9
Industrial feedstock	Ammonia production	9	9	9	9
	Methanol production	8	9	9	9
	Steel production	6	7	8	9
Heating	High temperature heat	6	7	8	9
Energy and electricity systems[28]	Demand response	8	9	9	9
	Energy security (large-scale storage)	6	7	8	9

Source: Castalia analysis

Examining barriers and risks to investable hydrogen end-use applications

The technological barriers and risks to investable hydrogen end-use applications were analyzed. These barriers and risks might limit the uptake of hydrogen in end-use applications. The definition of a technological 'barrier' and a 'risk' is:

- Barriers are certain and pivotal. If a barrier is not resolved, the development and uptake of the technology are unlikely.
- Risks are the possible factors that may impede the development or uptake of technology. A risk may or may not occur. If a risk occurs, it may or may not be pivotal.

Table A.5 outlines the methodology used to undertake the analysis.

Table A.5: Methodology to analyze barriers and risks

Barrier	Description
High	Very significant barrier. Unlikely to be overcome soon and critical to uptake
Medium	Moderate barrier. Likely to be overcome and critical to uptake
Low	Minor barrier. Likely to be overcome soon, or not relevant to uptake
Blank	Not a barrier

Source: Castalia

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[28] Demand response and energy security are complementary business models, not end-use applications

This section outlines the technological barriers and risks to investable hydrogen end-use applications. An overview of barriers and risks to investable hydrogen end-use applications is provided in Table A.6. Barriers and risks for each end-use application are further detailed below.

Table A.6: Overview of technological barriers and risks to investable hydrogen end-use applications

Category	End-use	General barriers and risks					Other specific barriers					
		Immature technology	High regulatory barriers	Limited supporting infrastructure	Long asset replacement cycles	High capital costs	Alternative clean competitors	Limited commercial models or projects	On-board storage constraints	Requires carbon feedstock	High cost of hydrogen fuel	
Heavy land vehicle	Trucks and buses			Fueling and service networks	Most fossil fuel trucks and buses can be used for around a decade	Trucks and buses are somewhat expensive	Evs may be competitive for lower end of heavy vehicle weight class	Not as many models as Evs				Off-take uncertainty
	Specialized vehicles	Not as advanced as trucks and buses	Safety issues in some industries	Hydrogen storage and transport	Specialized vehicles have varied lives (but usually long)	Specialized vehicles are usually expensive		Not yet available for niche vehicles				Off-take uncertainty
Aviation	Long-haul aviation	Technology remains in R&D phase	Likely high safety and certification requirements	Fueling and service networks; Hydrogen storage and transport	Very long and potentially mismatched aircraft lifecycles	Aircrafts are very expensive	Biofuels may be competitive for SAFs	In R&D phase	Highly space constrained: hydrogen may displace passenger or cargo volume	SAFs require sustainable carbon feedstock	Likely very fuel intensive	Unclear which mode of hydrogen will prevail
Maritime	Hydrogen ships (short haul)	In pilot phase	Standards uncertain but likely easy to overcome	Bunkering and service infrastructure	Short haul ships can be used for over a decade	Expensive vessels	Electric ferries are competitive	In pilot phase	Space constrained but less so than aircrafts			
	Ammonia ships (long haul)	In pilot phase	Standards uncertain but likely	Bunkering and service infrastructure	Long haul ships can be used for	Very expensive	Biofuels, synthetic fuels, or	In pilot phase	Space constrained but less so			

Category	End-use	General barriers and risks					Other specific barriers					
		Immature technology	High regulatory barriers	Limited supporting infrastructure	Long asset replacement cycles	High capital costs	Alternative clean competitors	Limited commercial models or projects	On-board storage constraints	Requires carbon feedstock	High cost of hydrogen fuel	
			easy to overcome		many decades		CCUS may be competitive		than aircrafts			
Industrial feedstock	Ammonia production			Hydrogen storage and transport	Industrial facilities are relatively long-lived (but green ammonia only requires partial replacement)	Equipment is expensive but only requires partial replacement	Biofuels could be competitive	Few commercial projects		Urea production (55% of ammonia) requires carbon	Feedstock intensive	Requires hydrogen storage
	Methanol production	Requires some catalyst advances		Hydrogen storage and transport	Industrial facilities are relatively long-lived (but green methanol only requires partial replacement)	Equipment is expensive but only requires partial replacement	Biofuels could be competitive	Few commercial projects		Requires carbon to produce methanol	Feedstock intensive	Requires hydrogen storage
	Steel production	In pilot phase	Standards uncertain but likely easy to overcome	Hydrogen storage and transport	Steel plants have very long lives	Steel plants are very expensive to set up	CCUS may be competitive	In pilot phase		Requires carbon to produce steel	Feedstock intensive	Requires high temperature heat
Heating	High temperature heat	In pilot phase	Standards uncertain but likely	Hydrogen storage and transport	Boilers/furnaces can be	Boilers/furnaces are expensive	Biofuels or advanced electric	In pilot phase			Combustion is fuel intensive	Alternatives may be

Category	End-use	General barriers and risks						Other specific barriers				
		Immature technology	**High regulatory barriers**	**Limited supporting infrastructure**	**Long asset replacement cycles**	**High capital costs**	**Alternative clean competitors**	**Limited commercial models or projects**	**On-board storage constraints**	**Requires carbon feedstock**	**High cost of hydrogen fuel**	
		🟧	🟨 easy to overcome	🟧	🟧 used for decades	🟧 to set up or retrofit	🟧 heating may be competitive	🟥			🟧	🟧 more competitive Retrofitting may increase nitrous emissions
Energy and electricity systems[29]	Demand response			🟥 Hydrogen production facilities								
	Large-scale storage	🟧 In pilot phase or R&D phase (depending on facility)	🟧 Standards uncertain and may be difficult to overcome	🟥 Hydrogen transport and electricity generation		🟥 Scale energy storage likely very expensive to establish	🟧 Various large scale energy storage schemes may be competitive	🟧 Range of existing projects but not at scale Other options in R&D phase		🟧 Energy-dense hydrocarbon fuels (from hydrogen) may be required in some locations		

Note: Red indicates a very significant barrier that is unlikely to be overcome soon and is critical to uptake. Orange indicates a moderate barrier that is likely to be overcome and is critical to uptake. Yellow indicates a minor barrier that is likely to be overcome soon or is not highly relevant to uptake. Blank indicates that there is no barrier.
Source: Castalia analysis; Abbreviations: CCUS, Carbon capture, utilization, and storage; SAF: Sustainable aviation fuels

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[29] Demand response and energy security are complementary business models, not end-use applications

Heavy trucks and buses and specialty vehicles

Heavy land vehicles, specifically large trucks, are likely to be an early end-use application because technology is advanced. Supporting the adoption of hydrogen-powered heavy land vehicles can create demand for hydrogen production at scale, even at relatively low volumes or levels of adoption. A fleet of 80 vehicles[30] travelling 50km per day would be enough demand for hydrogen to sustain a one-megawatt (MW) hydrogen plant.[31] This scale is likely achievable for even the smallest countries. However, other factors also limit uptake. For example, the suitability of the road network, the ability of the country to domestically produce hydrogen, import options, and high upfront investments.

Heavy land vehicle demand will likely be a key justification for scale hydrogen production. Table A.7 describes technological barriers and risks that might limit the uptake of hydrogen in heavy land vehicle applications.

Table A.7: Technological barriers and risks for heavy land vehicles

Barrier or risk	End-use	Description
Immature technology	▪ Specialized vehicles	▪ Not as advanced as trucks and buses, but are being developed
High regulatory barriers	▪ Specialized vehicles	▪ Experience safety concerns in some industries
Limited supporting infrastructure	▪ Heavy trucks and buses	▪ Require refueling and service network[32] which does not exist or is scarce in most countries
	▪ Specialized vehicles	▪ Require storage and transport options, which are currently limited
Long asset replacement cycles	▪ Heavy trucks and buses	▪ Users may not want to replace vehicles before the end of useful life, meaning turnover could take a long time if it is only done on a cost basis[33]

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[30] An estimate of the number of vehicles necessary can be calculated by the daily production divided by daily demand, that is, the product of the fuel economy and the average distance travelled

[31] Assumptions for this calculation:

- 1MW hydrogen electrolysis plant can produce up to 400kg of green hydrogen per day
- Fuel economy of a hydrogen fuel powered bus is approximately 0.1kg hydrogen per km
- Daily average distance travelled by a heavy land vehicle varies by country. A conservative estimate is 50 km per day

D. W. Pederzoli, C. Carnevali, R. Genova, M. Mazzucchelli, A. Del Borghi, M. Gallo, L. Moreschi (2022), Life cycle assessment of hydrogen-powered city buses, SN Applied Sciences, 4, 57 (2022), DOI: https://doi.org/10.1007/s42452-021-04933-6

[32] Service network includes technical capabilities for servicing hydrogen vehicle fleet and refueling network, which might not exist in-country, or might have limited capacity.

[33] The fleet turnover rate of heavy land vehicles is approximately 15 years, which could be slightly longer in developing countries. Zen Clean Energy Solutions (2021).

Barrier or risk	End-use	Description
		▪ Most fossil fuel trucks and buses can be used for around a decade
	▪ Specialized vehicles	▪ Specialized vehicles have varied lives, but are usually long
High capital costs	▪ Heavy trucks and buses	▪ Somewhat expensive
	▪ Specialized vehicles	▪ Usually expensive
Alternative clean competitors	▪ Heavy trucks and buses	▪ EVs may be competitive for lower end of heavy vehicle weight class ▪ Other low-carbon heavy land vehicles or alternative fuels are in development (for example battery EV trucks (B-Evs) and drop-in biofuels), which could be more economical than hydrogen-powered vehicles
Limited commercial models or projects	▪ Heavy trucks and buses	▪ Not as many models of hydrogen-powered heavy trucks and buses as Evs ▪ More demand of vehicles than there is supply.[34] Gap between supply and demand could delay uptake in developing countries ▪ Developed countries are more likely to receive vehicles first because they can pay high prices (and have been on waitlists).[35]
	▪ Specialized vehicles	▪ Not yet available for niche vehicles
High cost of hydrogen fuel	▪ Heavy trucks and buses and specialized vehicles	
Other specific barriers	▪ Heavy trucks and buses and specialized vehicles	▪ Increased demand from heavy land vehicles is unlikely without adequate supply, while adequate supply is unlikely to emerge without demand from heavy land use vehicles

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[34] Castalia (2021), personal communication with hydrogen stakeholders. Heavy trucks are commercially available from companies including Hyzon Motors and Hyundai, and are being trialed by other companies such as Toyota. Specialty vehicles also in development and some (for example forklifts) are commercially available.

Hydrogen-powered EVs use the same drive train platform as B-EVs (except for the fuel cell). Barriers to scale production are confined to key components only, that is, the fuel cell and hydrogen storage components of the vehicle (not the electric vehicle drive system or overall chassis and body).

[35] Castalia modeling suggests that uptake in heavy land vehicles in least developed countries in Asia is possible from 2030 if there are incentives, or could be slightly delayed without

Note: Red = high barrier, orange = medium barrier, yellow = minor barrier. Full methodology outlined in A.3
Source: Castalia analysis

Long-haul aviation

Hydrogen will likely to be used in long-haul aviation applications after 2035; however, it is not clear what the preferred technology will be (for example, combusted, in a hybrid HFC-combustion aircraft or used as an input to Synthetic Sustainable Aviation Fuel (SAF)). Table A.8 describes technological barriers and risks that might limit the uptake of hydrogen in long-haul aviation applications.

