Transitioning China's Industries

Creating Clusters for Large-scale Green Hydrogen Integration

Report / September 2024

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Table of Contents

Introduction

The industrial sector is currently China's largest consumer of hydrogen and is expected to hold its prominent position as a primary market for large-scale green hydrogen utilization in the future. In 2020, a total of 31.73 million tons of hydrogen were consumed in China, with the chemical industry accounting for 70% and the oil refining industry for 24% of this consumption.[1] Domestic hydrogen consumption is expected to increase more than 2.5 times by 2060, to reach an estimated 75 million to 100 million tons annually. Industrial demand is expected to continue dominating hydrogen utilization — at an estimated 60% of the overall consumption, marking a 1.5-fold increase in absolute demand.[2]

Within the industrial landscape, nearly half of the hydrogen demand arises from the chemical industry, while the steel industry is emerging as a growth sector and is expected to account for approximately one-third of the utilization. Currently, over 95% of the world's hydrogen originates from fossil fuels as "gray hydrogen," and less than 5% originates as "green hydrogen" (i.e., produced via electrolysis fueled by renewable energy). Over the long run, the hydrogen supply mix is expected to evolve such that green hydrogen will predominate. By 2060, if China's green hydrogen accounts for 75% of the total supply — that is, 56 million to 75 million tons per year— the volume of green hydrogen utilized in industry will reach 34 million to 45 million tons per year.

In industry, green hydrogen can be used as an alternative fuel and feedstock. As a fuel, green hydrogen can quickly increase the temperature of the reactor through combustion, reaching extremely high temperatures that are difficult to achieve with green electric heating. As a feedstock, green hydrogen can replace the coke that is now commonly used as a reducing agent in steel production. In chemical production, green hydrogen can replace gray hydrogen as a feedstock to greatly reduce carbon emissions in the reaction process.

The steel and chemical industries have great potential for large-scale utilization of green hydrogen. By 2050, up to 20% of the country's total steel is expected to come from hydrogen-based production.[3] The demand for green hydrogen in the steel industry is expected to grow to around 7 million tons, an increase of more than 4.5 times in 20 years. In the chemical industry, green hydrogen–based ammonia and methanol production is expected to account for 70% and 74% of total production, respectively, by 2050,[4] at which point green hydrogen will replace coal as the main feedstock. The demands for green hydrogen for ammonia and methanol production will reach around 11 million tons and 9 million tons, respectively.

China has carried out extensive efforts in green hydrogen and its utilization in industry. At the policy level, nearly 10 provinces have proposed quantitative renewable-based hydrogen production targets and coverage of utilization in chemical, steel, and other industries. For the steel industry, the important role of hydrogen-based metallurgy has been emphasized in policy documents such as technical research policies, capacity replacement policies, and standard system construction policies. At the local level, all provinces with steel production capacity have expressed support for hydrogen-based metallurgy in their policies, and some of them also specifically lay out hydrogen-based metallurgy quantitative targets, pilot development plans, and financial guidelines.

Current domestic hydrogen-based metallurgy initiatives include pilot projects employing various technological approaches — including hydrogen-rich blast furnaces, hydrogen-based direct reduced iron, and hydrogen-based smelting — with a total capacity of over 9 million tons per year based on available public data. Within these initiatives are many large-scale projects, such as HBIS' two-phase hydrogen-based metallurgy demonstration of 1.2 million tons per year in Zhangjiakou, and Baowu's 1 million tons per year of hydrogen-based direct reduced iron demonstration in Zhanjiang. In the chemical industry, the use of green hydrogen is more common. At this stage, most of the large-scale green hydrogen production and utilization projects in China are for ammonia and methanol production, accounting for 68% and 16%, respectively.

Despite the progress, it is crucial to continue exploring effective models and accelerating implementation to expand the application and scale of green hydrogen in the industrial sector. Currently, most hydrogen sources in hydrogen-based metallurgy projects are gray hydrogen and by-product hydrogen. Among the 12 existing hydrogen-based metallurgy projects, only four declare green hydrogen planning. For instance, HBIS' and Baowu's hydrogen-based direct reduced iron demonstration projects utilize by-product hydrogen such as coke oven gas in the initial phase and plan to incorporate green hydrogen in the second phase. The design of these projects has incorporated "green hydrogen switching" to enable the use of a higher proportion of hydrogen-rich reducing gas, pure hydrogen, and a gradual transition to 100% green hydrogen. In the chemical industry, there is significant geographical clustering in development of projects for producing green ammonia and green methanol utilizing green hydrogen as a feedstock. For example, the number and scale of green ammonia and green methanol projects in Inner Mongolia rank highest in China, with planned production capacity accounting for 57% and 41% of the national total, respectively. However, only 10%–15% of these projects have begun construction or started operation, while most are still in the planning stage.

During this period of development, it is crucial to establish several viable, sustainable, and reproducible models. The widespread utilization of green hydrogen in industry requires addressing two main challenges. First, the supply of green hydrogen must reach a significant scale and stability. Second, the high cost of hydrogen utilization needs to be addressed.

The demand for hydrogen from a typical industrial site is significantly greater than in other sectors. For instance, in steel production, a typical hydrogen-based metallurgical facility with a capacity of 1 million tons/year requires approximately 60,000 tons/year of hydrogen, which is nearly 40 times the demand of a single hydrogen refueling station. Similarly, in the chemical industry, the annual hydrogen demand for ammonia and methanol production in a single plant exceeds 10,000 tons. Furthermore, to support continuous industrial production, the supply of hydrogen as a feedstock and fuel must be consistent and stable to prevent additional costs associated with intermittent supply.

However, there is a geographical mismatch between areas with high potential for green hydrogen production and areas with more industrial capacity in China, posing challenges to ensuring consistent large-scale supply of green hydrogen and providing low-cost green hydrogen in industrial areas.

To address these challenges, this research introduces a "cluster development" model for efficiently deploying green hydrogen on a large scale in industry. This approach prioritizes locations where the production and consumption of green hydrogen are well aligned, aiming to optimize the economic feasibility through a "production-storage-transportation-utilization" green hydrogen system while deploying coordination methods based on technical feasibility. The goal is to ensure a large-scale, consistent, and stable supply of green hydrogen at the lowest cost. It is important to note that the cluster development model not only enhances the physical optimization of the production-storage-transportation-utilization of green hydrogen for industries but also facilitates risk management and stakeholder coordination by bringing together upstream green hydrogen producers, midstream hydrogen storage and transportation infrastructure providers, and downstream industrial users, thus catalyzing the large-scale adoption of green hydrogen in industry.

This report suggests and interprets the cluster development model in light of the critical requirements for the widespread utilization of green hydrogen in industry, and the distribution of industrial capacities and availability of green hydrogen resources in China. Specifically, the report conducts techno-economic analysis of green hydrogen production, storage, transportation, and utilization in industry, forming a foundation for achieving cost-efficiency when technically feasible during the cluster development process.

Additionally, to facilitate practical implementation, the report outlines methods for industry cluster forming and cost optimization in two common scenarios: when hydrogen supply and utilization are in the same location and when they are in different locations. The report also uses examples of industrial hydrogen utilization in Qinghai, Shanxi, and Zhejiang to aid in comparison and cost estimation of hydrogen supply and utilization schemes. Lastly, the report provides five actionable recommendations to speed up the adoption of large-scale green hydrogen in the low-carbon and zero-carbon transition of industry.

1. Accelerating Utilization of Large-Scale Green Hydrogen

1.1 Green hydrogen is critical to decarbonizing the industrial sector

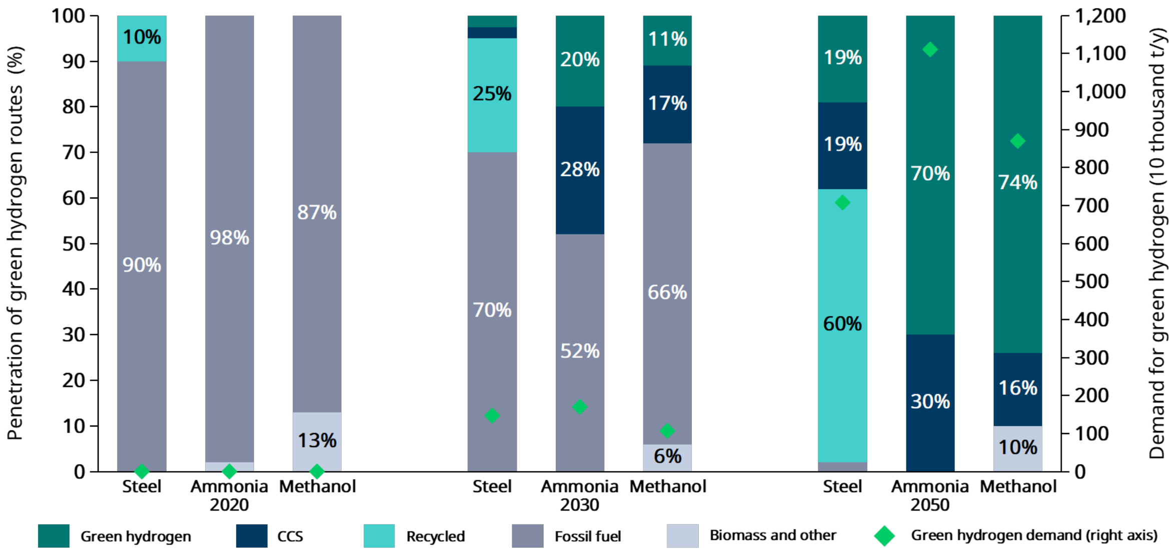
The utilization of green hydrogen, as a key carbon reduction measure, holds particular importance in tackling industrial sector emissions. As a fuel, green hydrogen is used to rapidly increase the reactor temperature through combustion reaction, achieving high temperatures that are hard to attain with green electric heating. Green hydrogen can serve as a feedstock, replacing coke in steel production as a reducing agent and substituting for gray hydrogen in chemical production to significantly reduce carbon emissions during the reaction process. Looking ahead, terminal demand for hydrogen in the China industrial sector will grow over time and is expected to reach 20% by 2060, accounting for more than half of non-electric energy demand.[5] Accordingly, hydrogen utilization in industrial sectors is expected to avoid over 8 billion tons of greenhouse gas emissions between 2020 and 2060.[6]

The steel and chemical industries have great potential for large-scale utilization of green hydrogen, and the proportion of total output based on green hydrogen production routes will increase year by year (see Exhibit 1).

In the steel industry, hydrogen-based production is one of the vital production routes to low-carbon metallurgy. By 2030, the annual output of hydrogen-based production of crude steel is expected to reach 250,000 tons. By 2050, hydrogen-based production is expected to exceed 120 million tons, accounting for 20% of total domestic steel production,[7] at which time the demand for green hydrogen in the steel industry is expected to grow to around 7 million tons per year.

In the chemical industry, the production of ammonia and methanol using green hydrogen is expected to reach 20% and 11% of total production by 2030, respectively. By 2050, the production of ammonia and methanol based on green hydrogen is expected to reach 70% and 74% of the total production, respectively,[8] at which time green hydrogen will replace coal as the most important feedstock. Ammonia and methanol production will then require about 11 million tons and 9 million tons of green hydrogen, respectively.

Exhibit 1: Green hydrogen–based production routes and green hydrogen demand in typical industries



Note: The green hydrogen–based production routes for methanol include green hydrogen–coupled coal and Power-to-X. CCS = carbon capture and storage.

RMI Graphic. Source: RMI

In addition to the steel and chemical industries, other sectors have potential for utilizing green hydrogen — though on a smaller scale. For example, in the cement industry, green hydrogen could be used as a fuel to provide high temperatures, but other alternative fuels may be more desirable in terms of feasibility and economic efficiency. This study therefore focuses on the steel, ammonia, and methanol industries, and explores ways to achieve large-scale utilization of green hydrogen.

1.2 Requirements for scalability, continuity, and stability of hydrogen supply in industry

Hydrogen for industrial production has greater volume demand and continuous supply requirements than other utilization cases. Exhibit 2 compares the typical capacities and scale of hydrogen utilization in several use cases. In terms of the **scalability** of hydrogen supply requirements, the hydrogen demand of a typical industrial hydrogen utilization is significantly larger. For example, hydrogen utilization in transportation is mostly distributed, with a single refueling station requiring 1.8 thousand tons/year, based on a typical hydrogen demand of 4.8 tons/day. In industry, to realize economies of scale, production capacities are more centralized, and the scale of hydrogen utilization is larger. For instance, in the steel industry, a typical hydrogen-based metallurgical site with production capacity of 1 million tons/year requires around 60 thousand tons of hydrogen per year — nearly 40 times more than the demand of a single hydrogen refueling station. In the chemical industry, the annual hydrogen demand of a single plant for ammonia and methanol is over 10 thousand tons.