Table A.8: Technological barriers and risks for long-haul aviation

Barrier or risk	Description
Immature technology	▪ Technology remains in R&D phase
High regulatory barriers	▪ Likely high safety and certification requirements
Limited supporting infrastructure	▪ Requires fueling and service networks and hydrogen storage and transport, which are scarce
Long asset replacement cycles	▪ Very long and potentially mismatched aircraft lifecycles
High capital costs	▪ Aircrafts are very expensive
Alternative clean competitors	▪ Biofuels may be competitive for SAFs
Limited commercial models or projects	▪ In R&D phase
Onboard storage constraints	▪ Highly space constrained: hydrogen may displace passenger or cargo volume
Requires carbon feedstock	▪ SAFs require sustainable carbon feedstock
High cost of hydrogen fuel	▪ Likely very fuel intensive

Note: Red = high barrier, orange = medium barrier, yellow = minor barrier. Full methodology outlined in A.3
Source: Castalia analysis; Abbreviations: SAF, Sustainable Aviation Fuel

Maritime vessels

Ammonia-powered ships are likely to a commercially available after 2030 onwards because technology is still developing and being proven.[36] Table A.9 describes technological barriers and risks that might limit the uptake of hydrogen in maritime vessel applications.

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[36] Other hydrogen-powered or hydrogen-derivative powered ships are not competitive with viable low-carbon alternatives, so they have been removed from this analysis.

Table A.9: Technological barriers and risks for maritime vessels

Barrier or risk	Description
Immature technology	🟧 ▪ In pilot phase.[37]
High regulatory barriers	🟨 ▪ Maritime guidelines and storage regulations for hydrogen fuel and technologies need to be updated to take into account risks such as toxicity and combustion
Limited supporting infrastructure	🟧 ▪ Require bunkering and service infrastructure, which is currently limited ▪ Existing ammonia terminals and storage facilities can be repurposed
Long asset replacement cycles	🟥 ▪ Long haul ships can be used for many decades
High capital costs	🟧 ▪ Very expensive vessels
Alternative clean competitors	🟥 ▪ Electric ferries are competitive
	🟨 ▪ Biofuels, synthetic fuels, or CCUS may be competitive
Limited commercial models or projects	🟥 ▪ In pilot phase
Onboard storage constraints	🟧 ▪ Space constrained but less so than aircrafts
High cost of hydrogen fuel	🟨

Note: Red = high barrier, orange = medium barrier, yellow = minor barrier. Full methodology outlined in A.3
Source: Castalia analysis; Abbreviations: CCUS, Carbon capture, utilization, and storage

Industrial feedstock

Hydrogen could possibly replace existing fossil fuel feedstocks (such as natural gas and oil) that are currently used in industrial processes—hydrogen feedstock may be utilized for ammonia and methanol production by 2030, and for steel production after 2030. These end-use applications are only likely to emerge if the industrial sector is required to decarbonize and other lower-cost production methods are not found.

Table A.10 describes technological barriers and risks that might limit the uptake of hydrogen as an industrial feedstock. A key barrier is the cost for industrial feedstocks in the chemical and refining industries where hydrogen is essential. In petrochemical production such as methanol, vast quantities of clean hydrogen plus a readily available source of carbon dioxide would be required to replace the current fossil gas-based process completely. Gray or brown hydrogen from methane or other fossil fuel is considerably cheaper. The use of clean hydrogen is in the very early stages of development, and given the scale of demand, the challenges are significant.

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[37] Vessels are still in development or are being trialed. Some vessels, such as NYK Group's ammonia-fuel ready LNG-fueled vessel.

Table A.10: Technological barriers and risks for industrial feedstock

Barrier or risk	End-use	Description
Immature technology	Methanol production	Requires some catalyst advances
	Steel production	In pilot phase
High regulatory barriers	Steel production	Standards are uncertain but likely easy to overcome
Limited supporting infrastructure	Ammonia, methanol, and steel production	Hydrogen storage and transport is required, but is currently limited
Long asset replacement cycles	Ammonia and methanol production	Industrial facilities are relatively long-lived (but green ammonia only requires partial replacement)
	Steel production	Steel plants have very long lives
High capital costs	Ammonia and methanol production	Equipment is expensive but only requires partial replacement
	Steel production	Steel plants are very expensive to set up
Alternative clean competitors	Ammonia and methanol production	Biofuels could be competitive
	Steel production	CCUS may be competitive
Limited commercial models or projects	Ammonia and methanol production	Few commercial projects
	Steel production	In pilot phase
Requires carbon feedstock	Ammonia production	Urea production (55% of ammonia) requires carbon
	Methanol production	Requires carbon to produce methanol
	Steel production	Requires carbon to produce steel
High cost of hydrogen fuel	Ammonia, methanol, and steel production	Feedstock intensive
Other specific barriers	Ammonia and methanol production	Requires hydrogen storage
	Steel production	Requires high-temperature heat

Note: Red = high barrier, orange = medium barrier, yellow = minor barrier. Full methodology outlined in A.3
Source: Castalia analysis; Abbreviations: CCUS, Carbon capture, utilization, and storage

High-temperature heat

Hydrogen could also be used for high-temperature heat to decarbonize the production of goods such as cement, wood, pulp and paper, petroleum, and rubber. This technology is still developing and is unlikely to be commercially available before 2030. This end-use application is only likely to emerge if the industrial sector is required to decarbonize and other lower-cost production methods are not found.

Table A.11 describes technological barriers and risks that might limit the uptake of hydrogen for high-temperature heat. Overcoming these barriers and risks will be challenging. The relative cost of alternative energy storage options appears to rule out significant investment in large scale hydrogen storage, except in locations with existing natural features like salt caverns or gas wells.

Table A.11: Technological barriers and risks for high-temperature heat

Barrier or risk	Description
Immature technology	▪ In pilot phase
High regulatory barriers	▪ Standards are uncertain but likely easy to overcome
Limited supporting infrastructure	▪ Hydrogen storage and transport is required, but is currently limited
Long asset replacement cycles	▪ Boilers and furnaces can be used for decades
High capital costs	▪ Boilers and furnaces are expensive to set up or retrofit
Alternative clean competitors	▪ Biofuels or advanced electric heating may be competitive
	▪ CCUS may be competitive
Limited commercial models or projects	▪ In pilot phase
High cost of hydrogen fuel	▪ Combustion is fuel intensive
Other specific barriers	▪ Alternatives likely more competitive ▪ Retrofitting may increase nitrous emissions

Note: Red = high barrier, orange = medium barrier, yellow = minor barrier. Full methodology outlined in A.3
Source: Castalia analysis; Abbreviations: CCUS, Carbon capture, utilization, and storage

Demand response

Demand response is a viable business model for a hydrogen producing firm, where there is domestic demand elsewhere in the economy. No barriers or risks specific to demand response are present. Instead, demand response is likely to emerge in the short- to medium-term as hydrogen production scales up.

Large-scale storage

Large-scale storage of hydrogen for energy security is a viable business model for a hydrogen producing firm, if the country also has appropriate storage facilities, such as salt caverns, aquifers, or rock caverns (see discussion in Section C.3). Table A.12 describes technological barriers and risks that might limit the uptake of hydrogen for large-scale storage.

Table A.12: Technological barriers and risks for large-scale storage

Barrier or risk	Description
Immature technology	▪ In pilot phase or R&D phase (depending on facility) ▪ Salt caverns are the most viable underground storage option, but they are rare.[38] ▪ More common underground storage facilities, such as aquifers and rock caverns, but have varying suitability for long-term storage, such as requiring purification before use and limited energy efficiency
High regulatory barriers	▪ Standards are uncertain but likely easy to overcome
Limited supporting infrastructure	▪ Requires hydrogen transport and electricity generation (at scale), which is currently limited
High capital costs	▪ Scale energy storage likely very expensive to establish.[39]
Alternative clean competitors	▪ Various large scale energy storage schemes may be competitive
Limited commercial models or projects	▪ Range of existing projects but not at scale ▪ Other options in R&D phase
Required carbon feedstock	▪ Energy-dense hydrocarbon fuels (from hydrogen) may be required in some locations

Note: Red = high barrier, orange = medium barrier, yellow = minor barrier. Full methodology outlined in A.3
Source: Castalia analysis

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[38] Six salt caverns are currently used to store hydrogen (in Texas, United States, and Teesside, United Kingdom), and the viability of other salt caverns is currently being explored.

Ongoing pilot projects include: https://www.cedigaz.org/underground-gas-storage-in-the-world-2020-status/; Vattenfall, Swedish steelmaker SSAB, and Swedish state-owned miner LKAB—https://www.pv-magazine.com/2022/07/14/swedens-first-rock-cavern-for-green-hydrogen-storage-now-ready-to-operate/

[39] Project developers are drawing on expertise and learnings from procedures from storing natural gas and apply this to large-scale hydrogen storage.

Appendix B: Detailed assessment of hydrogen production

This Appendix provides a detailed assessment of engagement points in clean hydrogen production. It outlines the analytical framework and analyses used to identify countries with potential in clean hydrogen production. The analysis was undertaken in three main parts:

- Assessing business models for hydrogen production (B.1)
- Assessing countries with potential for domestic hydrogen production, based on their renewable energy endowment and potential domestic demand for hydrogen (B.2)
- Analyzing technology readiness of hydrogen production technologies and examining barriers and risks in hydrogen production (B.3).

B.1 Assessing business models for hydrogen production

Basic business models for hydrogen production were assessed using extensive primary and secondary research and analysis. This research and analysis indicated that there are two basic business models for hydrogen production:

- **Scale-production**—production at scale at a centralized location, with distribution to end-users via truck, rail, or pipeline. Scale production benefits from lower capital costs per unit, but higher distribution costs.
- **Distributed production**—production at smaller volumes where end users take hydrogen directly from the production site. Smaller volume production has higher capital costs per unit, but no (or low) distribution costs.

Detailed discussion of these two business models is provided in Section C.3.

B.2 Assessing hydrogen production potential of countries

This section outlines the approach to determining countries with high potential to produce hydrogen at scale. Countries that have high potential to produce hydrogen should have the:

- Ability to produce hydrogen (capacity factors).
- Willingness to produce hydrogen (priority factors).

Table B.1 below summarizes the information collected for analyzing each country's hydrogen production potential. A range of sources was used to answer the questions, including data and analysis by the Energy Sector Management Assistance Program

(ESMAP), IRENA, and the Pacific Northwest National Laboratory. These resources have some limitations, but they are unlikely to impact the results of this study.[40]

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[40] Key potential limitations include low model granularity, poor model behavior, transient factors, and lack of verification. Low model granularity refers to the low resolution of the modelling, which could impact the accuracy for specific sites. Poor model behavior refers to potentially breakdown in model results near highly complex terrain. Transient factors refer to highly complex and variable factors that may impact renewable energy potential, such as microclimates, aerosols, or reflective surfaces. Lack of verification refers to an absence of verified field results in certain regions. However, since the analysis in this section focuses on the country level, these limitations are likely to have negligible impact.

Modelled results should also be interpreted carefully. Modelled results do not indicate the total amount of renewable energy resources available to each country but serve as an indicator of a country's renewable energy potential compared against other countries and against benchmarks. Some studies measure absolute potential (independent of technical, economic, financial, and social viability), while others incorporate these factors to various extents. For this reason, results should be interpreted narrowly and within the category only.

Table B.1: Research questions for hydrogen production potential analysis

Theme	Question	Information captured	Information source	Notes
Capacity factors	What is the country's renewable energy potential for each of the four main renewable resources (solar, wind, hydropower, and geothermal)?	▪ Solar—high, medium, or low based on practical output.[41] ▪ Wind—high, medium, or low based on mean power density.[42] ▪ Hydropower—high or low based on mix of existing classification.[43] ▪ Geothermal—high or low based on existing capacity.[44]	▪ Solar—Global Solar Atlas.[45] ▪ Wind—Global Wind Atlas.[46] ▪ Hydropower—IRENA,[47] Delft University of Technology,[48] Pacific Northwest National Laboratory.[49] ▪ Geothermal—United Nations University.[50] and ThinkGeoEnergy.[51]	Countries that do not have access to renewable energy resources are unlikely to produce green hydrogen competitively

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[41] Thresholds sourced from ESMAP (2020), Global Photovoltaic Power Potential by Country, over 4.5 is high, between 3.5 and 4.5 is medium, and below 3.5 is low, available: https://documents1.worldbank.org/curated/en/466331592817725242/pdf/Global-Photovoltaic-Power-Potential-by-Country.pdf

[42] Thresholds sourced from National Renewable Energy Laboratory, over 600 is high, between 300 and 600 is medium, and below 300 is low. Adapted version available: http://web.mit.edu/wepa/WindPowerFundamentals.A.Kalmikov.2017.pdf

[43] The classification used for hydropower in this study combines information from several sources. These sources do not always agree, so some judgement was applied.

[44] Existing geothermal capacity provides a good proxy for geothermal potential. It is difficult to measure geothermal potential directly because the identification of geothermal sites is expensive. Countries that are not already using geothermal energy are unlikely to pursue it at scale in the medium-term. Source: IRENA

[45] Global Solar Atlas, 90th percentile level one practical output, available: https://globalsolaratlas.info/map. The analysis in this section uses 90th percentile potential (that is, the land with the top ten percent highest potential) since only the most promising resources are likely to be developed.

[46] Global Wind Atlas, 90th percentile mean power density at 100m, available: https://globalwindatlas.info/

[47] IRENA (2022), Renewable Energy Capacity Statistics 2022, available: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/Apr/IRENA_RE_Capacity_Statistics_2022.pdf

[48] O. Hoes, LJJ, Meijer, R. van der Ent, N. van de Giesen (2017), Systematic high-resolution assessment of global hydropower potential, PLoS ONE, DOI: https://doi.org/10.1371/journal.pone.0171844

[49] Y. Zhou, M. Hejazi, S. Smith, J. Edmonds, H. Li, L. Clarke, K. Calvin, A. Thomson (2015), A comprehensive view of global potential for hydro-generated electricity, Energy Environ. Sci., 2015, 8, 2622, DOI: 10.1039/c5ee00888cc

[50] United Nations University (2013), Geothermal Energy in Developing Countries and the MDGS, available: https://unu.edu/publications/articles/geothermal-energy-in-developing-countries-and-the-mdgs.html

[51] ThinkGeoEnergy (2021), ThinkGeoEnergy's Top 10 Geothermal Countries 2020—installed power generation capacity (MWe), available: https://www.thinkgeoenergy.com/thinkgeoenergys-top-10-geothermal-countries-2020-installed-power-generation-capacity-mwe/

Theme	Question	Information captured	Information source	Notes
	Is the country likely to have surplus renewable energy potential to produce hydrogen?	High or low based on the number of renewable resources available to a country.[52]	N/A	Countries that have limited access to renewable energy may not have excess capacity to produce green hydrogen
Priority factors	Does the country's population have high rates of electricity access?	High or low based on the country's electrification rate.[53]	World Bank Global Electrification Database.[54]	Countries with low electrification rates are more likely to prioritize improving access to electricity over producing green hydrogen
	Is the country's electricity generated from mostly renewable resources?	High or low based on the country's proportion of electricity generated from renewable sources.[55]	Our World in Data.[56]	Countries that generate electricity predominantly from non-renewable sources are more likely to prioritize decarbonizing their grid over producing green hydrogen
	Has the country stated an intent to produce and export green hydrogen?	Yes or no based on classification by Castalia	Castalia	Countries that have published a hydrogen strategy and the strategy includes an intent to produce green hydrogen.[57]
Other factors	Are there any other factors that could impede this country from producing hydrogen at scale?	Yes or no based on the country's population size, population density, or adverse political situations	World Bank	▪ Countries that have very small populations may not have institutional capacity to produce green hydrogen at scale ▪ Countries with high population density may not be able to fully develop renewable energy resources ▪ Countries with adverse political situations may not prioritize exporting hydrogen

Source: Castalia

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[52] Countries with access to at least three medium-rated renewable resources (or equivalently, one high and one medium) are rated high.

[53] Countries with electrification rate over 99 percent are rated high. Otherwise, they are rated low.

[54] World Bank, Global Electrification Database, available: https://data.worldbank.org/indicator/EG.ELC.ACCS.ZS

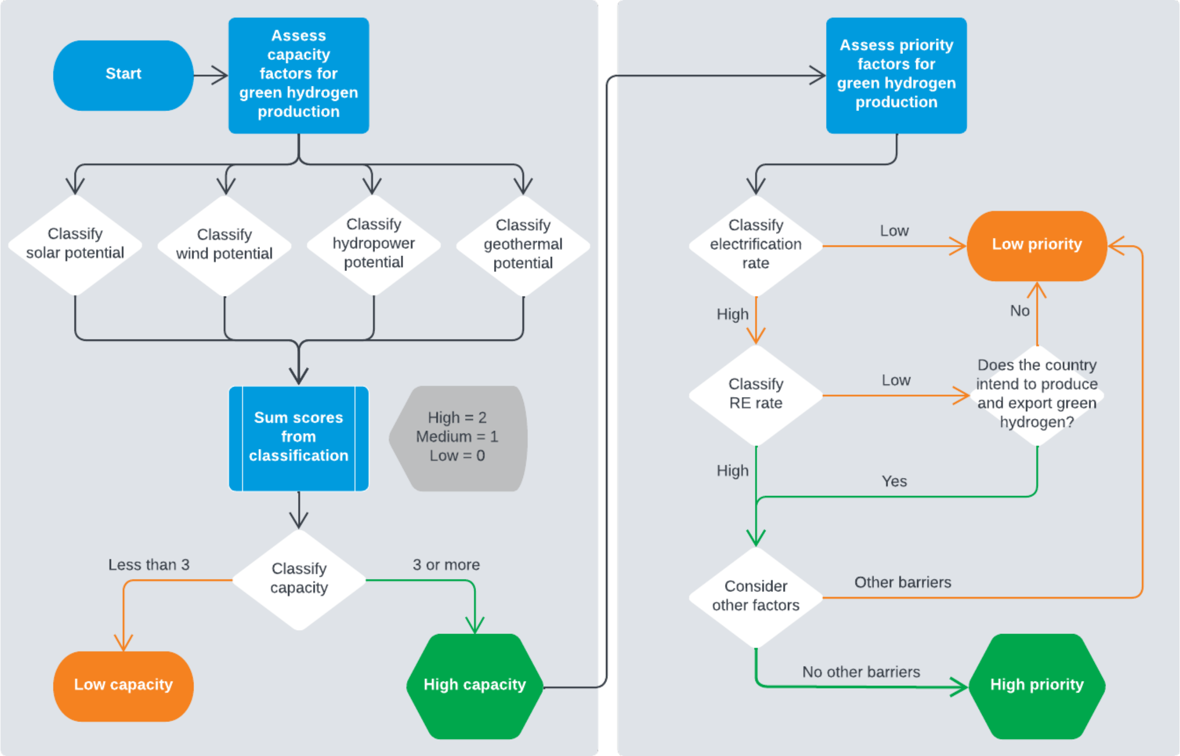
[55] Countries generating over half of their electricity from renewable sources are rated high. Otherwise, they are rated low.

[56] Our World in Data, Renewable Energy, available: https://ourworldindata.org/renewable-energy

[57] These countries are likely to prioritize hydrogen, if they have the capacity to do so.

This information was then analysed to determine the production potential of countries. Figure B.1 provides an overview of the analytical approach.

Figure B.1: Overview of hydrogen production potential analysis



Source: Castalia; Abbreviations: RE, Renewable energy

B.3 Analyzing technology readiness of and barriers and risks to investable hydrogen production segments

Analyzing the TRL of and barriers and risks in hydrogen production informed the investment approach discussed in Section 3.

Determining technology readiness of hydrogen production

The readiness of hydrogen production over the short-to-medium term was analyzed. The same methodology discussed in A.3 was used to undertake this analysis. The results of the analysis are provided in Table B.2.

Table B.2: Technology readiness timeline of clean hydrogen production

	Now	Short-term	Medium-term	Long-term
Large-scale production	8	9	9	9
Distributed production	9	9	9	9

Examining barriers and risks to hydrogen end-use hydrogen production

This section outlines the technological barriers and risks in hydrogen production. The same methodology discussed in A.3 was used to undertake this analysis.

Various barriers and risks currently limit the commercialization of clean hydrogen production (both scale and distributed). The key barriers and risks are high production costs (including compared to alternative production methods), and uncertainty about the competitiveness of other energy sources. Some of these can be overcome with technological developments, such as advances in clean hydrogen production, particularly through improving the efficiency of the electrolysis process, and lowering the costs of the inputs. An overview of these barriers and risks are presented in Table B.3, while more detailed discussion is provided below.

Table B.3: Technological barriers and risks in hydrogen production

Category	**General barriers and risks**				
	High production costs	**Slow scale-up of renewable electricity**	**Hydrogen competitors**	**Alternative clean competitors**	**Off-take uncertainty**
Scale and distributed production	▪ High input costs and potentially short supply of materials used for PEM electrolysis ▪ High operating and maintenance costs of alternative production methods, e.g., alkaline electrolyzers and anion exchange membrane (AEM) electrolysis ▪ Other production methods, e.g., oxide electrolyzers (high electrical efficiency) and membrane free electrolysis (lower capital costs) are in early stages of development ▪ Low energy efficiency of converting electricity to hydrogen ▪ Optimal electrolyser development is still ongoing (so costs are likely to decrease and	▪ Slow scale-up on renewable electricity, resulting in limited supply of renewable electricity for hydrogen production and high unit price	▪ Technological advances in competing hydrogen production techniques (blue hydrogen and CCUS) could undermine investment in clean hydrogen production	▪ Battery electric technologies and biofuels are competing for fuel sources to hydrogen as an energy carrier in many end-use applications ▪ May reduce competitiveness of hydrogen	▪ Chicken and egg problem ▪ No global hydrogen market

Category	General barriers and risks				
	High production costs	**Slow scale-up of renewable electricity**	**Hydrogen competitors**	**Alternative clean competitors**	**Off-take uncertainty**
	efficiency is likely to increase)				

Note: Red = high barrier, orange = medium barrier, yellow = minor barrier. Full methodology outlined in A.3
Source: Castalia analysis; Abbreviations: CCUS, Carbon capture, utilization, and storage; PEM, Polymer Electrolyte Membrane

High production costs need to fall significantly for hydrogen to be an economically viable fuel

The high cost of production hydrogen, largely due to high capital costs and production inefficiencies, is a key barrier to commercializing hydrogen production. Production costs for clean hydrogen need to fall substantially before it can be economical compared to other energy sources. Clean hydrogen production is currently significantly more expensive than conventional gray or blue hydrogen production, outlined in

Table B.4 shows that, currently, green hydrogen production costs approximately USD4-6 per kg, but costs are expected to fall to around (or under) USD2 per kg in 2030 for the most competitive hydrogen production locations.[58] By 2050, most sources estimate the green hydrogen could cost USD1 per kg to produce.