Exhibit 2: **Requirements for hydrogen scale in different utilization cases**

Metrics	Hydrogen refueling station	Steel	Ammonia	Methanol
Hydrogen use per unit* (ton of hydrogen/ton of production)	1.0	0.06	0.18	0.09–0.19
Typical large capacity (1,000 tons/year)	3.3†	1,200	500	1,800
Hydrogen demand at large capacity scale (1,000 tons/year)	3.3	72	90	162–342
Typical capacity scale (1,000 tons/year)	1.8‡	1,000	300	600
Hydrogen demand at typical capacity scale (1,000 tons/year)	1.8	60	54	54–114

* Hydrogen use per unit refers to hydrogen in a hydrogen refueling station, and to the amount of hydrogen required per unit of industrial product. The hydrogen use per unit for steel production is based on the direct reduction of iron. The hydrogen use per unit for methanol depends on the different production routes, ranging from 0.09 in the green-hydrogen-coupled coal route to 0.19 in the Power-to-X route.
† Typical large capacity of the hydrogen refueling station is based on planning for a heavy truck hydrogen refueling station at a Shanxi steel plant, where the hydrogen consumption of a single station is 9.0 tons/day.
‡ Typical capacity scale of a hydrogen refueling station is based on the Daxing International Hydrogen Demonstration Area, where the hydrogen consumption of a single station is 4.8 tons/day.

RMI Graphic. Source: RMI

In terms of **stability** requirements, due to the continuous production process, industry requires a continuous and stable supply of hydrogen as feedstock and fuel to avoid equipment shutdown and startup costs. In addition, it is difficult to meet complete peak-shaving demand in industry by only equipping current mainstream pressurized storage tanks, given that a stable supply of hydrogen sources is essential. For example, to meet the hydrogen demand of 10,000 tons in industry requires a large 6-ton capacity hydrogen storage tank[i] — which has a large property footprint and comes at a high cost.

However, a geographical mismatch exists between regions with high potential for green hydrogen production and those with concentrated demand. This not only poses challenges to ensuring a large-scale, continuous, and stable supply of green hydrogen but also makes it challenging to provide low-cost green hydrogen in regions with high demand for it.

In terms of the demand for green hydrogen, this study analyzes the transition pathway of each province based on its existing industrial capacity as well as resource endowment related to low-carbon transition, and identifies the demand for green hydrogen from typical heavy industries in each (see Exhibit 3). By 2030, the five provinces with the greatest demand for green hydrogen — Hebei, Shandong, Inner Mongolia, Henan, and Jiangsu — are projected to have combined demand of nearly 2 million tons/year, accounting for 40% of China's total industrial green hydrogen demand, and they are expected to achieve a high level of green hydrogen geographic clustering.

[i] This refers to the single-tank hydrogen storage capacity in the planning of a heavy-duty truck hydrogen refueling station of a steel enterprise in Shanxi.

By 2050, the advancement of hydrogen-based metallurgy will drive green hydrogen demand in the major steel provinces. For instance, industrial green hydrogen demand in Hebei province will grow from 450,000 tons in 2030 to 2.38 million tons in 2050, with the steel industry contributing nearly 70% of the incremental demand. Moreover, the utilization of green hydrogen in the production of ammonia and methanol will increase significantly, contributing to an overall rise in green hydrogen demand in relevant provinces.

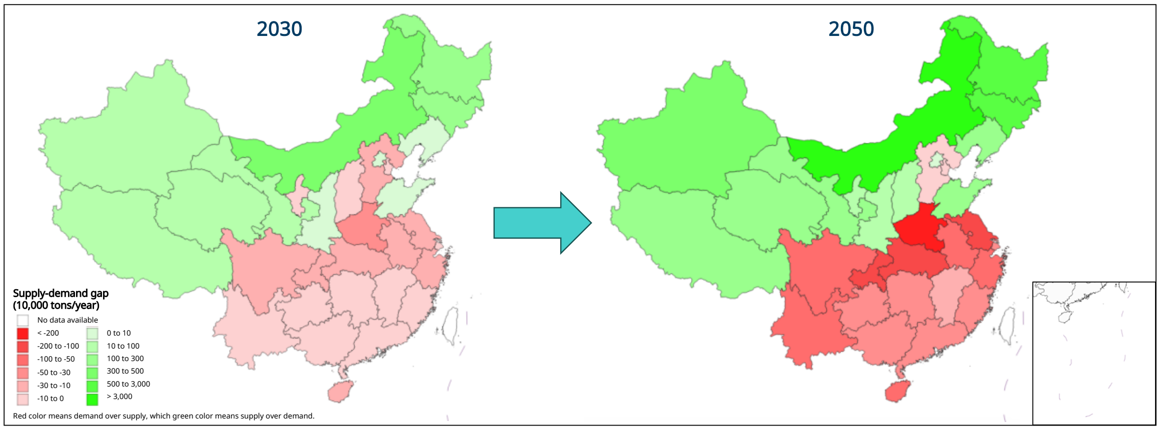
In terms of green hydrogen supply, differences in the endowment of wind and solar resources across regions have led to different geographic distribution of green hydrogen supply potential. Xinjiang, Inner Mongolia, and Heilongjiang have 42% of economically exploitable potential for wind and solar photovoltaics (PV).[ii] Inner Mongolia alone has reached 2 billion kilowatts (kW) — 40 times the provincial median level.[9] The projected green hydrogen supply potential of each province by 2030 and 2050 can be estimated on the basis of its wind and solar capacity as well as the development of hydrogen production by electrolysis. The supply potential of green hydrogen in Inner Mongolia is higher than that of other provinces, and its supply capacity is expected to grow rapidly from 2030 to 2050.

In terms of industrial green hydrogen demand and supply potential, the supply of green hydrogen in the northwestern, northern, and northeastern regions generally exceeds demand, while in the eastern and southern provinces, green hydrogen is mostly in short supply. Regions with an excess of green hydrogen need to create suitable utilization cases, while regions with limited green hydrogen should explore hydrogen supply solutions.

In the long term, the growth rate of green hydrogen supply in some provinces, such as Shanxi, will exceed the growth rate of demand, alleviating the short supply of green hydrogen. However, most of the eastern coastal provinces will still have large-scale unmet demand for green hydrogen — for instance, Jiangsu and Zhejiang may experience a green hydrogen demand gap as high as 1 million tons/year. In pursuit of the carbon neutrality goal, the mismatch between green hydrogen supply and demand will be mitigated by the transfer of energy-intensive industries from eastern to western provinces or solved by the intra- and inter-regional transportation of green hydrogen. The cluster development model in this study is a specific analysis of the latter.

[ii] In this study, onshore wind power is considered, while offshore wind power is not.

Exhibit 3: **Geographic mismatch between green hydrogen supply and industrial green hydrogen demand**



Note: This exhibit only assumes future changes in industrial capacity in each province with changes in total national capacity based on current size and relevant policies, and makes assumptions based on the development of green hydrogen-based production routes to estimate green hydrogen demand in each province. In the estimation of green hydrogen supply potential, only onshore wind power and centralized PV are considered, and other forms of renewables are not included in the current research phase. The project team will continue to research uncertainties of the supply and demand of green hydrogen under the influence of the above factors.

RMI Graphic. Source: RMI

1.3 Optimized allocation of green hydrogen resources through cluster development

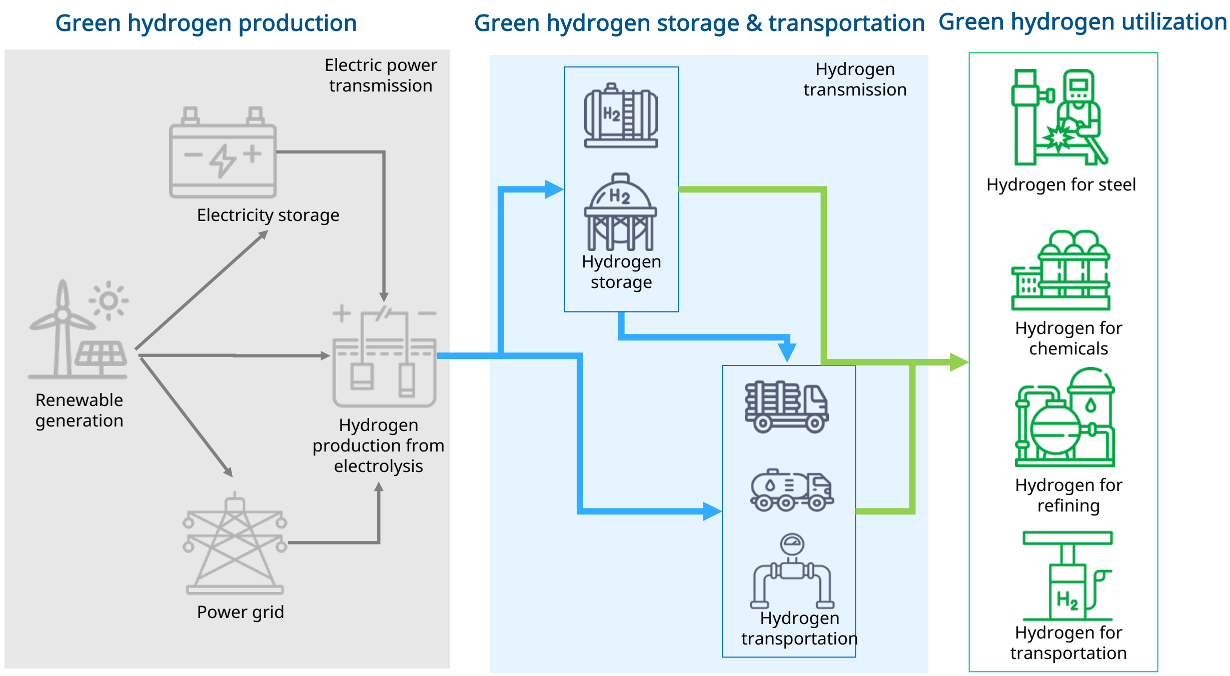
This study proposes a "cluster development" model for the large-scale utilization of green hydrogen in industry. This entails prioritizing areas where green hydrogen supply and demand are relatively matched, and it is premised on technological feasibility and optimizing "production-storage-transportation-utilization" and complementary methods to achieve optimal economics, with the goal of ensuring a large-scale, continuous, stable, and cost-effective green hydrogen supply in industry. Notably, the cluster development model not only realizes the physically optimized "production-storage-operation-utilization" of green hydrogen required in industry, but also gathers upstream green hydrogen producers, midstream storage operators, downstream industrial companies, and other stakeholders. The goal is to achieve effective management and risk diversification to help accelerate the large-scale development of green hydrogen in industry. The industrial clustering areas where the cluster development is achieved will be referred to in this report as "industry clusters."

The key points for the construction of the cluster development model include:

Optimizing for the best economic efficiency that is technically feasible

Various options are available for sustained and stable supply of green hydrogen (see Exhibit 4). For example, if utilizing on-site wind and solar resources to produce green hydrogen, there are several feasible options for filling the gap caused by the intermittency of renewables, including producing hydrogen with supplementary grid electricity; producing hydrogen off-site and transporting it to where it will be used; and producing hydrogen with supplementary power from energy storage discharge and releasing the stored hydrogen. Although all these options are technically feasible, the combination of options with the best economic efficiency should be chosen and tailored to local conditions. Chapter 2 analyzes the economic efficiency and factors influencing the "production-storage-transportation-utilization" of green hydrogen for industrial utilization to provide a basis for optimizing economic efficiency. Chapter 3 demonstrates the method and process of optimizing economic efficiency by taking two typical scenarios as examples.

Exhibit 4: Approaches for sustained and stable supply of green hydrogen

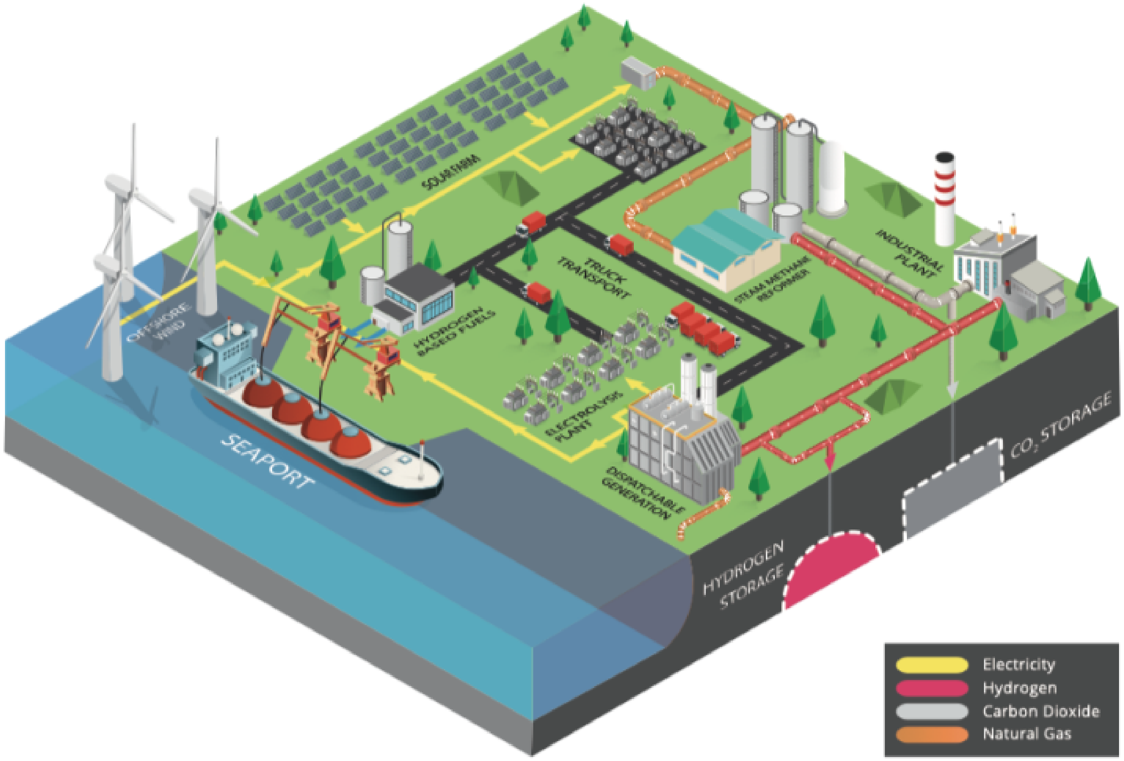


RMI Graphic. Source: RMI

Synergetic interaction between multiple low/zero-carbon resources, their infrastructure, and industrial capacity

In the industrial low-carbon and zero-carbon transition, the typical layout of areas that can achieve cluster development includes industrial capacity and relevant low/zero-carbon resources and their infrastructure, such as green electricity and green hydrogen, as shown in Exhibit 5.[10] Successful cases have the following features: local adaptation that selects appropriate industrial production methods based on capacity and resources; application of advantageous local low/zero-carbon resources and necessary infrastructure, which, in the case of green hydrogen, should include renewable generation installations and electrolyzers for hydrogen production as well as auxiliary facilities for the storage and transportation of hydrogen; and reasonable leveraging of existing obsolete facilities for orderly phase-out or transformation. For example, existing natural gas pipelines can be utilized and integrated with the green hydrogen value chain system.