Table B.4: Global cost of hydrogen production overtime (estimated) (US per kg of hydrogen)

Hydrogen form		Year			
		Current (actual)	**2030 (est.)**	**2040 (est.)**	**2050 (est.)**
Gray hydrogen		0.7-2.2[59]	May increase depending on carbon price		
Blue hydrogen[60]	Production	1-1.8			
	Capex (including CCUS)	0.6			
	Total	1.5-2.30[61]	1.35-2.07[62]	Unlikely to fall below 1[63]	
Green hydrogen	IRENA[64]	2-5	1.5-4	1-3.7	>1-3.3[65]
	BloombergNEF[66]	<4	>2 (most locations)		>1
	Castalia	4	3.4	2.9	2.4

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[58] https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Nov/IRENA_Green_Hydrogen_breakthrough_2021.pdf?la=en&hash=40FA5B8AD7AB1666EECBDE30EF458C45EE5A0AA6#:~:text=The%20electrolyser%20investment%20cost%20for,over%20the%20period%202020%2D2050; https://www.bloomberg.com/news/articles/2021-12-16/market-risks-white-elephant-in-push-for-blue-hydrogen-bnef-view?leadSource=uverify%20wall

[59] https://www.energy-transitions.org/wp-content/uploads/2021/04/ETC-Global-Hydrogen-Executive-Summary-Short.pdf

[60] Assumes steam methane reformation with CCUS. https://www.globalccsinstitute.com/wp-content/uploads/2021/04/Circular-Carbon-Economy-series-Blue-Hydrogen.pdf. Source also includes other blue hydrogen estimates

[61] https://www.globalccsinstitute.com/wp-content/uploads/2021/04/Circular-Carbon-Economy-series-Blue-Hydrogen.pdf

[62] Expected to fall by 10 percent. Bloomberg (2021), https://www.bloomberg.com/news/articles/2021-12-16/market-risks-white-elephant-in-push-for-blue-hydrogen-bnef-view?leadSource=uverify%20wall

[63] “Natural gas prices would have to fall to implausibly low prices, near zero, for blue hydrogen to cost USD1 per kilogram.” Bloomberg (2021), https://www.bloomberg.com/news/articles/2021-12-16/market-risks-white-elephant-in-push-for-blue-hydrogen-bnef-view?leadSource=uverify%20wall

[64] IRENA (2020), https://www.irena.org/publications/2020/Dec/Green-hydrogen-cost-reduction

[65] Range indicates cost under low electricity price (USD20/MWh) and high electricity price (USD65/MWh)

[66] BloombergNEF (2021), https://www.bloomberg.com/news/articles/2021-12-16/market-risks-white-elephant-in-push-for-blue-hydrogen-bnef-view?leadSource=uverify%20wall

	Year			
Hydrogen form	**Current (actual)**	**2030 (est.)**	**2040 (est.)**	**2050 (est.)**
Renewable ammonia[67]	0.72-1.40	0.48 (ideal locations)[68]		0.31-0.61
LOHC[69]	1.39-4.08	Expected to decrease		

Note: Est. refers to estimated costs
Source: IRENA, BloombergNEF, Castalia, EU, PV Magazine, H2B, Henry Royce Institute, ETC, Global CCS Institute; Abbreviations: CCUS, Carbon capture, utilization, and storage

Technological developments in hydrogen production are expected to lead to reduction in the capital costs of production facilities, leading to more efficient electricity and water use, and lower energy losses. However, these production options are not yet available. It is inherently very difficult to estimate the timeframes for technological breakthroughs. A discussion of these technological developments is provided below.

Establishing alternative production methods that reduce use of expensive materials

Materials used for polymer electrolyte membrane (PEM) electrolysis are expensive and increase the cost of clean hydrogen production. PEM electrolyzers use catalysts from rare platinum group metals (PGM) (mainly iridium and platinum) at both the anode and cathode. These materials help to reduce energy consumption and to withstand harsh conditions in the electrolyzers. These metals are costly[70] and rare.[71] Ongoing R&D aims to reduce electrolyzer costs over time. PEM electrolyzer manufacturers are developing solutions that reduce the amount of PGM materials used, while maintaining (or improving) electrolyzer efficiency and durability.[72] Research is also looking at alternative materials that can be used

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[67] Hybrid plants (i.e. co-production of fossil-based hydrogen and renewable hydrogen) are expected to be lower, at USD0.3-0.4 per kg in 2025, falling to around USD0.25 per kg by 2050. IRENA (2022), https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/May/IRENA_Innovation_Outlook_Ammonia_2022.pdf.

[68] Locations with excellent solar and wind resources

[69] EU (2019), https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5c551f4c2&appId=PPGMS

[70] The cost of platinum is around USD1,100 per ounce, while the cost of iridium is approximately USD1,700 per ounce. For comparison, the cost of gold is around USD1,900 per ounce. Cost of pure materials make up approximately 40 percent of total cost of PEM electrolyzer. https://www.h2bulletin.com/platinum-hydrogen-economy-wpic/; https://www.royce.ac.uk/content/uploads/2021/06/Royce-Hydrogen-PEM-Catalysts-Summary.pdf; https://pv-magazine-usa.com/2020/03/26/electrolyzer-overview-lowering-the-cost-of-hydrogen-and-distributing-its-productionhydrogen-industry-overview-lowering-the-cost-and-distributing-production/#:~:text=A%202018%20study%20by%20Fraunhofer,one%20hour%20at%20around%20%247%2C600

[71] IRENA states that current production of iridium and platinum will only support an approximately 3 gigawatts (GW) to 7.5 GW of annual PEM electrolyzer manufacturing capacity, compared to an estimated annual manufacturing requirement of around 100 GW by 2030. IRENA (2021), https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Nov/IRENA_Green_Hydrogen_breakthrough_2021.pdf?la=en&hash=40FA5B8AD7AB1666EECBDE30EF458C45EE5A0AA6#:~:text=Electrolyser%20costs%20reach%20USD%20130,of%20capacity%20deployed%20by%202050

[72] Castalia recently worked with a confidential client who is developing a technology that reduces the cost of the catalyst coated membrane.

instead of PGM materials. Cost savings can also be achieved by increasing electrolyzer production (economies of scale). IRENA estimates that 1,000 units (or 1MW) per year for PEM electrolyzers enables a 50 percent cost reduction in stack manufacturing.[73]

Alternative hydrogen production methods that avoid the use of such materials are also being developed. For example, alkaline electrolyzers and anion exchange membrane (AEM) electrolysis involve passing negatively charged ions (OH-) through a membrane, which avoids the use of the precious metals required as catalysts in PEM electrolysis. These methods tend to have cheaper capital costs than PEM electrolysis, but higher operating and maintenance costs due to additional parts required for the process (such as pumps for the electrolyte and solution washing). The current capital cost estimate for large stacks (less than 1MW) for alkaline electrolyzers costs is approximately USD270 per Kilowatt electric (kW_e), compared to USD400 per kW_e for PEM electrolyzers.[74] The cost of electrolyzers is set to fall due to scale-up of manufacturing.[75]

Membrane free electrolysis has also been developed. For example, CPH_2 has created a method of production that produces co-mingled hydrogen and oxygen gas streams, and the comingled gas is separated by cryogenic separation. The system utilizes commonly available materials and does not require exotic metals, meaning they have lower capital costs. CPH_2 and Fabrum have partnered to manufacture these hydrogen production systems.[76]

Production efficiency improvements

Improving energy efficiency for converting electricity to hydrogen is a significant cost barrier. Approximately 1 unit of electricity turns into 0.4 units of energy stored as hydrogen.[77] Until hydrogen production efficiency improves, there may also be more economical uses of renewable energy, such as decarbonising electricity production. The next-generation electrolyzers aim to increase conversion efficiency significantly. For example, Australian company Hysata says its new capillary-fed electrolyzer aims to deliver 95 percent overall system efficiency, equivalent to 41.5 kWh per kg of green hydrogen (compared to 75 percent

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[73] IRENA (2021), https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Nov/IRENA_Green_Hydrogen_breakthrough_2021.pdf?la=en&hash=40FA5B8AD7AB1666EECBDE30EF458C45EE5A0AA6#:~:text=Electrolyser%20costs%20reach%20USD%20130,of%20capacity%20deployed%20by%202050.

[74] IRENA (2021), https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Nov/IRENA_Green_Hydrogen_breakthrough_2021.pdf?la=en&hash=40FA5B8AD7AB1666EECBDE30EF458C45EE5A0AA6#:~:text=Electrolyser%20costs%20reach%20USD%20130,of%20capacity%20deployed%20by%202050

[75] https://pv-magazine-usa.com/2020/03/26/electrolyzer-overview-lowering-the-cost-of-hydrogen-and-distributing-its-productionhydrogen-industry-overview-lowering-the-cost-and-distributing-production/#:~:text=A%202018%20study%20by%20Fraunhofer,one%20hour%20at%20around%20%247%2C600

[76] Fabrum (2022)

[77] Castalia analysis.

or less for existing electrolyzer technologies).[78] Other production methods, such as solid oxide electrolyzers, which have high electrical efficiency, are also being explored.[79]

IRENA also states that implementing modular plant designs can also support production efficiency improvements. Power supply represents large efficiency losses at low loads. Modular plant designs, which can be multiplied depending on the project scale, can support efficiency increases.[80]

Technology advances in blue hydrogen are a risk to hydrogen production commercialization

Technological advances in competing hydrogen production techniques could undermine investment in clean hydrogen production. For example, blue hydrogen is currently reliant on 80 percent effective carbon capture technology (meaning some emissions remain). The captured carbon then needs to be stored. Carbon capture and storage (CCUS) is currently viable in specific locations and at high cost. CCUS could develop so it is as low-emissions as green hydrogen (that is, close to zero emissions), and at lower cost. This could limit investments in green hydrogen production in the short-to-medium-term, as investors wait to see which technologies are most competitive.

Competing technologies might reduce the competitiveness of hydrogen

Competing technologies could offer lower cost emissions reductions, which could reduce the competitiveness of hydrogen. Battery electric technologies and biofuels are competing for fuel sources to hydrogen as an energy carrier in many end-use applications. Battery electric and biofuel technologies are mature and readily used in applications such as transport, and biofuel is also used as an industrial feedstock and heat source. However, the competitiveness of battery electric technology is limited due to having lower-energy density and longer refueling (recharging) times, while biofuels are limited by supply and cost. If these technologies become more advanced and more competitive with hydrogen, and at lower costs, then demand for hydrogen might reduce.

Off-take uncertainty (demand risk) is a barrier to production investment

The scaling up of hydrogen production projects is constrained by off-take uncertainty. Significant capital investment is required to establish hydrogen production plants, and investors are cautious about sinking capital if the return on investment is unclear. At the same time, demand is constrained due to the lack of supply (chicken and egg problem).

A global hydrogen market does not yet exist, and several technical and economic limitations may mean that it might not develop (discussed in more detail in Appendix C). This limits the

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[78] The company plans to have the technology commercialized and up to "gigawatt-scale hydrogen production capacity" by 2025. https://newatlas.com/energy/hysata-efficient-hydrogen-electrolysis/

[79] IRENA (2021), https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Nov/IRENA_Green_Hydrogen_breakthrough_2021.pdf?la=en&hash=40FA5B8AD7AB1666EECBDE30EF458C45EE5A0AA6#:~:text=Electrolyser%20costs%20reach%20USD%20130,of%20capacity%20deployed%20by%202050

[80] IRENA (2022), https://www.irena.org/publications/2022/Apr/Global-hydrogen-trade-Part-II

export and distribution of hydrogen at large scale, which further emphasizes off-take uncertainty.

Appendix C: Detailed assessment of hydrogen logistics

This Appendix provides a detailed assessment of promising engagement points in hydrogen logistics. It outlines the analytical frameworks and analyses used to identify hydrogen logistics engagement points. The analysis was undertaken in three main parts:

- Assessing business models for hydrogen logistics (C.1).
- Assessing countries with promising export potential (C.2).
- Analyzing technology readiness of hydrogen logistics technologies and examining barriers and risks in hydrogen logistics (C.3).

C.1 Assessing business models for hydrogen logistics

Basic business models for hydrogen logistics were assessed using extensive primary and secondary research and analysis. The analysis was undertaken in two main steps. First, the logistics of the hydrogen market were mapped, shown in Table C.1. Second, the advantages and disadvantages of different conversion and storage options, and transport and transfer options, were examined. Key research questions were developed to guide research, outlined in Table C.2:. Detailed discussion of hydrogen logistics business models is provided in Section C.3.

Table C.1: Summary of logistics of hydrogen

	Conversion/reconversion	Storage	Transport	Transfer	Most viable distance and volume
Compressed hydrogen	Compression	Compressed gas storage tanks Underground storage	Truck	Pumped through pipe Dry port	Up to 10 tonnes per day (t/d), under 100 km
			Pipeline	Pumped through pipe Direct to user	Up to 100 t/d, under 1,000 km
Liquid hydrogen	Liquefaction Regasification	Cryogenic tank	Truck[81]	Pumped through liquid dispenser	Up to 10 t/d, around 500-5,000 km
Ammonia	Ammonia synthesis Ammonia cracking	Liquified in isothermal tank	Ship	Pumped through liquid dispenser Port	Over 10 t/d, over 1,000 km
		Compressed	Existing ammonia pipelines	Pumped through pipe Direct to user	Not available
LOHC	Hydrogenation Dehydrogenation	Liquid in existing oil facilities	Ship	Pumped through pipe to port or terminal (existing infrastructure)	Over 10 t/d, over 1,000 km

Source: IRENA (2022); Abbreviations: LOHC, Liquid organic hydrogen carrier

Table C.2: Research questions used in logistics analysis

Logistics area	Research question	Information captured
Conversion and storage	Is the hydrogen form regularly converted and stored at large-scale (that is, is there an existing market)?	Yes or no Record answers to questions

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[81] Tank-trainers by rail are also possible, but is only likely to be competitive with trucked hydrogen where there is existing rail infrastructure to end-users.