Exhibit 5: **Example of typical layout of low/zero-carbon industrial clusters**



Source: Deloitte

Considering the roles of all stakeholders to drive rapid development of the cluster

Deep carbon reduction in industry, especially in heavy industry, is usually costly. This can easily lead to the “chicken-and-egg” problem of whether to develop lower-carbon industrial production to create demand for green hydrogen, or to ensure the supply of green hydrogen for industrial production. As a result, in formulating a business model, it is necessary to prioritize deployment of anchor projects and to leverage the early supply and demand of green hydrogen, thereby accelerating the development of the entire cluster.

In this process, all stakeholders have roles to play: industrial companies should deploy low/zero-carbon production as early as possible to create sufficiently large-scale utilization cases for green hydrogen; the supply side of green hydrogen should strive to guarantee a sufficiently large-scale and cost-effective supply; the infrastructure for storage and transportation should be in place to match the supply and demand; and the stakeholders in finance, policy, and others should provide sufficient support, especially in the early development stage. Chapter 3 of this report analyzes feasible business models and the roles of stakeholders focusing on two case studies in the United Kingdom and the United States.

2. Technological and Economic Considerations for Cluster Development

2.1 Green hydrogen production

At present, there are four main technology routes for hydrogen production using electrolyzers: alkaline electrolysis (ALK), proton exchange membrane electrolysis (PEM), anion exchange membrane electrolysis (AEM), and solid oxide electrolysis (SOEC). ALK is the most mature and low-cost technology in China that has been applied at scale; PEM is efficient and flexible in start/stop, but it is still in the early stage of commercialization in China (see Exhibit 6). AEM and SOEC are still under R&D. Considering the maturity and application status of the technology, this study mainly looks at ALK as an example to analyze its economics and potential for cost reduction.

In producing hydrogen using electrolysis, the capital expenditure (capex) includes electrolyzer equipment cost, installation cost, and land cost; the operating expenditures (opex) include electricity, water, operations and maintenance, etc. In regions with richer renewable resources and lower green power prices, the cost of producing green hydrogen through ALK was around RMB 18/kg in 2023, which was still significantly higher than that of producing hydrogen from fossil fuel (RMB 10–12/kg).[11] In the mid- and long term, as the cost of electricity and equipment declines, the production cost of green hydrogen is expected to drop to RMB 11/kg by 2030 and RMB 7/kg by 2050, which is 62% lower than the cost in 2023. The economics of green hydrogen gradually improve compared with the cost of fossil fuel–based hydrogen and industrial by-product hydrogen (see Exhibit 7).

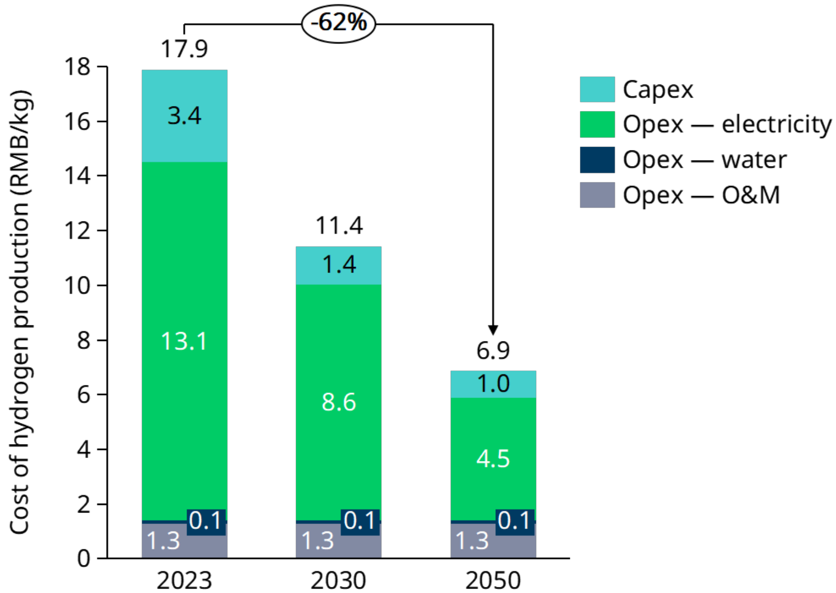
Exhibit 6: **Major technologies for producing hydrogen from electrolysis in China**

	ALK	PEM	AEM	SOEC
Operating temperature (℃)	70–90	70–80	40–60	600–1,000
Maximum size per unit (Nm^3/h)	2,000	260	0.5	n/a
Current density (A/cm^2)	0.25–0.45	1.0–2.0	0.2–2	0.2–1.0
Power consumption (kilowatt-hours/Nm^3)	4–5.5	4.3–6	4.5–5.5	3.0–4.0
Start/Stop speed (hot | cold)	Minute-level | > 60 minutes	Second-level | 5–10 minutes	n/a	Slow start/stop
Development stage	Commercially available	Early stage of commercialization	Technology R&D	Technology R&D
Advantages	-Low equipment cost -Mature technology	-High current density -High intermittent power adaptability -Low O&M cost	-Low material cost -Non-precious metal catalysts applicable	-High efficiency in theory -Non-precious metal catalysts applicable
Disadvantages	-Low current density -Low adaptability to indirect power sources -Corrosive electrolyte -High O&M cost	-High equipment cost -High cost and scarcity of precious metal catalysts	-Difficult mass production of anion exchange membranes -Still under technology R&D	-Limited application cases because reaction requires high temperature -Still under technology R&D

Note: Nm^3/h = normal cubic meters per hour. A/cm^2 = amperes per square centimeter. O&M = operations and maintenance.

Source: Ping An Securities; Eastmoney Securities

Exhibit 7: **Cost structure of hydrogen production from ALK**



Key assumptions: electrolyzers are utilized 3,500 hours/year, with a designed life of 50,000 hours or 25 years; the price of electricity is RMB 0.25/kWh, RMB 0.18/kWh, and RMB 0.10/kWh in 2023, 2030, and 2050, respectively; the cost of the electrolyzer is RMB 1,750/kW, RMB 805/kW and RMB 560/kW in 2023, 2030, and 2050, respectively; and power consumption for hydrogen production is 4.7 kWh/Nm^3, 4.3 kWh/Nm^3, and 4.0 kWh/Nm^3 in 2023, 2030, and 2050, respectively.

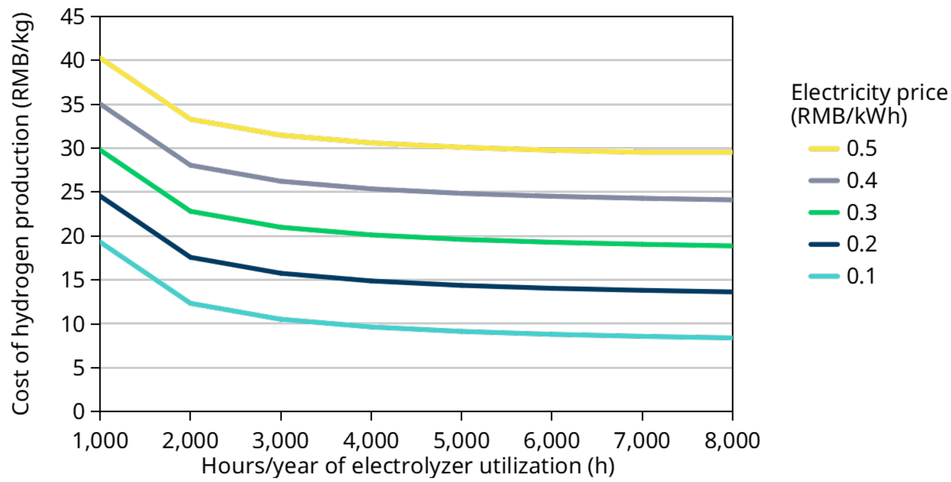
RMI Graphic. Source: RMI analysis of BNEF data (**https://about.bnef.com/blog/1h-2024-hydrogen-market-outlook-targets-meet-reality/**) and Topsperity data (**https://pdf.dfcfw.com/pdf/H3_AP202210071578934755_1.pdf**)

Electricity accounts for nearly 70% of the total cost of green hydrogen production, so reducing its cost is key to improving the economics of green hydrogen. Over the past 10 years, the levelized cost of electricity (LCOE) of solar and wind power in China has decreased by as much as 89% and 66%, respectively.[12] By 2030, the LCOE of solar and wind power is expected to fall to RMB 0.21/kWh and RMB 0.19/kWh, respectively; and to RMB 0.14/kWh and RMB 0.15/kWh by 2050.[iii]

Under a conservative scenario in which all other parameters remain at 2023 levels, every RMB 0.1/kWh reduction in electricity price would result in a nearly RMB 5 reduction in the cost of producing 1 kg of green hydrogen (see Exhibit 8). In the medium and long term, assuming at-scale deployment of electrolyzers, improvements in efficiency and life span, and increased utilization hours, the cost of green hydrogen production will be further reduced. Electricity cost remains the most important factor in green hydrogen cost, and its contribution in this respect will reach 69% and 91% by 2030 and 2050, respectively.

[iii] BNEF, 1H 2022 LCOE Update report prediction: China PV $0.023–$0.042/kWh in 2030 (taking the median value of $0.03/kWh = RMB 0.21 /kWh) and $0.016–$0.028/kWh in 2050 (taking the median value of $0.02/kWh = RMB 0.14 /kWh); onshore wind $0.019–$0.034/kWh in 2030 (taking the median value of $0.027/kWh= RMB 0.19 /kWh); $0.015–$0.026/kWh in 2050 (taking the median value of $0.021/kWh = RMB 0.15 /kWh).

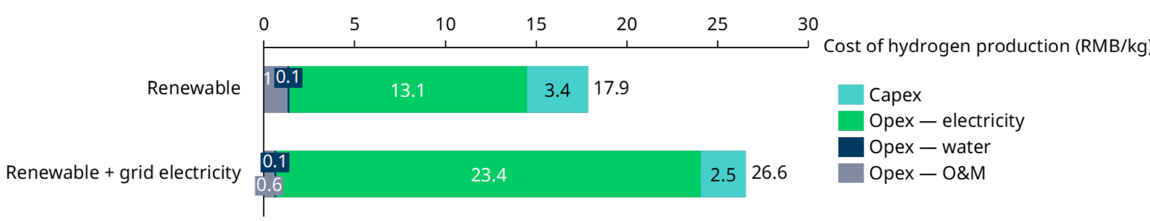
Exhibit 8: **Hydrogen production cost under different electricity prices and utilization hours**



RMI Graphic. Source: RMI

However, to meet the requirements for continuous and stable hydrogen supply in industry, the actual hydrogen utilization cost may be elevated. In the 2023 estimation, combining on-site green electricity with grid electricity allows electrolyzers to run continuously for 8,000 hours annually, with the associated hydrogen production cost nearing RMB 27/kg (see Exhibit 9). Even if the utilization of grid electricity significantly improves the annual utilization hours of the electrolyzer, the higher electricity cost still increases the hydrogen production cost. In addition, when the grid is not yet able to reach zero or near-zero carbon emissions, hydrogen producers are potentially required to purchase green certificates to fulfill compliance with the definition of "green hydrogen."

Exhibit 9: **Hydrogen production cost based on renewable and grid electricity**



Note: Key assumptions: annual electrolyzer utilization is 3,500 hours and 8,000 hours, respectively; renewable electricity prices and large industrial grid electricity prices are RMB 0.25/kWh and RMB 0.6/kWh; the cost of electrolyzer is RMB 1,750/kW; and hydrogen production electricity consumption is 4.7 kWh/Nm³.