Logistics area	Research question	Information captured
	▪ Could the market be scaled? How easily could it be scaled? ▪ What are the challenges to scaling it? ▪ What are the approximate costs of scaling it?	▪ Yes or no ▪ Record answers to questions
	▪ Is it efficient to convert and store hydrogen in this form? How can efficiency be improved?	▪ Yes or no ▪ Record answers to questions
Transport and transfer	▪ Can the transport option currently transport hydrogen, or is new technology required?[82]	▪ Yes or no ▪ Record answers to questions
	▪ Could the market be scaled? ▪ What are the costs of scaling it?	▪ Yes or no ▪ Record answers to questions
	▪ Is it efficient to transport hydrogen using this option, or are energy losses high? ▪ How can efficiency be improved?	▪ Yes or no ▪ Record answers to questions
	▪ At what distances and volumes is this transport option most competitive?	▪ Yes or no ▪ Record answers to questions
	▪ Is there existing infrastructure that could support the transport and transfer of this hydrogen form (e.g., ports, pipelines, terminals)?	▪ Yes or no ▪ Record answers to questions
	▪ If the transport option does not transport hydrogen already, how mature is the technology (e.g., ships)?	▪ Yes or no ▪ Record answers to questions
	▪ What are the approximate costs to repurpose or build the new transfer infrastructure required to facilitate the transport option?	▪ Yes or no ▪ Record answers to questions

Source: Castalia

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[82] For example, existing ammonia ships can continue to transport ammonia and compressed hydrogen can be blended into existing pipelines.

C.2 Assessing countries with promising export potential

This section outlines the analytical framework used to identify countries that are likely to export hydrogen (or transport large volumes of hydrogen domestically) at a competitive price. It is important to note that a global hydrogen market does not yet exist, and several technical and economic limitations may mean that it might not develop. Specifically, hydrogen cannot yet be stored and transported in large volumes, and it is not clear that the costs of transporting hydrogen over large distances will be low enough to be economical compared to hydrogen production closer to the point of use (even if the electricity and other production input costs are higher).[83] If limitations are overcome and an export market emerges, countries that are likely to be competitive at exporting hydrogen should have:

- Access to the infrastructure needed for hydrogen export (such as ports or pipelines).
- Existing experience in exporting hydrogen-like commodities.
- High domestic demand for hydrogen.

Information was collected in a data repository. A range of sources was used to answer the questions.[84]

This analysis builds off the production potential analysis undertaken in Section B.2. That is, countries that have potential for hydrogen production were analyzed further to understand their hydrogen export potential. Table C.3 below summarizes the information collected for analyzing countries' hydrogen export competitiveness. An overview of the analysis is displayed in Figure C.1.

Table C.3: Research questions for hydrogen export competitiveness analysis

Question	Information collected	Notes
Does the country have potential for clean hydrogen production?	Yes, likely, or no, based on analysis undertaken in B.2. If yes, likely, then move onto the next question. If no, then filter-out country	The analytical framework to analyzing country's hydrogen production potential is detailed in B.2
Does the country have access to hydrogen export infrastructure, such as ports or pipelines?	Yes, likely, or no, based on whether a country owns or is likely to have access to a good port or pipeline	Countries with good ports or gas pipelines are the best-positioned to export hydrogen. Countries that are close to ports or pipelines in nearby countries may also be able to export hydrogen competitively

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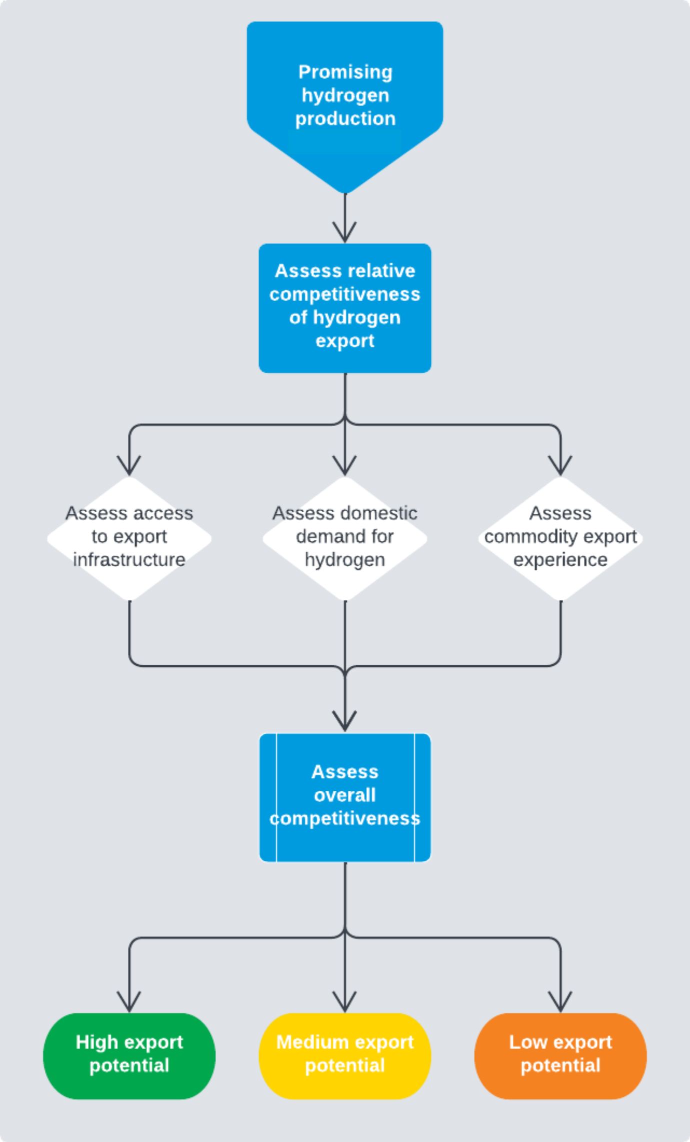
[83] It is far cheaper to transport electricity than it is to transport large volumes of hydrogen.

[84] A key limitation of this approach is that the information gathered may not be exhaustive. The information is often highly qualitative, so some judgement was required to synthesize insights and provide high-level assessments.

Question	Information collected	Notes
Does the country have existing commodity export experience?	Yes or no, based on whether the country exports commodities similar to hydrogen, such as petroleum, natural gas, and ammonia	Countries that export commodities similar to hydrogen are likely to have high technical expertise, and may be able to repurpose existing infrastructure
Is the country likely to have domestic demand for scale production?	Yes or no, based on whether the country is likely to use hydrogen at scale domestically, especially in industry and transport	Countries that have large domestic uses for hydrogen are likely to have first-mover advantage and benefit from economies of scale, relative to countries that have limited domestic uses for hydrogen

Figure C.1: Overview of hydrogen export potential analysis



Source: Castalia

C.3 Analyzing technology readiness of and barriers and risks in hydrogen logistics

Analyzing the TRL of and barriers and risks in hydrogen logistics informed the investment approach, discussed in Section 4.

Determining technology readiness of hydrogen logistics applications

The technology readiness of hydrogen logistics over the short-to-medium term was analyzed. The same methodology discussed in A.3 was used to undertake this analysis. The results of the analysis are provided in Table C.4.

Table C.4: Technology readiness timeline of hydrogen logistics

			Now	Short-term	Medium-term	Long-term
Compression	Conversion		9	9	9	9
	Storage[85]	Natural formations	6	7	8	9
	Transport	Trucks	9	9	9	9
		Repurposed pipelines	6	7	8	9
		New pipelines	9	9	9	9
Liquefaction	Conversion	Liquefaction	8	8	9	9
		Regasification	9	9	9	9
	Storage	Cryogenic tanks	8	8	9	9
	Transport	Trucks	9	9	9	9
Ammonia[86]	Conversion	Ammonia synthesis and liquefaction	9	9	9	9
	Storage	Liquified ammonia tank	9	9	9	9
	Transport	Pipelines	9	9	9	9
		Conventional ships	9	9	9	9
		Ammonia ships	7	8	9	9
LOHC[87]	Conversion	Hydrogenation	7	8	9	9
		Dehydrogenation	7	8	9	9

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[85] Compressed tanks are not a viable solution to storing large volumes of compressed hydrogen because it is much less energy dense than liquid hydrogen and ammonia. Compressed hydrogen on trucks could be viable for short distances.

[86] Ammonia is currently commercially converted, stored, and transported. However, ratings reflect the need for ammonia production to be scaled-up significantly to support hydrogen use.

[87] LOHCs currently rely on oil to be produced and can let out fossil fuels when recycled. Low-carbon solutions are being explored, such as direct air capture (DAC) and using biomass.

			Now	Short-term	Medium-term	Long-term
	Storage	Hydrocarbon facilities	9	9	9	9
	Transport	Conventional ships	9	9	9	9

Abbreviations: LOHC, Liquid organic hydrogen carrier

Examining barriers and risks in hydrogen end-use hydrogen production

This section outlines the technological barriers and risks in hydrogen logistics. The same methodology discussed in A.3 was used to undertake this analysis.

Various barriers and risks currently limit the commercialization of hydrogen logistics. A global hydrogen market does not yet exist, and several technical and economic limitations may mean that it might not develop. Key barriers and risks are large conversion, storage, and transport losses, immature technology, limited commercial models or project variety, high capital costs, and high regulatory standards (among others). An overview of the barriers and risks is provided in Table C.5 below, separated by ‘form’ of hydrogen[88] and logistics category. A more detailed discussion on these technologies and associated barriers and risks is provided below.

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[88] That is, compressed or liquid hydrogen, ammonia, and LOHC.

Table C.5: Current barriers and risks to uptake in hydrogen logistics

Category			General barriers and risks									Other specific barriers
Hydrogen form	**Logistics area**		**Large conversion losses**	**Large storage or transport losses**	**Immature technology**	**Limited commercial models or project variety**	**Low purity**	**Low hydrogen content**	**High capital costs**	**High regulatory standards**	**May involve fossil fuels**	
Compression	Conversion					Scaling-up volume is challenging			But less than other hydrogen conversion processes			
	Storage[89]	Natural formations			Limited suitable sites	Pilot projects in few locations	Purification may be required before use		Storage facilities expected to be costly to transform	Regulatory changes primitive until technology develops		
	Transport	Trucks			Volume constraints in current models	Limited number of trucks available		Unlikely viable beyond regional distances	Costly to purchase		If a fossil fuel powered truck	
		Repurposed pipelines			Repurposing technologies still developing and being piloted	Only viable where pipelines currently exist			Costly to repurpose (but likely less than new pipelines)	Regulation likely to be stringent		Limited availability of existing pipeline Unlikely viable for

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[89] Compressed tanks are not a viable solution to storing large volumes of compressed hydrogen because it is much less energy dense than liquid hydrogen and ammonia. Compressed hydrogen on trucks could be viable for short distances.