RMI Graphic. Source: RMI analysis of BJX-power data (**https://m.bjx.com.cn/mnews/20210113/1129229.shtml**)

2.2 Green hydrogen storage

The primary types of hydrogen storage technologies are physical, chemical, and geological. Each has its own utilization cases due to differences in scale, storage cycles, and flexibility (see Exhibit 10).

Hydrogen storage is broadly divided into small to medium scale (<1,000 tons) and large scale (>1,000 tons). For small- and medium-scale storage, the most common method uses pressurized tanks. For example, Sinopec's Xinjiang Kuqa Green Hydrogen Demonstration Project, which produces 20,000 tons of hydrogen per year from electrolyzed water, deploys 10 sets of hydrogen storage spherical tanks with a volume of 2,000 m^3 each and a pressure of 1.5 megapascals (MPa). In large-scale hydrogen storage, salt cavern hydrogen storage is more desirable in terms of technological maturity and safety when geological resources allow. China has more than 1 trillion tons of underground salt reserves. The salt cavern resources are mainly located in Northwest, North, and East China and other renewable resource-rich areas or capacity-intensive regions.[13]

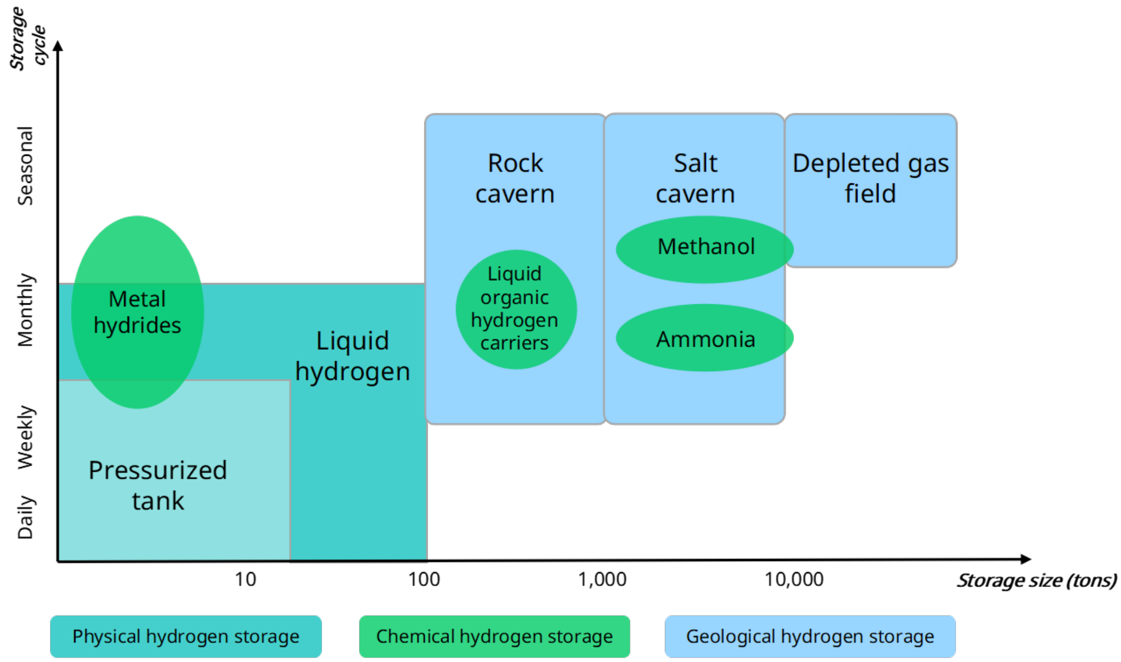
Exhibit 10: **Comparison of hydrogen storage technologies**

Indicators	Small- to medium-scale hydrogen storage					Large-scale hydrogen storage			
	Pressurized tank	**Liquid hydrogen**	**Metal hydrides**	**Liquid organic hydrogen carriers**	**Rock cavern**	**Methanol**	**Ammonia**	**Salt cavern**	**Depleted gas field**
Type of hydrogen storage	Physical	Physical	Chemical	Chemical	Geological	Chemical	Chemical	Geological	Geological
Flexibility	●	◕	◕	◑	◕	◑	◑	◑	◔
Storage stability	●	◔	◕	◕	●	◕	◕	◕	◑
Hydrogen purity	●	●	◕	◕	●	◑	◑	●	◔
Geographical availability	●	●	●	●	◕	●	●	◑	◑
Technology maturity	●	◕	◕	◕	◑	●	●	●	◑
Safety	◕	◕	◕	◕	●	◑	◔	●	●

RMI Graphic. Source: RMI

In addition to scale, the cycle time of hydrogen storage is also an important consideration in selecting a hydrogen storage method for a particular demand case (see Exhibit 11). Daily or weekly storage mainly addresses short-term fluctuations in renewables, such as the absence of sunlight at night, while monthly or seasonal hydrogen storage mainly addresses long-cycle energy fluctuations, such as dry periods in hydropower. Physical hydrogen storage is mainly applied in small-scale and short-cycle cases, while geological hydrogen storage is usually used in large-scale and long-cycle scenarios. Among the chemical hydrogen storage methods, the metal hydrides method is more flexible in small-scale cases, and most of the rest are suitable for hydrogen storage with medium- to large-scale and medium- to long-cycle.

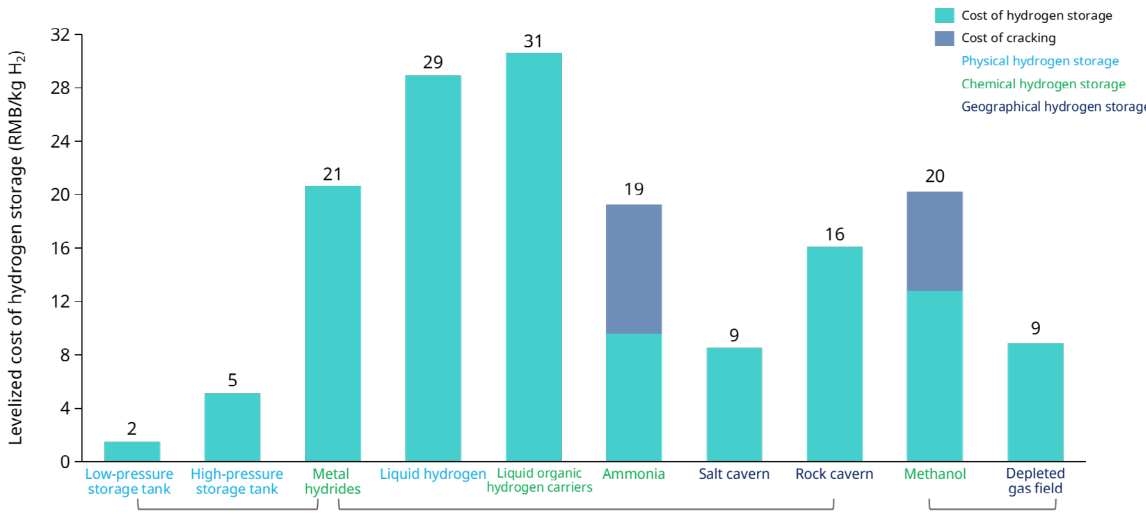
Exhibit 11: **Technologies for different hydrogen storage cases**



RMI Graphic. Source: RMI

Exhibit 12 compares the levelized cost of different current hydrogen storage technologies under suitable cycles to compare economic efficiency. Among the options, low-pressure and high-pressure storage tanks are more economical, both below RMB 5/kg hydrogen. However, pressured tanks require more land area. In the western provinces where space is relatively abundant, the deployment of low- or high-pressure tanks can be prioritized. For large-scale hydrogen storage, which is more likely in industrial cases, geological hydrogen storage offers better economic efficiency and can be prioritized when geological resources are suitable. Salt caverns and rock caverns for hydrogen storage have been successfully used in industrial scenarios in Europe. For example, the Hybrit hydrogen metallurgy pilot project in Sweden features a 100 m^3 underground rock cavern for hydrogen storage, with plans to increase the capacity to 100,000 m^3 in the future.[14]

Exhibit 12: **Levelized cost of different hydrogen storage methods**



Note: The cost of hydrogen from cracking or reforming is an additional cost for ammonia and methanol as they can be utilized directly in some application cases. Pressurized storage tanks include low-pressure tanks up to 10 MPa and high-pressure tanks around 30 MPa.

RMI Graphic. Source: RMI, BNEF, ETC, Energy Conversion and Management

2.3 Green hydrogen transportation

There are various hydrogen transportation methods which can be divided by physical state — gas, liquid, and solid — or by carrier, into tube trailers, tankers, trucks, ships, pure hydrogen pipelines, and hydrogen-blended natural gas pipelines (see Exhibit 13). This study focuses on tube trailer, pure hydrogen pipeline, and liquid hydrogen tanker, taking into consideration transportation volume and distance requirements for hydrogen in China, and the stage of development for different transportation modes.

Exhibit 13: **Summary of major hydrogen transportation methods**

Hydrogen State	Transport Method	Capacity	Development Stage	Suitable Scenarios
Gas	Tube trailer	~350 kg per vehicle	Mature	Small volume; short distance
	Pure hydrogen pipeline	/	Large-scale, long-distance pure hydrogen pipeline is in the early development stage; research is still needed for the use of higher-grade steel materials.	Large volume; point-to-point
	Hydrogen-blended natural gas pipeline	/	Engineering, demonstration, and verification stage; can meet the technical and safety requirements of hydrogen blending ratio up to 10%. Higher proportion of hydrogen mixture, hydrogen embrittlement, and other problems still need to be studied.	Large volume; mostly used for hydrogen-blended city gas pipelines and long-distance natural gas pipelines
Liquid	Liquid hydrogen tanker	~2,500 kg per vehicle	More mature and used mainly in aerospace and military in China.	Large volume; short to medium distance
	Ship (liquid ammonia-based hydrogen transportation)	1,800–12,000 kg per ship	Commercially available, transported in the form of liquid ammonia.	Large volume; Very long distance
Solid	Truck	700–1,500 kg per vehicle	R&D	/

Note: Ocean shipping vessels typically have a volume of 15,000–100,000 m^3. Assuming the density of liquid ammonia is 0.68 kg/m^3, the volume of ammonia transported per shipment is 10,200–68,000 kg, which equals 1,800–12,000 kg hydrogen transported per shipment.

RMI Graphic. Source: ETC (**https://www.energy-transitions.org/publications/making-clean-hydrogen-possible/**), Guosen Securities, and expert interviews

Tube trailer

Tube trailers have the advantages of simple operation, short hydrogen compression and release time, mature technology, and complete industrial chain support — and are currently the dominant method of hydrogen transportation in China. At the application level, metal cylinders with a design pressure of

20 MPa are most common, offering a single hydrogen transportation capacity of ~280–350 kg. Looking ahead, this hydrogen transportation method will evolve toward higher-pressure and large-volume hydrogen storage cylinders.

Liquid hydrogen tanker

Liquid hydrogen tankers transport hydrogen that is liquified by low temperatures. Despite large single-vehicle capacity and high transport efficiency, this method is mostly suitable for large-scale, medium- and long-distance transportation due to the energy-intensive liquefaction process. Further breakthroughs in technologies, equipment manufacturing, product quality, and cost are anticipated.

Pure hydrogen pipeline

Given the geographical mismatch between the regions in China with high demand for green hydrogen and those supplying it, pure hydrogen pipelines are expected to become the main means of large-scale, long-distance hydrogen transportation. Due to factors including equipment manufacturing, cost, engineering design, and other aspects, global pure hydrogen pipelines are mainly at the pressure of 4 MPa. In October 2023, China had a total of about 100 km of pure hydrogen pipelines built and in use. Since the issuance of the National Implementation Program for the Construction of One National Oil and Gas Network that year,[15] the effort to build pipelines has accelerated — with more than 1,000 km planned or under construction. China is expected to have 3,000 km of long-distance hydrogen pipelines by 2030.[16]

This study analyzes the cost of the above three methods of hydrogen transportation based on the current typical technology level and cost breakdown. The change of levelized cost of hydrogen transportation (LCOT) with transportation distance for 100% and 50% utilization is shown in the left part of Exhibit 14 based on the following assumptions: tube trailers use 20 MPa pipes; for liquid hydrogen transportation, the hydrogen liquefaction capacity is 5 tons/day and the single-truck load is 2,500 kg/vehicle; for pipeline transportation, the pipe diameter is 273 mm and the hydrogen transportation capacity is 29,000 tons/year operating at full capacity. The right part of Exhibit 14 shows the cost structure for 200 km in length.[iv] The major findings are as follows:

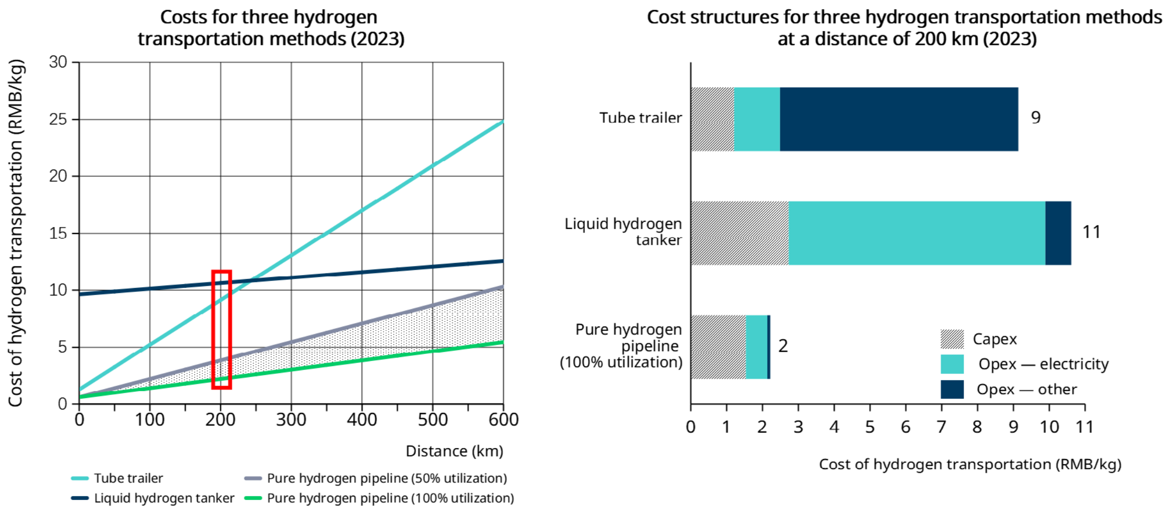
Tube trailer: More economical for transportation distance shorter than 250 km; at a transportation distance of 200 km, operating expenditures account for over 85% of LCOT — primarily for operation and maintenance costs such as labor and oil.

Liquid hydrogen tanker: More economically viable in medium- and long-distance transportation with large volume; at a transportation distance of 200 km, electricity and liquefaction equipment cost make up 90% of LCOT, accounting for 67% and 23%, respectively.

Pure hydrogen pipeline: Assuming 100% utilization, the unit cost of pipeline transportation is the lowest of the three methods. At a transportation distance of 200 km, the LCOT is just one-fourth that of a tube trailer and one-fifth that of a liquid hydrogen tanker. In terms of cost components, 70% of the cost comes from up-front capital expenditure investment (i.e., depreciation of the pipeline and the construction and maintenance of the compressors).

[iv] In this study, the hydrogen transportation distance of 200 km is selected with reference to the distance from Ordos, Inner Mongolia, which is rich in renewables, to Yulin, Shaanxi, the site of hydrogen utilization.

Exhibit 14: **Cost comparison of three hydrogen transportation methods**



RMI Graphic. Source: RMI

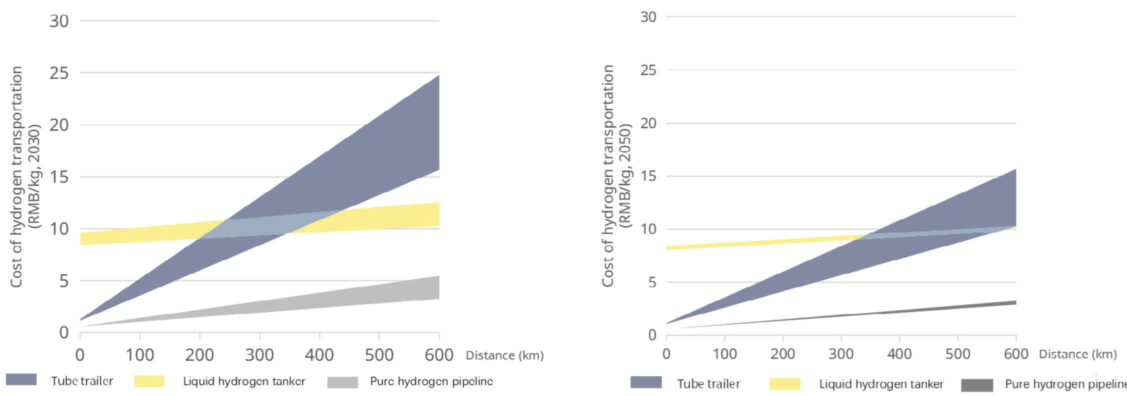
To meet the future demand for large-scale hydrogen transportation, each of the hydrogen transportation methods will evolve toward larger capacity per load. Tube trailers can reduce transportation cost by increasing the pipe pressure from the current 20 MPa to 30 MPa by 2030 and 50 MPa by 2050. At present, most liquid hydrogen plants produce 5 tons/day for transport by tanker. That output can be increased to 30 tons/day and 100 tons/day by 2030 and 2050, respectively. The designed capacity of pipeline transportation is 20,000–30,000 tons/year,[v] and typically is used to move hydrogen a short distance. As the demand grows, the capacity of a single pipeline will typically reach 100,000 tons/year by 2030, and 400,000 tons/year by 2050.

Based on these expectations, Exhibit 15 shows the correlating cost changes for each hydrogen transportation method by 2030 and 2050. If 100% utilization is reached, hydrogen pipeline transportation will be most economical at any distance.[vi] By 2030, the upper limit of transportation distances over which tube trailers are cost-optimized over liquid hydrogen tankers will extend from 250 km to 350 km, thanks to the increased capacity of a single vehicle enabled by the advancement in high-pressure pipes. In the long term (2050), the further development of high-pressure pipes will raise this upper limit from 350 km to almost 600 km.

[v] Hydrogen pipelines are expected to increase in diameter and capacity. Assuming that the pipeline operates at 100% capacity, the pressure is 4 MPa, and the typical pipe diameters in 2020, 2030, and 2050 are 273 mm, 508 mm, and 1,016 mm, respectively; annual hydrogen transportation capacity will be 29,000 tons, 100,000 tons, and 400,000 tons.

[vi] Pipeline construction usually involves costs and expenditures for engineering design, exploration, land acquisition, pipes, compressors, construction, security, and others. Among these costs, the land acquisition is the largest variable. In this study, due to the limited public data related to pipelines, the construction cost of pipelines refers to the average values given by industry experts, and the specific costs should be based on actual expenditures.

Exhibit 15: **Cost changes of major hydrogen transportation methods by 2030 (left) and 2050 (right)**



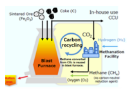
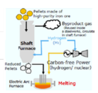
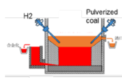
Note: Key assumptions: tube trailers of 20 MPa, 30 MPa, and 50 MPa can carry 350 kg, 500 kg, and 750 kg per vehicle, respectively, with an effective capacity rate of 75%, 85%, and 90%; liquid hydrogen tankers will be upgraded from 2,500 kg/vehicle at present to 4,000 kg/vehicle in the future; and investment per millimeter of pipe diameter is RMB 10,000 for pipeline transportation.

RMI Graphic. Source: RMI analysis of data from Huazhong University of Science and Technology; and Guangzheng Hang Seng Advisory(**http://qccdata.qichacha.com/ReportData/PDF/dfc9713e0408154e2b3f91c2f0e63527.pdf**)

2.4 Green hydrogen utilization

In the steel industry, there are three primary technical approaches for incorporating hydrogen (H_2) into production. The first is the hydrogen-rich blast furnace, which entails using existing blast furnace equipment to inject high-hydrogen-content reducing gas to replace some of the coke. Although the retrofit costs are relatively low, the potential for carbon reduction is limited. The second, hydrogen-based direct reduced iron, relies entirely on hydrogen as a reducing agent, offering a carbon emissions reduction potential exceeding 95%, but entailing high-grade pellets and relatively high capital costs. The third, hydrogen-based smelting reduction, involves injecting a certain proportion of hydrogen into smelting, but the technology for this method is still relatively immature. Exhibit 16 shows an overview and comparison of these technical methods.

Exhibit 16: **Main hydrogen-based technologies in steel production**

Hydrogen utilization method	Illustration	Technology description	Potential for emissions reduction*	Technology maturity	Pilot projects	Advantage	Disadvantage
Hydrogen-rich blast furnace H_2-BF		Reducing gas with high hydrogen content injected into the blast furnace	20%	5–9	Hydrogen-rich carbon cycle blast furnace, Bayi Iron and Steel; "Replacing coal with hydrogen" blast furnace ironmaking project, Thyssenkrupp	Low retrofit cost, economically efficient	Limited potential for emissions reduction in theory; technical difficulty in pure-hydrogen reducing
Hydrogen-based direct reduction H_2-DRI		Increasing the proportion of hydrogen in direct reduction ironmaking in gas-based shaft furnaces or fluidized beds	95%	6–8	Hydrogen-rich gas-based direct reduction iron project, HBIS; Direct reduction of iron project, ArcelorMittal in Germany	High potential for emissions reduction in theory, with relatively more international experience for reference	Difficult to retrofit from blast furnace; moderate research and project experience
Hydrogen-based smelting reduction H_2-SRI		Injection of a percentage of hydrogen-rich gas into the smelting reduction ironmaking process	95%	5	Hydrogen-based smelting reduction, Jianlong, Inner Mongolia	High potential for emissions reduction in theory	Fewer international advanced experiences, more difficulties in retrofitting, weak research and project experience

* Emissions reduction could be increased with the utilization of renewables, where direct reduction of iron is combined with electric furnace.

RMI Graphic. Source: RMI

The chemical industry currently has the largest supply of hydrogen, where the primary products are mostly hydrogen-based compounds, sourced mainly from gray hydrogen. Transitioning from gray hydrogen to green hydrogen can significantly reduce carbon emissions from producing gray hydrogen using coal or natural gas. Furthermore, utilizing the Power-to-X (P2X) route enables direct use of carbon dioxide and green hydrogen as feedstocks for the production of green methanol, green ethylene, and other chemical products. Exhibit 17 summarizes the utilization of green hydrogen in the production of key chemicals.

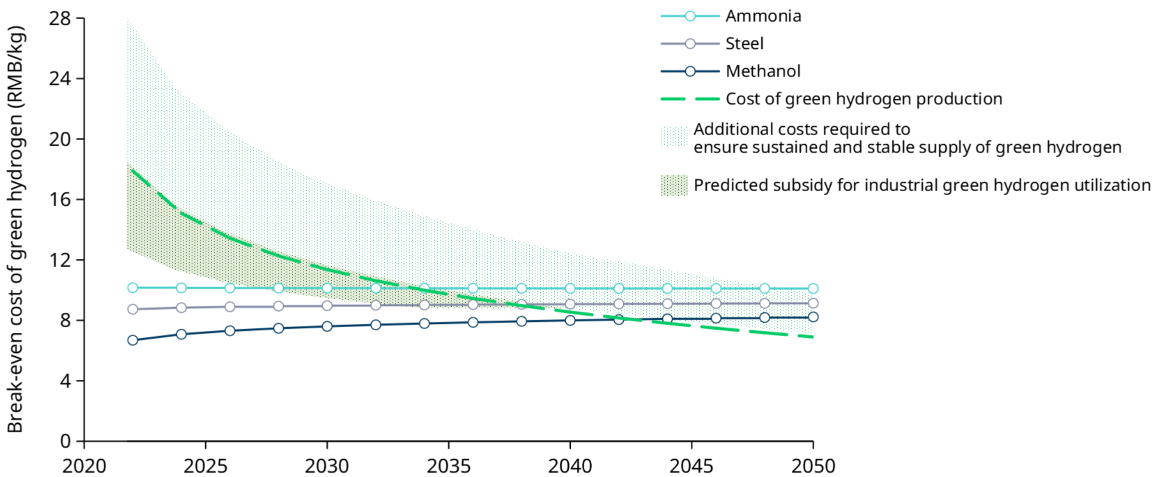
Exhibit 17: **Green hydrogen utilization in major chemical products**

	Hydrogen utilization method	Industry emissions	Hydrogen ratio*	Technology	Utilization category	Technology description	Pilot projects
	Ammonia	210 million tons/year	37%	Haber-Bosch method	Replacement of gray hydrogen	Producing ammonia using nitrogen and hydrogen, replacing gray hydrogen obtained from coal or natural gas with green hydrogen	Yara Green Ammonia Project, Norway
	Oil refinery	210 million tons/year	10%	Hydrotreating	Replacement of gray hydrogen	Hydrotreating the components after normal depressurization to reduce the sulfur content, lower the degree of unsaturation, and improve the stability of the oil product	Sinopec Xinjiang Kuqa green hydrogen demonstration project that supplies Tahe refinery
	Methanol	200 million tons/year	19%	Green hydrogen coupling coal	Replacement of gray hydrogen	Adjusting the ratio of carbon monoxide to hydrogen in syngas using green hydrogen for maximum conversion of carbon to methanol	Ningxia coal chemical coupling green hydrogen to methanol
				Power-to-X	Additional demand	Directly producing methanol using hydrogen and carbon dioxide	Henan Anyang carbon dioxide hydrogenation to methanol

* Hydrogen utilization amount per year in the sector over total national hydrogen utilization amount.

RMI Graphic. Source: RMI

Exhibit 18: **Time to parity between green hydrogen routes and traditional routes in steel, ammonia, and methanol**



Note: Representative low-carbon green hydrogen technologies are selected for each product, including ammonia representing green hydrogen alternatives, steel representing direct reduced iron (DRI), and methanol representing Power-to-X (P2X); the additional cost required to ensure sustained and stable supply of green hydrogen is the extra cost added by purchasing grid electricity or supporting energy storage to improve the scale and stability of electricity used for hydrogen production. The subsidy for green hydrogen for industrial use is based on the existing green hydrogen subsidy policy with reference to the green hydrogen subsidy of RMB 5.6/kg in Ningdong Base and assumes that the subsidy will be gradually decreased through 2040.