Category			General barriers and risks									Other specific barriers
Hydrogen form	**Logistics area**		**Large conversion losses**	**Large storage or transport losses**	**Immature technology**	**Limited commercial models or project variety**	**Low purity**	**Low hydrogen content**	**High capital costs**	**High regulatory standards**	**May involve fossil fuels**	
												intercontinental distances
		New pipelines			Hydrogen-compatible pipes developed, but not widely used	Some pilot projects ongoing			Costly to build	Regulation likely to be stringent (but less than repurposed pipelines)		
Liquefaction	Conversion	Liquefaction	High conversion losses		Converted at small-scale	Scaling up is challenging			Highly costly process			
		Regasification			Reconverted at small-scale	Scaling up is challenging			Costly process			
	Storage	Cryogenic tanks		Experiences losses during storage	Existing storage facilities at small-scale	Large-scale storage options are limited			Highly costly infrastructure	Regulatory charges likely required for large-scale		
	Transport	Trucks		Experiences losses during transport	Volume constraints in current models	Limited number of trucks available			Costly to purchase		If a fossil fuel powered truck	
		Ships		Experiences losses during transport	Technology still developing	In pilot phase			Expected to be extremely costly	Regulation likely to be stringent	If a fossil fuel powered ship	

Category			General barriers and risks									Other specific barriers
Hydrogen form	**Logistics area**		**Large conversion losses**	**Large storage or transport losses**	**Immature technology**	**Limited commercial models or project variety**	**Low purity**	**Low hydrogen content**	**High capital costs**	**High regulatory standards**	**May involve fossil fuels**	
Ammonia	Conversion	Ammonia synthesis and liquefaction	Some conversion losses			Ongoing at small-scale	Low purity compared with other forms		Costly process	Toxic and corrosive		
	Storage	Liquified ammonia tank		Experiences some losses during storage		Additional [71] infrastructure required for global market			Costly to build	Toxic and corrosive		
	Transport	Pipelines				Additional [71] infrastructure required			Costly to build	Toxic and corrosive		Unlikely viable for intercontinental distances
		Conventional ships				Additional ships required for global market			Costly to purchase	Toxic and corrosive	If a fossil fuel powered ship	
		Ammonia ships			Technology still developing	In pilot phase			Expected to be extremely costly	Toxic and corrosive		
LOHC [90]	Conversion	Hydrogenation			Technology still developing	In pilot phase	Low purity, but higher than ammonia	Approx. 4-7%	Costly to convert	Some are toxic and corrosive	Carriers currently rely on oil production	

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[90] LOHCs currently rely on oil to be produced. Low-carbon solutions are being explored, such as direct air capture (DAC) and using biomass.

Category			General barriers and risks									Other specific barriers
Hydrogen form	**Logistics area**		**Large conversion losses**	**Large storage or transport losses**	**Immature technology**	**Limited commercial models or project variety**	**Low purity**	**Low hydrogen content**	**High capital costs**	**High regulatory standards**	**May involve fossil fuels**	
		Dehydrogenation	Some losses occur (0.1% per cycle)		Technology still developing	In pilot phase	Low purity, but higher than ammonia	Approx. 4-7%	Costly to recycle	Some are toxic and corrosive	Small amount of fossil fuels released	
	Storage	Hydrocarbon facilities				Existing oil loading and storage facilities can be used, but are not widely available	Low purity, but higher than ammonia	Approx. 4-7%	Costly to purchase	Some are toxic and corrosive		
	Transport	Ships			Existing ships can be used, but are not widely available	In pilot phase	Low purity, but higher than ammonia	Approx. 4-7%	Costly to purchase	Some are toxic and corrosive	If a fossil fuel powered ship	

Note: Red = high barrier, orange = medium barrier, yellow = minor barrier. Full methodology outlined in A.3

Source: Castalia analysis; Abbreviations: LOHC, Liquid organic hydrogen carrier

Basic business models for hydrogen logistics: large-scale or distributed production

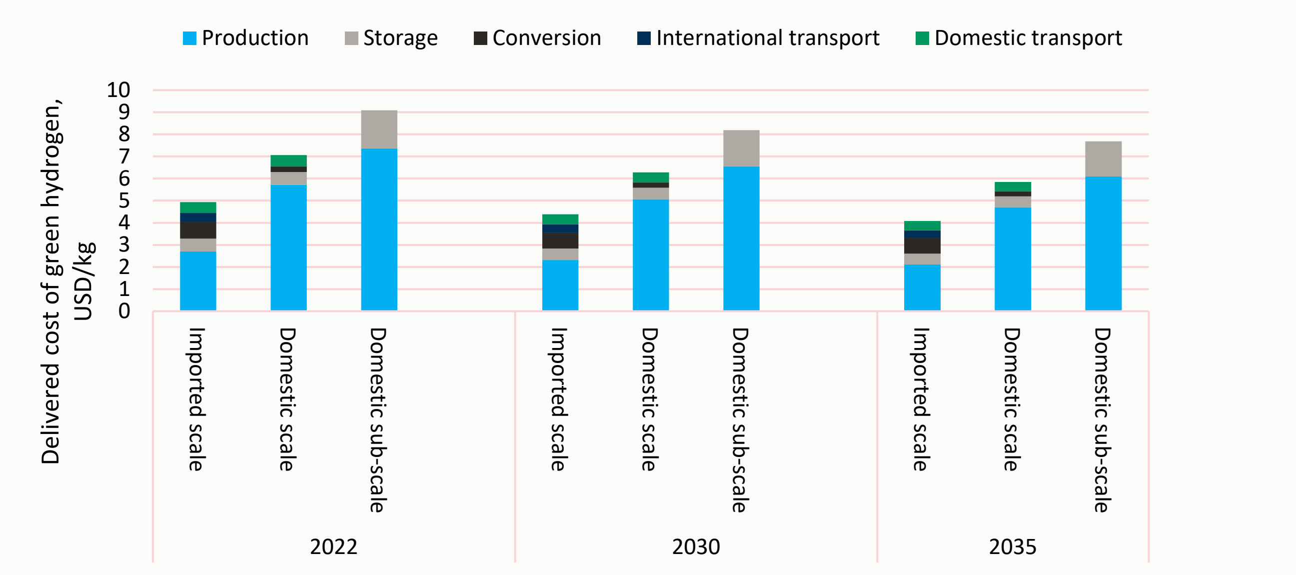
There are two basic business models for hydrogen production, which are important to understanding hydrogen logistics:

- **Centralized production at scale**—large scale with distribution to end-users, for example, truck, rail, pipeline, or ship. Scale production benefits from lower capital costs per unit, but higher distribution costs.
- **Distributed production at sub-scale**—smaller volumes where end users take hydrogen directly from the production site. Smaller volume production has higher capital costs per unit, but no (or low) distribution costs.

There are economies of scale from producing large volumes of hydrogen. Large-scale production can also benefit from lower cost electricity in specific locations, especially if there are abundant renewable energy sources and no transmission and distribution (T&D) costs. Since it is far cheaper to transmit electricity than it is to transport large volumes of hydrogen, large-scale hydrogen production could occur close to the location where off-takers use the fuel. If the hydrogen has to be transported to the end-user, then transport costs are a significant component of the landed cost of hydrogen. There is also significant uncertainty about the technical viability of large-scale hydrogen transport. Distributed production has higher production costs, but lower transport costs because a sub-scale electrolyzer is easier to locate close to hydrogen demand.

Figure C.2 shows the hypothetical cost of producing, transporting, and storing hydrogen at scale and distributed production under different assumptions. Under these assumptions, domestic production at scale is likely to be cheaper than distributed domestic production at sub-scale because the benefits of scale production outweigh the additional costs of conversion and transport. Imported hydrogen may be cheaper in the short-to-medium term because the most competitive locations can produce hydrogen at substantially lower costs, outweighing the additional cost of international transport. However, long-distance transport costs for hydrogen are highly uncertain, and costs depend on progress in both hydrogen and shipping technologies. The modelled cost of shipping liquid hydrogen over 5,000 km is around USD0.4 per kg in addition to conversion costs of around USD0.75 per kg. Importing hydrogen may become less economically competitive if transport costs are higher than expected.

Figure C.2: Cost comparison of producing and transporting centralized and distributed production



Notes: Assuming "Imported scale" is produced at a large scale centralized plant (300MW) with a capacity factor of 25 percent, renewable electricity cost of USD0.02/kWh, daily turnover rate during storage as compressed hydrogen (at an 18,000kg capacity facility), shipped over 5,000km as liquid hydrogen, and trucked 300m to the end-use site. "Domestic scale" is produced at a large scale centralized plant (300MW) with a capacity factor of 100 percent, grid electricity cost of USD0.1/kWh, daily turnover rate during storage as compressed hydrogen (at an 18,000kg capacity facility), and trucked 300km to the end use site. "Domestic sub-scale" is produced at a medium scale plant (30MW) with capacity factor of 100 percent and grid electricity cost of USD0.125/kWh, daily turnover rate during storage (at a 500kg capacity facility), and used on-site.

Conversion and storage of hydrogen

The sections below outline how each of the four forms is converted (and reconverted), and how they are stored, and highlight key barriers and risks limiting the conversion and storage of hydrogen.

Compression is not a viable way to store and transport large volumes of hydrogen

Conversion of hydrogen to compressed form has low capital costs, and reconversion is not required for most end-use cases. Compressed hydrogen is also regularly produced and stored, but only at small volumes. However, there are technological barriers for using and storing compressed hydrogen.

Compressed hydrogen can be directly used because it is readily produced and stored at small volumes. Compression of hydrogen has low capital costs (approximately USD0.25 per kg of hydrogen)[91], and reconversion is not required for most end-use cases. This cost is low compared to other hydrogen conversion processes. However, compressing hydrogen is not a viable solution to storing and transporting large volumes because it is much less energy dense than liquid hydrogen and ammonia.[92]

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[91] Castalia (2021).

[92] Energy densities: Compressed hydrogen 4.5 Megajoules per liter (MJ/L); liquid hydrogen 8.5 MJ/L, and ammonia 12.7 MJ/L, per M. Aziz, A. T. Wijayanta, A. B. D. Nandiyanto (2020), Ammonia as Effective Hydrogen Storage: A Review on Production, Storage, and Utilization, Energies 2020, 13(12), 3062, https://doi.org/10.3390/en13123062

Underground storage is a possible option for large-scale storage of compressed hydrogen. Salt caverns are the most suitable storage option because there are low (or no) hydrogen losses, and they maintain high purity of hydrogen. However, these facilities are not common globally. Depleted oil and gas fields, and aquifers and rock caverns could also be used for storage, and these are more commonly found than salt caverns.

Liquid hydrogen storage and transport

Liquefaction appears to be the more promising technical solution to storing and transporting economic quantities of hydrogen. It is already performed commercially today, but only on a very limited scale. Construction of several small hydrogen liquefaction plants has been announced, but these would need to be scaled up significantly to support global demand.

For conversion, there are technological barriers related to the conversion processes, high energy consumption, and small-scale plants. For storage, barriers include limited large-scale storage options and high capital costs. Technical solutions to some of these barriers are being developed.

Liquefaction process is currently only undertaken at small scale

Gaseous hydrogen is converted to liquid hydrogen by cooling it to below -253°C. Liquefaction has the advantage of not requiring any toxic components (unlike ammonia and some LOHCs), does not require any critical minerals, which may limit scaling up,[93] and also has greater energy density than compressed hydrogen and LOHC. However, there are barriers to increasing scale of converting liquified hydrogen. These are:

- **Cryogenic conversion process requires expensive equipment.** The cryogenic conversion process requires expensive equipment to reduce thermal losses and handle the cryogenic temperatures. The process results in high energy consumption, or leads to high boil-off losses that impact overall efficiency. Technological adjustments to the liquefaction process, which aim to improve efficiency of conversion, are currently being trialed.[94] These are expected to reduce costs significantly over the next five years. Increasing the plant capacity is also expected to decrease energy consumption by 30-38 percent.[95]
- **Current operational liquefaction plants are small, and scaling up is challenging.** Increasing the size of facilities is possible, but larger compressors and turbines are difficult to manufacture and transport.[96] Larger technology components are being developed, and alternative transport options are currently being tested, but these are not yet viable. Technologies from other industries, such as LNG and methanol, are also being adopted.

Regasification process does not involve barriers

Hydrogen regasification from liquid is a relatively simple process that does not involve any major technological barriers. Regasification uses seawater or air to heat the liquid

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[93] Such as polymer electrolyte membrane fuel cells (PEMFC) electrolyzers.

[94] Several technological adjustments are outlined on page 60. IRENA (2022), https://www.irena.org/publications/2022/Apr/Global-hydrogen-trade-Part-II

[95] IRENA (2022), https://www.irena.org/publications/2022/Apr/Global-hydrogen-trade-Part-II

[96] IRENA (2022), https://www.irena.org/publications/2022/Apr/Global-hydrogen-trade-Part-II

hydrogen, which is then transformed into a gaseous state. Hydrogen regasification does require materials that can withstand cryogenic conditions, but this is not considered a barrier. In addition, limited energy consumption is required.