RMI Graphic. Source: RMI

Exhibit 18 illustrates the cost of green hydrogen in steel, ammonia, and methanol production, when the green hydrogen routes are at parity with the conventional routes. To simplify the analysis, the additional costs required to ensure a continuous and stable supply of green hydrogen are not considered in the baseline analysis.

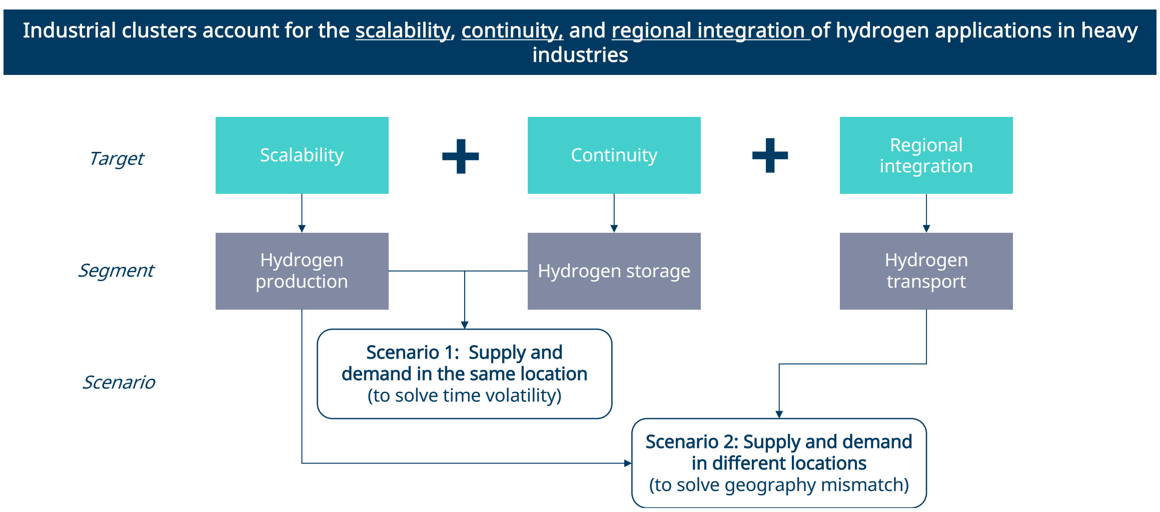
By comparing the cost of green hydrogen at parity with the cost trends of green hydrogen production, the time at which green hydrogen routes begin to achieve cost competitiveness can be roughly determined, which can help guide the deployment of projects. For example, green hydrogen–based ammonia and steel production is expected to reach parity with traditional fossil fuel energy production routes around 2035, with green hydrogen costs at approximately RMB 10.1/kg and RMB 9.0/kg, respectively. Green hydrogen–based methanol production is expected to achieve parity with traditional routes between 2040 and 2045, with the cost of green hydrogen at RMB 8.1/kg.

If the analysis includes costs required to ensure a continuous and stable supply of green hydrogen — such as the costs associated with integrating grid electricity to ensure stable hydrogen production power during periods of limited wind and solar output, the premiums for energy storage, suboptimal wind and solar resources, etc. — the cost of green hydrogen routes in industrial production increases. Consequently, the time at which green hydrogen routes achieve parity with traditional pathways will be delayed. However, under the push for low-carbon green development, policies and market factors such as subsidies for low-carbon production and carbon markets will bolster the cost competitiveness of green hydrogen routes, potentially advancing the time to parity.

3. Industry Cluster Scenarios and Business Models

Combined with the previous economic analysis, this chapter provides optimal green hydrogen utilization costs in two typical scenarios for constructing hydrogen supply and utilization schemes, as shown in Exhibit 19. Scenario 1 shows the optimized combination of hydrogen production and storage that enables sustained and stable supply of hydrogen when hydrogen supply and demand are in the same location. Scenario 2 shows hydrogen supply combined with hydrogen production and transportation when hydrogen supply and demand are in different locations.

Exhibit 19: **Analysis structure of industrial hydrogen utilization scenarios**



RMI Graphic. Source: RMI

3.1 Scenario 1: Hydrogen supply and demand in the same location

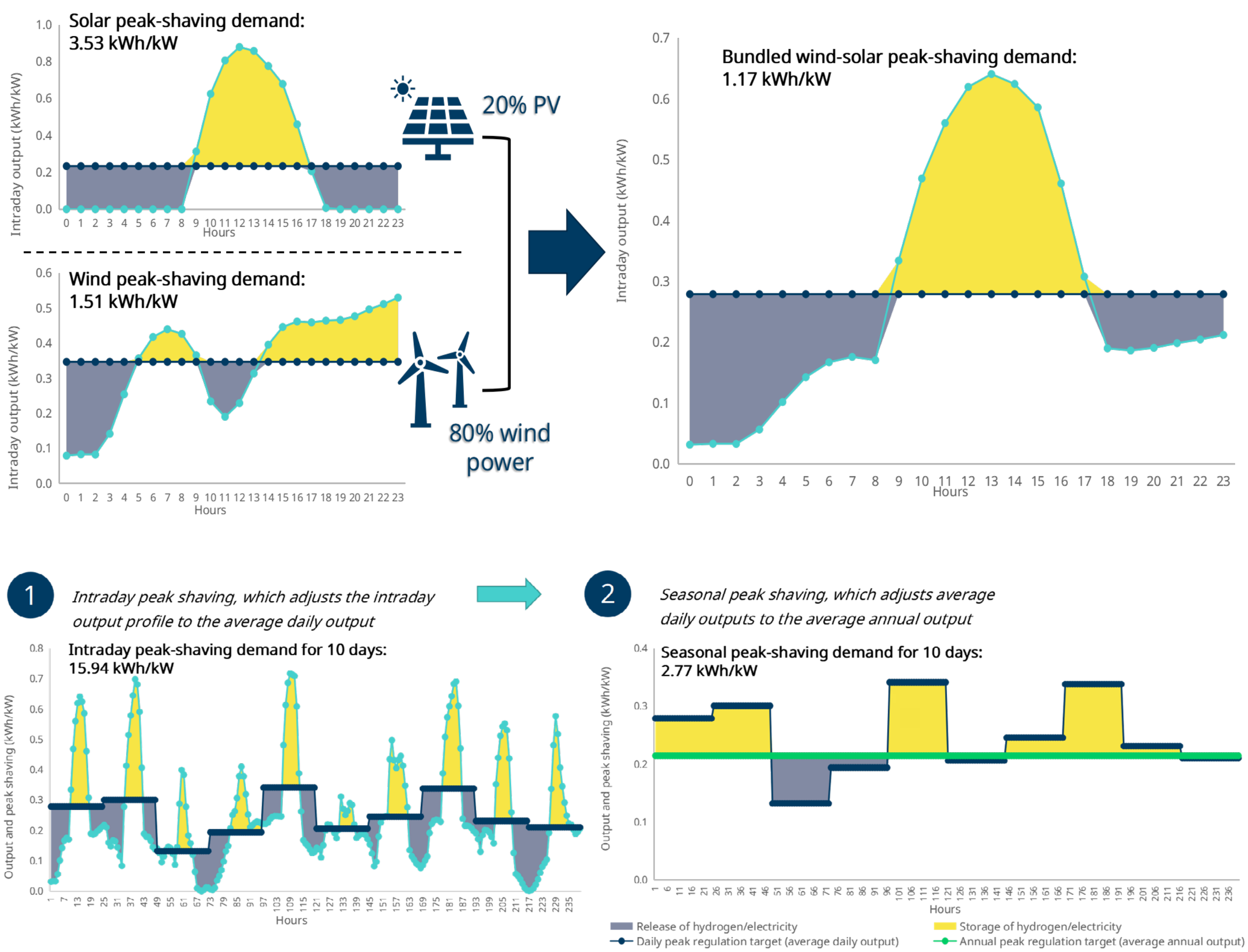
Where industrial production is in areas with abundant renewable resources, hydrogen supply and demand can address the fluctuations of hydrogen supply by optimizing the structure of hydrogen production and storage.

To fully leverage local wind and solar resources, it is best to deploy renewable energy generation and hydrogen production equipment as close to industrial production as possible. Due to the intermittency of wind and PV resources, additional peak-shaving measures are required to meet the stability requirement of industrial hydrogen utilization.

The extra peak-shaving requirements initially can be minimized through wind-solar bundling and ratio optimization, selecting from options available for daily and seasonal peak-shaving. On this basis, a comprehensive model calculation is conducted, taking into account the levelized cost of wind and solar power generation, the cost of peak-shaving measures, and the available land area. The goal is to achieve the lowest possible cost of hydrogen utilization in industry.

Qinghai province is an example of an area with rich renewable resources — its wind and solar outputs on a typical day are shown in Exhibit 20. If peak-shaving targets the average value of outputs on that day, when the output is higher than the target, the excess output will be stored in the form of electricity or hydrogen; when the output is lower than the target line, the storage energy will be discharged to ensure the stability of overall output. If only solar output is considered, the daily peak-shaving demand is 3.5 kWh/kW; if only wind output is considered, the peak-shaving demand is 1.51 kWh/kW; and with a certain ratio, for example, of 20% solar and 80% wind, the total intraday peak regulation-shaving is lowered to 1.17 kWh/kW. In the same way, the seasonal peak-shaving demand can be determined by taking the average of multiday outputs as the annual average output target.

Exhibit 20: **Intraday and seasonal peak shaving demand in Qinghai province when considering wind-solar bundling**



The assumptions for the above case in Qinghai province are as follows:[vii] the levelized costs of wind and solar are RMB 0.32/kWh and RMB 0.20/kWh, respectively.[17] The wind and solar installations by area are 5 megawatts (MW) per square kilometer (km^2) and 50 MW/km^2, respectively,[18] and renewables are used for on-site hydrogen production as much as possible where the land area allows. The 610 km^2 solar power generation park in Hainan prefecture, Qinghai province, provides a reference for the upper limit of the land area.[19]

In terms of peak-shaving methods, priority should be given to using low-pressure storage tanks for intraday hydrogen storage and salt caverns for seasonal hydrogen storage. When provided with hydrogen storage tanks, the maximum storage capacity is 30 tons of hydrogen assuming the maximum usable area is 1 hectare, with Sinopec Xinjiang Kuqa Green Hydrogen Demonstration Project as a reference.[viii] The rest of the intraday hydrogen storage demand can be met by supplementing with grid electricity for hydrogen production, and the cost is the difference between the cost of grid electricity and the feed-in tariff of residual renewables, which is assumed to be RMB 0.3/kWh.

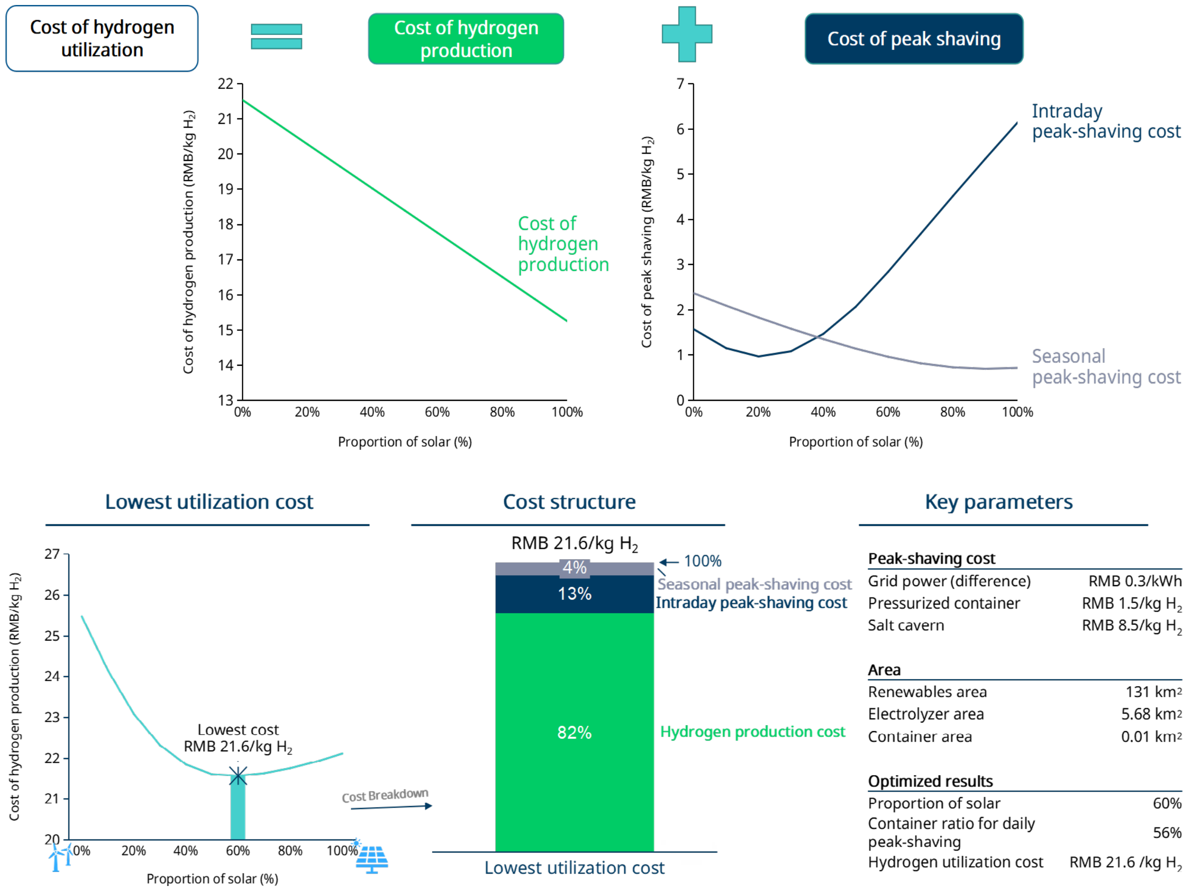
In this scenario, hydrogen supply and demand are in the same location, and no additional hydrogen transportation cost is incurred, so the cost of industrial hydrogen utilization is the sum of hydrogen production cost and peak-shaving cost. From the perspective of hydrogen production costs, since the levelized cost of local solar power is lower than that of wind power, the higher the proportion of solar in the wind-solar bundle, the lower the hydrogen production cost. Regarding peak-shaving costs, to meet intraday peak-shaving needs, the cost initially decreases and then increases as the proportion of solar in the wind-solar bundle rises, reaching its lowest point when solar accounts for about 20%. To satisfy seasonal peak-shaving needs, the peak-shaving cost decreases rapidly, then slowly as the solar proportion increases.