Storage of liquid hydrogen does not yet enable large-scale trade

Liquid hydrogen is currently stored at a large scale, but in static spherical tanks. Storage and transport options for liquid hydrogen do not facilitate significant trade. Barriers include:

- **More storage capacity is required to support global trade, but storage and transport options are limited.** Current storage facilities need to be scaled up. Currently, tanks are located on land. Smaller tanks can theoretically go on ships, but no ships that can transport liquid hydrogen currently exist.
- **High capital costs to build large bunkers.** IRENA estimates that the capital cost of liquid hydrogen bunkers is between USD15-45 per kg of hydrogen. Technological solutions to reduce storage costs are being developed at smaller storage scale. For example, Fabrum is developing an end-to-end solution for the production, transfer, and transport of liquid hydrogen, which includes propriety fuel tank and fuel transfer system (in development and timeframes for commercialization are unclear).[97] The technology is expected to reduce costs and support the trade of liquid hydrogen.[98]

Ammonia as a derivative or carrier of hydrogen

The liquefaction and storage of ammonia are already performed commercially today, but only on a very limited scale. These would need to be scaled up significantly to support global demand. The main barrier to scaling up the conversion and reconversion of ammonia is high capital cost. High energy consumption and energy losses and issues with toxicity are also technical challenges that will need to be overcome. Ammonia storage can use existing infrastructure, which makes storage relatively simple.

Ammonia synthesis from green hydrogen experiences challenges

The process of converting hydrogen to ammonia is called ammonia synthesis. Most ammonia is commercially produced today from natural gas by steam methane reforming and then via the Haber-Bosch process.[99] Green ammonia is also produced at small scale, and is a result of air separation to separate nitrogen, the production of green hydrogen via electrolysis, and finally the reaction of both via the Haber Bosch process to produce green ammonia. Compared to compressed hydrogen, ammonia is easier to liquefy and contains 1.7 times more hydrogen per unit of volume than liquid hydrogen.[100] Ammonia can also be used directly (and therefore doesn't require reconversion), or can be reconverted back to pure hydrogen, but reconversion is less economical.

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[97] Fabrum (2022)

[98] Fabrum (2022)

[99] Ammonia can also be produced directly from air and water. However, this method still needs further research to reach a commercial scale. This production process is not discussed. IRENA (2022), https://www.irena.org/publications/2022/Apr/Global-hydrogen-trade-Part-II

[100] IRENA (2022), https://www.irena.org/publications/2022/Apr/Global-hydrogen-trade-Part-II

The main barrier to widespread uptake and potential solutions to conversion is high unit capital costs of ammonia conversion. This barrier can be overcome by exploiting economies of scale, and exploring modularization of plants. There are examples of demonstration projects for small-scale and modular operations, but they are still at early stages of development.[101] Other technical challenges that will need to be overcome if ammonia is a widely used fuel are:

- **Ammonia conversion requires high energy consumption and experiences thermodynamic losses during conversion (and transport).** Making minor changes to the production process and using different 'control strategies' may overcome this technical challenge by improving efficiency, and reducing energy consumption. These are being explored and tested.[102]
- **Ammonia is toxic and corrosive.** Utilizing the already established practices for safe handling, and drawing on experience in the chemical industry, can help to overcome this challenge.

Ammonia cracking also faces some technological barriers, and is unlikely to be commercial

Ammonia cracking (also called dissociation or splitting) is the opposite reaction of the synthesis, converting ammonia to pure nitrogen and hydrogen. Cracking is unlikely to be commercial because it is an expensive and technically challenging process to undertake without fossil fuels. Instead, ammonia is more likely to be used directly. For example, ammonia could be used directly as an industrial feedstock and possibly for fuel for shipping.

Ammonia can be stored in existing facilities

Ammonia can be easily liquified (20°C at 7.5 bar or -33°C at 1 bar) and then stored in isothermal tanks (up to 45,000 tonne) or spherical pressure tanks (1,000-2,000 tonne). A key benefit of ammonia is that it can utilize existing ammonia terminals and storage facilities, particularly as a starting point until other storage facilities are available. There are multiple ammonia storage facilities around the world both at ports and inland facilities. Pipelines transporting ammonia inland are also present (such as in the USA and Russia), which could also be an option (more discussion on transport of hydrogen via pipeline is provided below). Some regulatory changes may be needed to increase the scale of ammonia storage. However, this is not considered a key barrier.

LOHCs as a carrier

LOHCs are compounds that react with hydrogen and can be used multiple times. There is no clear winner for the chemical carrier to be used, although there are various promising options, such as toluene and methylcyclohexane, dibenzyltolune, and n-ethyl carbazole. Production of LOHCs need to be tested and scaled up significantly to support global demand. Storage of LOHCs is promising because LOHCs can use existing storage facilities, be stored for long periods of time, are non-toxic, and can be used directly and not converted back to hydrogen (with minor changes to infrastructure). Key barriers for converting and recovering LOHCs include significant energy required, limited

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[101] Modular plants can result in up to 25 percent lower capital expenditure. IRENA (2022), https://www.irena.org/publications/2022/Apr/Global-hydrogen-trade-Part-II

[102] Such as conduct synthesis at lower operating pressure (production process), or varying the pressure of the synthesis loop (control strategy).

hydrogen content of LOHCs, and unclear sustainable pathways for carriers. There are some technological solutions to overcome these barriers, but these are still early stages of development.

LOHC hydrogenation and LOHC dehydrogenation

The conversion and reconversion of LOHCs are called LOHC hydrogenation and LOHC dehydrogenation, respectively. LOHCs are compounds that react with hydrogen and be used multiple times. Hydrogen is bound to a liquid hydrocarbon which is released at the importing terminal. The carrier is then regenerated upon dehydrogenation so it can be transported back to the exporting terminal for another cycle.[103] Key barriers include:

- **Significant heat is required to recover hydrogen from the carrier**. Medium temperature heat (270-320°C) is required to recover the hydrogen from the carrier. This energy consumption is approximately 30-40 percent of the energy contained in the hydrogen.[104] Several LOHC conversion and transportation projects are ongoing. These aim to test the viability of LOHCs and see whether quantity can be scaled. Leading companies for LOHC are Hydrogenious LOHC Technologies (uses benzyltoluene as a carrier) and Chiyoda Corporation (SPERA hydrogen). Other companies are developing LOHC solutions, including H2-Industries, Framatome/Covalion (owned by EDF), Hynertech, and Petronas and Eneos.
- **Losses occur as the carrier is recycled, and LOHCs have relatively low hydrogen content.** Losses of about 0.1 percent per cycle occur when the LOHC is recycled. Without effective carbon capture technology, the recycling process results in a small amount of fossil fuels being released in the process.[105] LOHCs also have relatively low hydrogen content, approximately 4-7 percent by weight.
- **Sustainable pathways for the carriers have not been proven and currently rely on oil production.** A solution to this barrier includes technological solutions, such as direct air capture (DAC), which are being explored. For example, Global Thermostat has large-scale proposals for a high-temperature variation of DAC, while Climeworks and Carbon Engineering are targeting low-temperature variations at similar costs to Global Thermostat. The other sustainable CO_2 sources, such as biomass, are also being tested.

Storage of LOHCs is possible in existing petrochemical storage facilities

Storage of LOHCs is promising because LOHCs are mostly oil derivatives and can therefore use existing loading and storage facilities used for oil products. Given that LOHCs are liquid at ambient conditions, boiloff losses are minimal and the carriers can remain in hydrogenated state for long periods of time without losses or significant costs. They are also mostly non-toxic and not flammable. No barriers for storing LOHCs exist at this stage.

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[103] IRENA (2022), https://www.irena.org/publications/2022/Apr/Global-hydrogen-trade-Part-II

[104] IRENA (2022), https://www.irena.org/publications/2022/Apr/Global-hydrogen-trade-Part-II

[105] The amount of released emissions (in CO_2-e) depends on the LOHC used. IRENA (2022), https://www.irena.org/publications/2022/Apr/Global-hydrogen-trade-Part-II

Transport and transfer of hydrogen

The transport of hydrogen is a key cost component for centralized production. It matters for cost-competitiveness with other energy sources. Transport cost is mainly a function of the volume of hydrogen transported and the distance. Hydrogen can be transported in different ways. Hydrogen can be transported by:[106]

- Ship—liquid hydrogen, ammonia, or LOHC
- Pipeline—compressed hydrogen (or blended hydrogen)
- Trucks—compressed or liquid hydrogen.

Transfer points are intermediary points between transport and storage facilities. Key transfer points include:

- Ships—hydrogen (or hydrogen carrier) is pumped through a pipe onto storage unit on the ship, which is then unloaded at a port by pumping the hydrogen through another pipe into the storage facility (for example, at a port).[107]
- Pipeline—hydrogen is pumped through a pipe into a distribution or transmission pipeline, and then smaller pipes are connected to the end user. This uses a similar approach to natural gas.[108]
- Trucks—hydrogen is pumped through a pipe onto the tank unit on the truck through a pipe or liquid dispenser. The truck then transports the hydrogen to another storage facility (for example, at a port) and hydrogen is unloaded via pipe (and vice versa).

There is extensive analysis of the cost associated with transporting hydrogen. Often the costs associated with transferring hydrogen are combined with their transport or storage costs, so transfer costs are more difficult to isolate. In general, the following findings about the transport of hydrogen are considered reliable:

- Trucks can be cost-effective for small volumes and short distances. Compressed hydrogen is mostly cost-effective at distances up to around 100 km, and liquid hydrogen at distances from around 100 km to under 1,000 km
- Pipelines are more cost-effective as volume and distance increase, for example, between 10-100 tonnes per day and for distances up to around 1,000 km
- Ships are most attractive for long distances or routes across water bodies. There is debate over which form of hydrogen or carrier is most competitive. Other institutions, such as Liebreich Associates, state that long-distance shipping of hydrogen is unlikely to be economic.[109]

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[106] Rail transporting compressed or liquified hydrogen is also possible, but rail is likely to only be competitive with other options hydrogen when there is existing rail infrastructure to end-users.

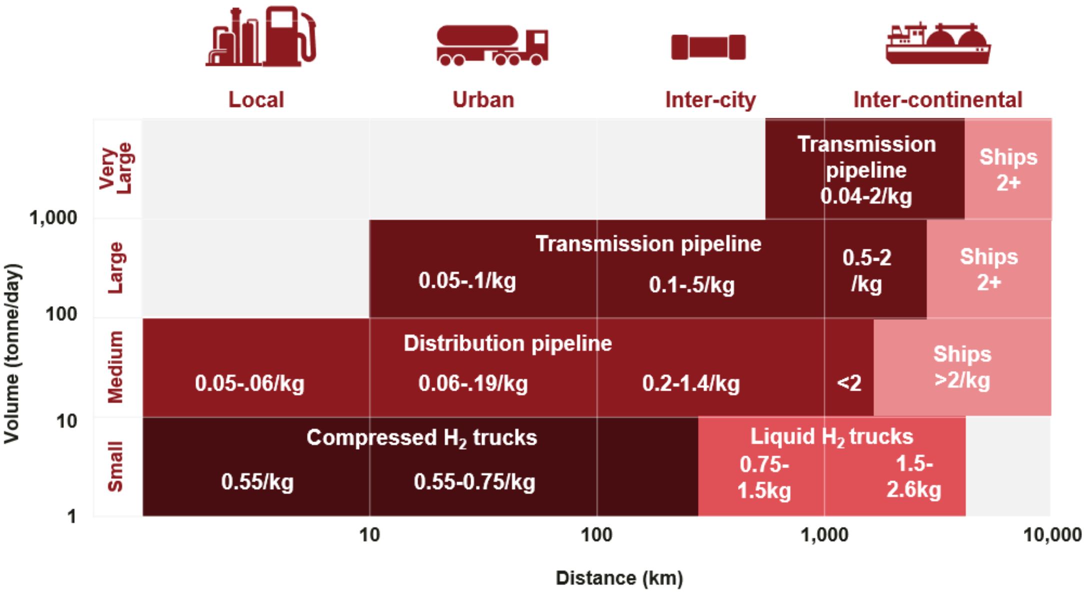
[107] Different pipes are required for each hydrogen type. For example, liquid hydrogen requires pipes that are vacuum jacketed. For liquid hydrogen, piping is about 10 percent of the total cost.

[108] Similar to natural gas, e.g., a compressor is a machine driven by an internal combustion engine or turbine that creates pressure to "push" the gas through the lines.

[109] https://www.rechargenews.com/energy-transition/not-going-to-be-a-thing-it-will-be-too-expensive-to-ship-hydrogen-around-the-world-says-liebreich/2-1-1293562

Transport costs are displayed in Figure C.3. Bloomberg NEF outlines similar transport costs.[110]

Figure C.3: Hydrogen transport cost based on distance and volume (2022)



Source: IRENA (2022)

The sections below outline methods to transport hydrogen and under which circumstances each option is most viable, and highlights key barriers and risks limiting the transport and transfer for hydrogen.

Ship transport of hydrogen or derivatives

Hydrogen transport via ship makes sense for long distances. Liquid hydrogen, ammonia, and LOHC can all theoretically be shipped, but there is debate over which hydrogen form is the most cost effective and efficient. For example, the European Commission indicates that shipping liquified hydrogen, ammonia, and LOHC are broadly competitive with each other,[111] while IRENA states that ammonia and LOHC are slightly cheaper to transport than liquid hydrogen.[112]

Overarching barriers to shipping hydrogen include high capital costs and lack of technological maturity for hydrogen carrying ships, and energy losses during transportation, and regulatory constraints. Technological developments aim to overcome these barriers; however, technology is still in early stages of development.

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[110] BloombergNEF (2022), Hydrogen: The Economics of Pipeline Transport.

[111] European Union Joint Research Centre (2021), Assessment of Hydrogen Delivery Options, available: https://joint-research-centre.ec.europa.eu/system/files/2021-06/jrc124206_assessment_of_hydrogen_delivery_options.pdf

[112] IRENA (2022), https://www.irena.org/publications/2022/Apr/Global-hydrogen-trade-Part-II

Ammonia

Ammonia is advantageous as a hydrogen carrier because it is already transported via ship, existing transfer infrastructure (such as jetties and terminals) can be used, and there are existing trade routes which can be utilized. However, existing ammonia ships have limited volume. Larger ammonia vessels are in development. However, the ultimate costs of these are uncertain as the technology develops. IRENA estimates that the costs of ammonia carrier ships (60,0000 tonne carrier) are between USD900 per tonne of ammonia (optimistic) and USD1,750 per tonne of ammonia.[113]

Other barriers to shipping ammonia are the high capital costs of building new terminal and storage facilities. Utilizing existing ammonia storage and transfer is likely to be the most cost-effective solution in the short-term, at least until the market is more developed. In addition, ammonia is toxic and corrosive, which poses issues with maritime regulation. There is ongoing work to ensure standards and regulations are fit-for-purpose, but these could take time to be finalized.[114]

Liquid hydrogen

Small liquid hydrogen tanks can theoretically be transported via ship, but no ships currently transport liquid hydrogen at large or small-scale. IRENA states this area is still about a decade away from large scale implementation. Demonstration projects have successfully shipped liquid hydrogen at small scale,[115] but no large-scale shipping options currently exist.

Ships that are in development are expected to have high capital costs and limited volume. IRENA estimates that shipping costs for liquid hydrogen will be higher than for ammonia or LOHCs. Manufacturers of commercial hydrogen ships are targeting capacities of 11,000-12,000 tonnes of liquid hydrogen, which is a lower volume range than for ammonia and LOHC carriers (around 60,000 tonnes and 110,000 tonnes, respectively). The lower weight of liquid hydrogen ships can be beneficial because they have lower energy consumption. However, more ships would be needed to move the same volume as ammonia and LOHC. This is offset by lower costs of converting the shipped product back to gaseous hydrogen where that is required. Some companies are developing larger liquid hydrogen ships that could satisfy large-scale transport of liquid hydrogen. However, these are not expected to be technology-ready before five years and would then need to be scaled-up for commercial use.[116]

LOHCs

Shipping LOHC has advantages because they are handled in the same way as oil derivatives. This means that they can be stored and shipped in atmospheric conditions and only present minor hazards in case of a spill. However, no ships currently transport

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[113] IRENA (2022), https://www.irena.org/publications/2022/Apr/Global-hydrogen-trade-Part-II

[114] Key learnings from liquid natural gas (LNG) regulations are being used to speed up regulation. As a reference, LNG took six years between the first interim guidelines and the final adoption of the code.

[115] For example, the 2022 HySTRA project, which involved the first shipment of 75 tonnes of liquid hydrogen from Australia to Japan.

[116] For example, Kawasaki is developing a larger liquid hydrogen ship, while Hyundai Heavy Industries, Korea Shipbuilding and Offshore Engineering, and Hyundai Mipo Dockyard are developing a ship that uses any boil-off gas from the cargo to drive the ship using fuel cells. Hyundai aims to have the technology ready by 2025. IRENA (2022), https://www.irena.org/publications/2022/Apr/Global-hydrogen-trade-Part-II

LOHC. LOHC ships are in development but are expected to have high capital costs, and are unlikely to be competitive with alternatives. IRENA estimates that a LOHC ship, with capacity above 60,000 deadweight tonnage (dwt) will cost approximately USD800 per tonne of LOHC, which is between the estimated cost of ammonia ships and liquid hydrogen ships.[117] Existing oil and chemical tankers could be used in the meantime to facilitate the shipping on LOHCs, and reduce the overall cost of landed LOHCs. However, this would need to be tested.

Another barrier to shipping LOHCs is that LOHCs have lower hydrogen content than other hydrogen derivatives. This results in higher per unit costs compared with ammonia ships, as well as lower efficiency due to higher weight and energy losses. No clear solutions exist for this barrier at this stage.

Pipeline conveyance of hydrogen

Pipelines are more cost-effective as volume and distance increase, that is, between 10-100 tonnes per day and for distances up to around 1,000 km. Transporting hydrogen via pipeline is already a mature technology, and there are 4,600 km of pure hydrogen pipelines in the United States and Europe.[118] More pipelines are required to support global hydrogen trade. These will need to be built, or existing natural gas transmission pipelines could be repurposed and upgraded.

A key barrier to utilizing pipelines for hydrogen transportation is the high capital costs associated with building new and repurposing existing pipelines. Zen Energy Solutions estimate a newly built 100 tonne per day capacity pipeline costs approximately USD0.38, USD1.00, and USD1.60 per kg of hydrogen for 100, 300, and 500 km distances, respectively.[119] Projects to build new hydrogen pipelines are ongoing globally.[120] Existing natural gas pipelines can be repurposed in some locations,[121] but will need to be upgraded for high concentrations of hydrogen.[122] Upgrading existing infrastructure is likely to be a costly exercise, but likely less than new pipelines. IRENA estimates that in cases where repurposed pipelines are possible, the investment cost can be 65-94

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[117] IRENA (2022), https://www.irena.org/publications/2022/Apr/Global-hydrogen-trade-Part-II

[118] IRENA (2022), https://www.irena.org/publications/2022/Apr/Global-hydrogen-trade-Part-II

[119] The cost of implementing new hydrogen pipelines is expected to be high, but costs vary depending on geography, existing infrastructure, and pipe type and throughput.

Zen Energy Solutions (2021), analysis from several hydrogen projects. IRENA provides an estimate of the costs for implementing new hydrogen pipelines under different pipeline diameter. See page 112. IRENA (2022), https://www.irena.org/publications/2022/Apr/Global-hydrogen-trade-Part-II

[120] For example, the Government of Germany recently announced EUR 8 billion of investment across the entire hydrogen value chain to develop large-scale hydrogen domestically. 15 projects targeted infrastructure, potentially adding up to 1,700 km of new hydrogen pipeline. IRENA (2022), https://www.irena.org/publications/2022/Apr/Global-hydrogen-trade-Part-II

[121] Such as North America, eastern China, Europe, and Russia.

[122] Currently, a natural gas network can support blended hydrogen and natural gas of up to 20 percent hydrogen. This is being trialed globally. As hydrogen concentrations increase, pipeline infrastructure will have to be updated or replaced to prevent embrittlement. IEA (2021), Global Hydrogen Review 2021. https://iea.blob.core.windows.net/assets/5bd46d7b-906a-4429-abdae9c507a62341/GlobalHydrogenReview2021.pdf

percent lower than the cost of a new hydrogen pipeline.[123] Projects repurposing existing networks are being explored globally.[124]

The opportunities to develop pipelines to transport hydrogen will be highly idiosyncratic—depending on geography, distance from producers to consumers and existing infrastructure. In some cases, blending hydrogen in gas pipelines can catalyze the take-up of production and justify later conversion. The later conversion will depend on significant falls in clean hydrogen production costs, relative to alternative energy sources.

Truck transport of hydrogen

Trucks can be cost-effective for small volumes and short distances. Compressed hydrogen is most cost-effective at distances up to around 100 km, and liquid hydrogen is most cost-effective at distances from around 100 km to under 1,000 km. Trucks enable hydrogen to be delivered without large transfer infrastructure costs, such as large terminals or jetties). The main barrier to scaling up the transport of hydrogen by truck is the limited number of hydrogen carrier trucks available (tube trailers and liquid tankers). More trucks are expected to be manufactured over the next 5 to ten years to support this transport option.

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[123] IRENA (2022), https://www.irena.org/publications/2022/Apr/Global-hydrogen-trade-Part-II

[124] For example:

- Important Projects of Common European Interest (IPCEI) is looking at developing a hydrogen network of 5,900 km, of which 90 percent would comprise repurposed natural gas pipelines
- Germany is also actively collaborating with neighboring countries in projects for repurposing pipelines and transporting hydrogen (MosaHYC project)
- Two transmission system operators (TSOs), one from Denmark and another from Germany, found that the two countries could be connected via a 340 km pipeline
- In Australia, the TSO (APA Group) announced a project to repurpose 43 km of natural gas pipeline

IRENA (2022), https://www.irena.org/publications/2022/Apr/Global-hydrogen-trade-Part-II

The **Asian Infrastructure Investment Bank (AIIB)** is a multilateral development bank (MDB) whose mission is financing the Infrastructure for Tomorrow—infrastructure with sustainability at its core. We began operations in Beijing in January 2016 and have since grown to 106 approved members worldwide. We are capitalized at USD100 billion and Triple-A-rated by the major international credit rating agencies. Collaborating with partners, AIIB meets clients' needs by unlocking new capital and investing in infrastructure that is green, technology-enabled and promotes regional connectivity.

Castalia is a global strategic advisory firm with over 40 years of experience in financial, economic, and policy advisory to increase and improve global access to sustainable infrastructure services. We design innovative solutions to the world's most complex infrastructure, resource, and policy problems. We are experts in finance, economics, and policy of infrastructure, natural resources, and social service provision. We help governments and companies to transform sectors and enterprises, design markets and regulation, set utility tariffs and service standards, and appraise and finance projects. We deliver concrete measurable results applying our thinking to make a better world.

We take sustainability and transition seriously as advisors on over 600 climate mitigation resilience projects globally, including pioneering work on hydrogen development across the Asia-Pacific region. We deeply understand how to effectively integrate hydrogen into existing markets in a way that benefits whole energy systems. Castalia has modelled and assessed clean hydrogen feasibility and investment opportunities for multilateral development banks, governments, and investors.

Developing a robust clean hydrogen sector will enable developing countries in Asia and beyond to decarbonize hard-to-abate sectors and accelerate their transition towards a clean energy system. International financial institutions (IFIs) can play an important role to de-risk and bring this promising low-carbon technology closer to commercial stage. To support the development of clean hydrogen, this report assesses the critical pathway for the commercialization of clean hydrogen value chain over a multi-year time horizon. Recognizing the barriers to clean hydrogen development at its early stage and IFIs' role to catalyze its commercialization, it seeks to shed light on how IFIs can effectively deploy their financial instruments to support clean hydrogen's critical pathway along each phase. The study reviewed the global conditions for clean hydrogen production and use cases to identify possible engagement points for IFIs. Economic modelling identified likely least cost hydrogen production locations and hydrogen use cases in countries with significant potential, based on short-, medium- and long-term technical and economic viability.

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