As shown in Exhibit 21, when the solar proportion is 60%, the cost of hydrogen utilization is the lowest, which is RMB 21.6/kg. Of that cost, hydrogen production accounts for 82%, intraday peak regulation 13%, and seasonal peak regulation 4%. In this scenario, the land area required for the renewable installation is 131 km^2, which is lower than the available amount of space, so the potential for local hydrogen production from renewable power is maximized. Due to space constraints, only 56% of the daily peak regulation demand is met by the tanks, while the rest is provided by grid electricity.

[vii] This section serves solely as a scenario demonstration. Under different assumptions, calculations can be performed by referring to the methods mentioned in this study.

[viii] The Sinopec Xinjiang Kuqa Green Hydrogen Demonstration Project is China's first 10,000-ton renewable-based hydrogen production project. It is designed for hydrogen storage capacity of 210,000 standard cubic meters, corresponding to 10 2,000-cubic meter, 1.5 MPa hydrogen storage spherical tanks, occupying an area of approximately 1 hectare.

Exhibit 21: **Minimum hydrogen utilization cost and cost structure**



RMI Graphic. Source: RMI

3.2 Scenario 2: Hydrogen supply and demand in different locations

Supply and demand for hydrogen may be in different locations when industrial production is in areas with poor renewable resources. Sustained and stable supply of hydrogen can be enabled through an optimized combination of hydrogen production and hydrogen transportation.

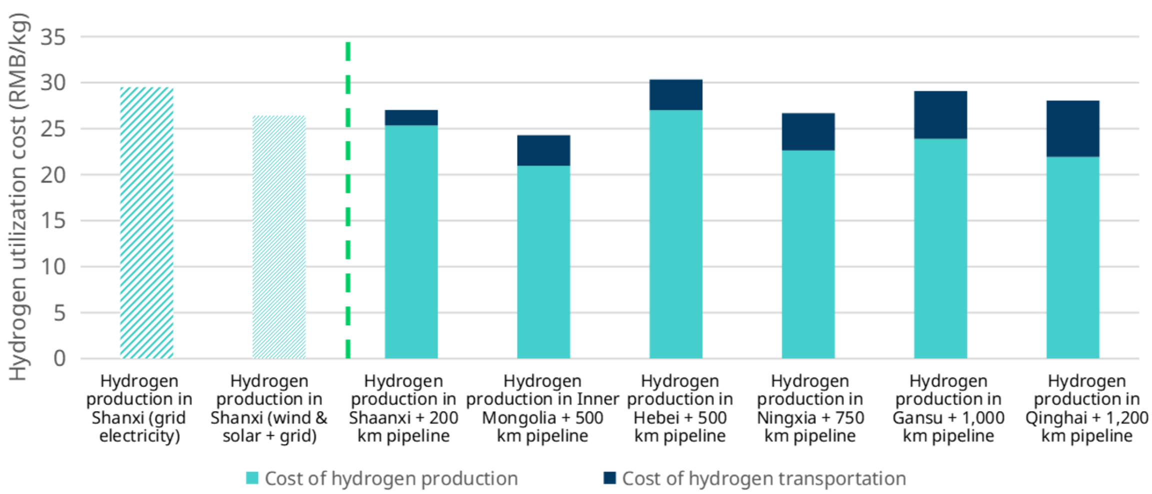
To optimize end-user hydrogen utilization cost when hydrogen supply and demand are in different locations, the key is finding the location where hydrogen production benefits from the electricity price while accounting for the transportation cost by distance and volume. On the hydrogen production side, to ensure stability of supply while maximizing the use of renewables, the shortfall in output caused by renewable intermittency can be made up with grid electricity.[ix] The hydrogen is then transported to the place of utilization in the most economical method based on the distance and volume of transportation.

[ix] Since grid electricity is not necessarily zero-carbon, hydrogen produced under these conditions may not qualify as "green hydrogen." As the grid becomes cleaner, the carbon emissions associated with hydrogen production will also decrease. Until the grid achieves complete zero-carbon, ensuring the "green" attribute of hydrogen will require measures such as purchasing green certificates.

This study assumes steel production capacity of 1 million tons/year, generating demand of about 50,000 tons of hydrogen/year at hydrogen demand sites in Shanxi and Zhejiang provinces. The local sustained hydrogen production models are taken as a reference, and four to six typical cases of off-site hydrogen production and transportation to Shanxi and Zhejiang are also used for comparison to show the combination that optimizes the terminal hydrogen utilization cost in each case. For this hydrogen demand and transportation distance, pipeline transportation is the most economical way to transport hydrogen.

Case 1: The hydrogen consumption site is located in Shanxi. Hydrogen production sites in Shaanxi, Inner Mongolia, Hebei, Ningxia, Gansu, and Qinghai are selected for comparison. Exhibit 22 compares the hydrogen production costs under different electricity costs in these regions, the transportation costs for different distances, and the terminal hydrogen utilization costs for off-site hydrogen production and transportation to Shanxi.

Exhibit 22: **Industrial hydrogen utilization costs when hydrogen supply and demand are in different locations (Shanxi province)**



RMI Graphic. Source: RMI

If hydrogen is produced locally in Shanxi by fully utilizing local renewables and supplementing with grid electricity, without the need for transportation, the terminal hydrogen utilization cost is RMB 26.4/kg. A comparison of the cost of hydrogen production and transportation to Shanxi from several different regions showed that the terminal hydrogen utilization cost of producing hydrogen in Inner Mongolia and transporting it to Shanxi is the lowest at RMB 24.3/kg. The wind and solar resources in Inner Mongolia are superior, the LCOE of local wind and PV is low, and the off-grid wind and solar contribute nearly 50% of power for hydrogen production. Meanwhile, the price of grid electricity is low, and the transportation cost is moderate.

In terms of hydrogen production, Qinghai province is second only to Inner Mongolia in terms of cost due to its low grid electricity price, but the longer transport distance raises the terminal hydrogen cost.

The wind and solar resources in each region and some assumptions are summarized in Exhibit 23.

Exhibit 23: Relevant assumptions and parameters with Taiyuan (Shanxi) as the site of hydrogen utilization

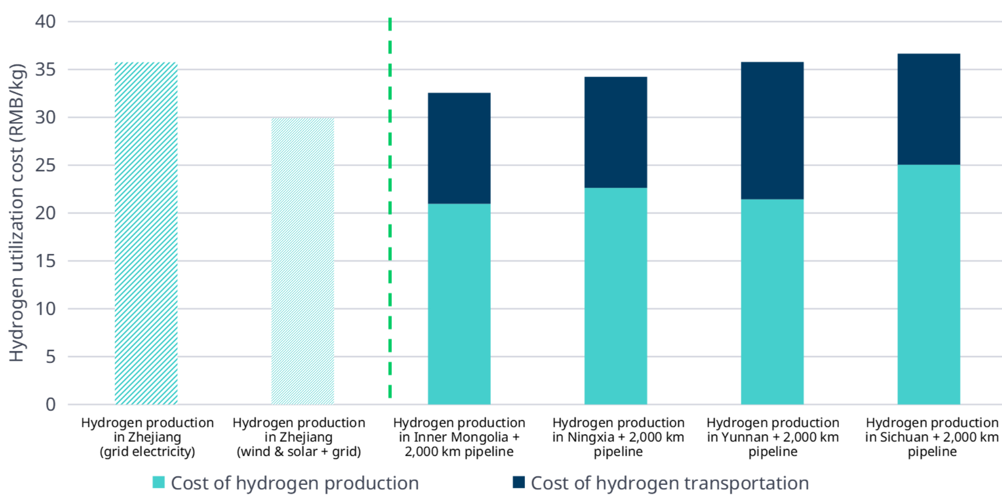
Region (provincial or municipal level)	Annual utilization hours of centralized PV hr/year	Annual utilization hours of onshore wind power hr/year	10kV grid electricity price for large industry RMB/kWh	Total electricity price for hydrogen production RMB/kWh	Distance (starting point in Shanxi) km
Shanxi (Taiyuan)	1,350	1,918	0.503	0.444	0
Shaanxi (Yulin)	1,557	1,931	0.507	0.424	200
Inner Mongolia (Ordos)	1,600	2,305	0.403	0.340	500
Hebei (Zhangjiakou)	1,375	2,144	0.563	0.455	500
Ningxia	1,500	1,811	0.395	0.371	750
Gansu	1,600	1,787	0.463	0.395	1,000
Qinghai	1,600	1,743	0.358	0.359	1,200

Note: Wind and solar power generation is prioritized within the effective utilization hours, with the target of 8,000 hours/year of electricity supply and the remaining hours to be supplemented by grid electricity. The weighted average electricity price for hydrogen production can then be calculated.

RMI Graphic. Source: BJX Power, **https://guangfu.bjx.com.cn/news/20210824/1172006.shtml**); **https://guangfu.bjx.com.cn/news/20210824/1172006.shtml**); China5e, **https://www.china5e.com/news/news-1099617-1.html**; and Energy & Investment, **https://mp.weixin.qq.com/s/qjAkBAqBX6w104idY5l1-w**

Case 2: The hydrogen utilization site is located in Zhejiang. In addition to local production in Zhejiang, hydrogen production sites in Inner Mongolia, Ningxia, Yunnan, and Sichuan were also selected for comparison. Considering the costs of hydrogen production under different electricity costs in the above regions and the transportation costs under different distances, the terminal hydrogen utilization costs for off-site hydrogen production and transportation to Zhejiang are compared in Exhibit 24.

Exhibit 24: Industrial hydrogen utilization costs when hydrogen supply and demand are in different locations (Zhejiang province)



RMI Graphic. Source: RMI

If hydrogen is produced in Zhejiang by fully utilizing local renewables and supplementing with grid electricity, without the need for transportation, the terminal hydrogen utilization cost is RMB 30/kg, which is higher than that in Shanxi province. The total wind and solar resource endowment of the two regions is similar, while the high price of electricity for large industry in Zhejiang raises the cost of hydrogen production.

Comparing cases where hydrogen is produced in several typical regions and transported to Zhejiang, the cost of hydrogen production in Inner Mongolia is the lowest. In terms of hydrogen transportation cost, pipeline transportation is more expensive in Zhejiang due to the distance from onshore renewable bases and may account for about one-third of the utilization cost. In this case, it is more appropriate to consider local hydrogen production with power transmission to the local area. Alternatively, the industrial user could also consider mobilizing industrial by-product hydrogen resources in the vicinity and hydrogen production from offshore wind power.

The wind and solar resources in each region and some assumptions are summarized in Exhibit 25.

Exhibit 25: **Relevant assumptions and parameters with Ningbo, Zhejiang province, as the site of hydrogen utilization**

Region (provincial or municipal level)	Utilization of centralized PV hr/year	Utilization of onshore wind power hr/year	10 kV grid electricity price for large industry RMB/kWh	Total electricity price for hydrogen production RMB/kWh	Distance to Ningbo, Zhejiang km
Zhejiang (Ningbo)	1,058	2090	0.622	0.510	0
Inner Mongolia (Ordos)	1,600	2,305	0.403	0.340	2,000
Ningxia	1,500	1,811	0.395	0.371	2,000
Yunnan	1,300	2,808	0.435	0.348	2,500
Sichuan	1,205	2,553	0.540	0.418	2,000

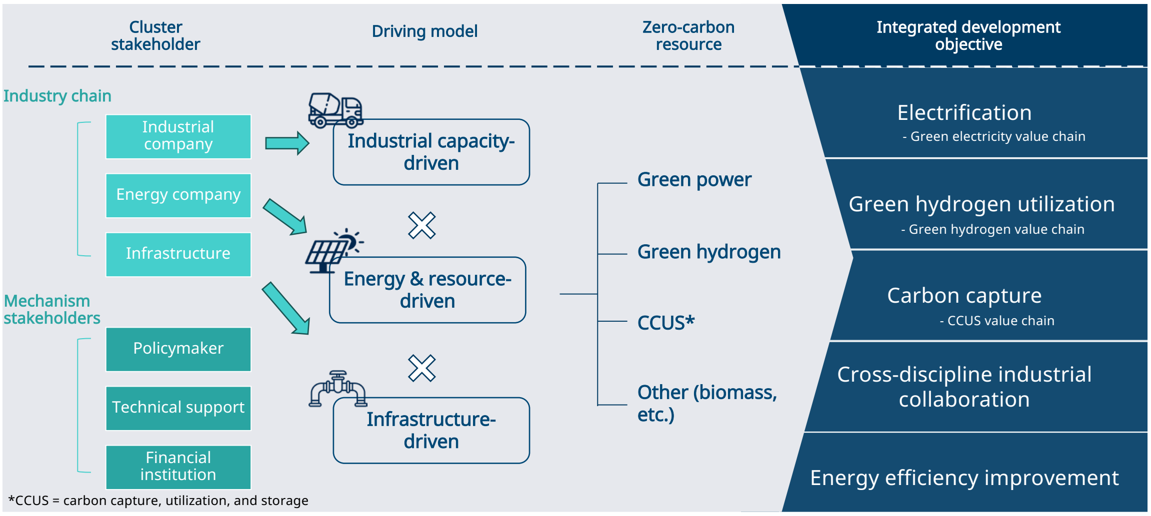
RMI Graphic. Source: RMI

3.3 Feasible business models and roles of stakeholders

In addition to optimizing and integrating the "production-storage-transportation-utilization" required for green hydrogen in industry, the successful construction and development of an industry cluster model also requires a viable business model. This involves bringing together various stakeholders, including upstream green hydrogen producers, midstream hydrogen storage and transportation infrastructure providers, and downstream industrial capacity users. By doing so, effective risk management and diversification can be achieved.

Exhibit 26 summarizes the main drivers for the formation of low/zero-carbon industrial clusters. The three key parts of the cluster are industrial capacity, energy resources, and infrastructure — each of which can drive the development of low/zero-carbon industrial clusters. These three models are not independent of each other but can work together.

Exhibit 26: **Driving models of low/zero-carbon industry clusters**



RMI Graphic. Source: RMI

In the industrial capacity–driven model, which is currently the most common, existing industrial clusters can be retrofitted to facilitate the application of low/zero-carbon energy and resources. The main advantage of this model is that it avoids large-scale stranding of the original capacity, and it includes the transformation of industrial clusters such as Teesside and Humber in the United Kingdom. The energy- and resource-driven model — exemplified by Ordos zero-carbon industrial park in Inner Mongolia — takes advantage of abundant low-cost low/zero-carbon resources to attract industrial capacity deployment. The infrastructure-driven model utilizes existing infrastructure such as natural gas pipelines and gas storage. It is mostly combined with other models to promote industrial clusters. For example, in the United States, the Houston area, which is rich in green and blue hydrogen resources and has a mature pipeline network, is a low/zero-carbon industrial cluster driven by both energy resources and infrastructure.

In the formation and development of low-carbon and zero-carbon industrial clusters, industrial companies, energy companies, infrastructure companies, policymakers, technology providers, and financial institutions should work together. International and domestic experience suggests five stages in the development of low/zero-carbon industrial clusters: cluster initiation, cluster formalization, net-zero strategy development, anchor projects and full-scale strategy implementation.[20] In the early stages, such as the initiation stage, technology providers and participants in the supply chain work together to improve low-carbon and zero-carbon technologies to a level suitable for large-scale development. During the formalization stage, government support through policy incentives and public funding is needed to promote the implementation of early projects. In subsequent stages, all relevant parties must collaborate to ensure the sustainable and market-oriented development of the clusters.

Looking at the UK and the United States as examples, the following case studies analyze the driving factors of low/zero-carbon industrial clusters and the coordination patterns of various stakeholders. In the UK case, industry clusters are driven mainly by industrial capacity, while those in the United States are driven by energy resources primarily represented by green hydrogen.

Case 1: UK

The UK's Industrial Decarbonization Strategy outlines the goal of establishing at least four low-carbon industrial clusters by 2030 and at least one zero-carbon industrial cluster by 2040.[21] Correspondingly, the country's Industrial Decarbonization Challenge provides £210 million of public funding support to promote carbon reduction in the steel, cement, and chemical industries. The purpose is to incubate at least one low-carbon industrial cluster by 2030 and the world's first zero-carbon industrial cluster by 2040.[22]

Of that £210 million fund, £170 million will be spent on project deployment in industrial clusters, £8 million on planning of an industrial cluster roadmap, and £20 million on industrial decarbonization innovation research. The main funding target is the six preexisting industrial clusters identified by the UK government, which account for more than 36 million tons/year of carbon emissions, or 10% of the country's carbon emissions in total (see Exhibit 27). The funding, led by Innovate UK, provided from 2019 to 2024, is expected to leverage £260 million of industry investment.

Exhibit 27: **UK industry clusters and carbon emissions**

RMI Graphic, Source: UK government, **https://assets.publishing.service.gov.uk/media/6051cd04e90e07527f645f1e/Industrial_Decarbonisation_Strategy_March_2021.pdf**

The Humber industrial cluster, or Humberside, is the largest carbon-emitting industrial cluster in the UK, releasing 10 million tons of CO_2 emissions per year. Two of its low-carbon projects have been selected for funding. Humber is one of the most successful industrial cluster transformations in the UK, covering key projects and businesses in industries, energy resources, and infrastructure (see Exhibit 28). The key low/zero-carbon resources for the Humber cluster — green hydrogen, blue hydrogen, and CO_2 — are connected by pipelines for supply and consumption. Equinor's H2H Saltend project is the anchor project for the Humber cluster, offering a clean source of hydrogen and incorporating hydrogen utilization in chemical production. It has created a complete supply and demand chain. The Humber cluster also works with the nearby BP-led Northern Endurance Partnership offshore CCS project, which stores carbon emissions from the industrial cluster in the saline aquifers under the seabed.

Exhibit 28: **Major stakeholders in the UK Humber cluster**

H_2 pipeline / CO_2 pipeline	Project	Operator	Project type	Positioning
	Drax	Drax	Bioenergy with carbon capture and storage	Energy & resources
	Keadby	SSE & Equinor	Electricity (hydrogen utilization and carbon capture)	Industrial capacities/ energy & resources
	British Steel	British Steel	Steel production (hydrogen utilization and carbon capture)	Industrial capacities
	Uniper's Humber Hub	Uniper	Blue and green hydrogen production	Energy & resources
Anchor project	H2H Saltend	Equinor	Hydrogen for chemicals + hydrogen production	Industrial capacities/ energy & resources
	Easington	Centrica	Offshore CCS	Energy & resources
	Deep-water port	ABP	Shipping transportation (CO_2, green hydrogen, and ammonia)	Infrastructure
	Aldbrough	SSE & Equinor	Hydrogen storage	Infrastructure
	Pipeline	National grid	Hydrogen pipeline and CO_2 pipeline	Infrastructure

RMI Graphic. Source: RMI

Case 2: United States

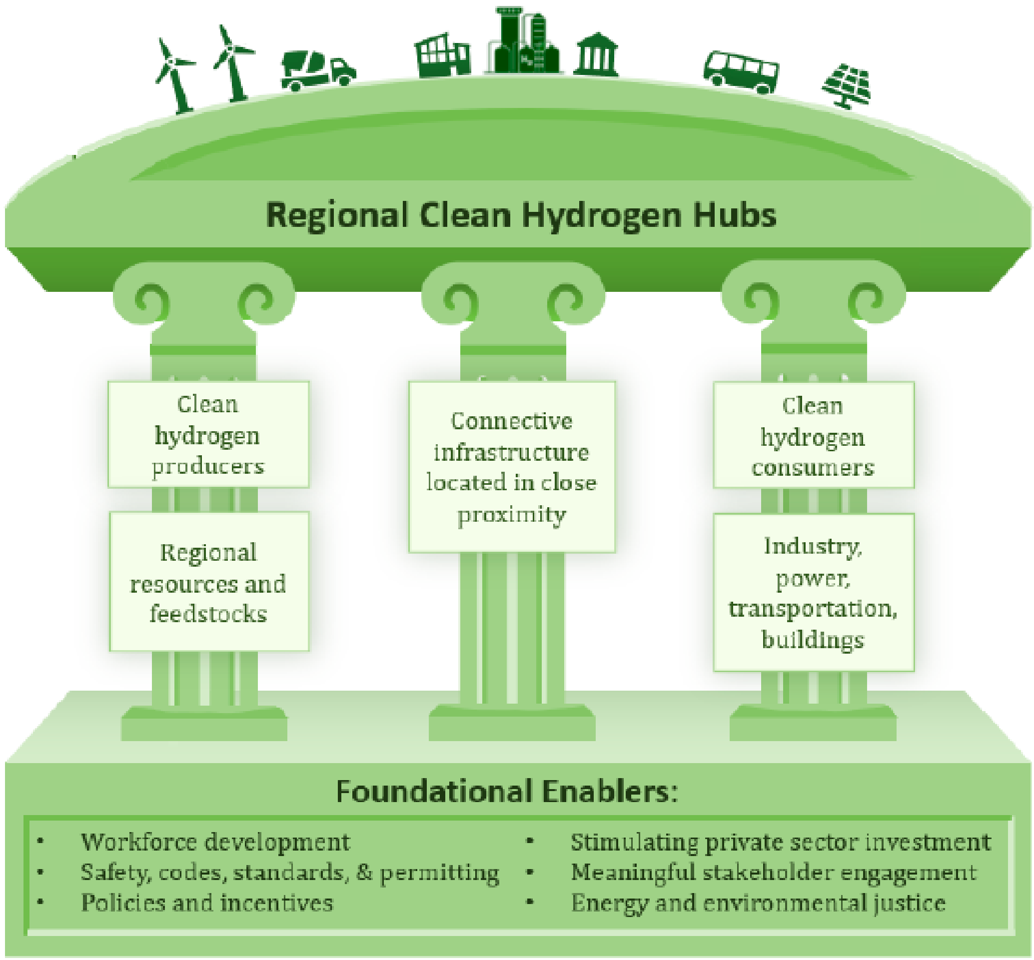
In 2023, the Department of Energy (DOE) issued the US National Clean Hydrogen Energy Strategy and Roadmap, which lays out multiple utilizations of clean hydrogen and paths to help several industries achieve decarbonization.[23] It sets targets for clean hydrogen production of 10 million tons by 2030, 20 million tons by 2040, and 50 million tons by 2050. In the same year, DOE announced seven regional clean hydrogen centers (see Exhibit 29) and plans to provide $7 billion in financial support for clean hydrogen development under the Bipartisan Infrastructure Law.[24] Each of the seven regional hydrogen hubs covers a combination of "production-storage-transportation-utilization" technology paths with regionally tailored development strategies.

Exhibit 29: **Seven regional clean hydrogen hubs in the United States**

Source: Office of Clean Energy Demonstrations (OCED)

The framework and entry points for clean hydrogen development in the United States include three pillars and a set of foundational enablers (see Exhibit 30). These features are exemplified by the Gulf Coast Hydrogen Hub.

Exhibit 30: **Key drivers for successful development of regional clean hydrogen hubs**



Source: DOE

Pillar 1: Hydrogen supply

Located in the south-central region of the United States, Texas is a vast state with plentiful oil, gas, and renewable resources. The state produces about 3.6 million tons of hydrogen per year, accounting for one-third of the country's annual total. With its abundant production and low natural gas prices, hydrogen production from natural gas is the main hydrogen production route in the region. Texas also has ample wind and solar resources. By the end of 2022, Texas was the number-one state for installed wind power in the country — with more than 40 GW or about one-third of the nation's total.[25] Abundant renewable resources will be the prerequisite for regional grid decarbonization and the development of clean hydrogen energy.

Pillar 2: Hydrogen storage and transportation

Texas has 900 miles (1,450 km) of hydrogen pipelines along the Gulf Coast, accounting for about half of the total in the United States and one-third of the world total. It also has a well-developed natural gas transmission network, which can be retrofitted to be hydrogen-blended for hydrogen transportation. In addition, its natural geology can store hydrogen and carbon dioxide for extended periods. Four hydrogen storage salt caverns are in operation worldwide, three of which are located on the Gulf Coast.

Pillar 3: Hydrogen utilization

The Texas Gulf Coast utilizes hydrogen for many applications involving industry, transportation, power, and heat. Considerations for clean hydrogen utilization orders include evolving industry requirements, affordability, decarbonization potential, and level of difficulty. As a feedstock, clean hydrogen can be prioritized for use in the refining, petrochemical, ammonia, and steel industries; as a fuel, it can be utilized in industrial process heating, transportation, and others. Given the development of industrial clusters and projected population growth, the demand for clean hydrogen in the region may hit 5 million tons by 2035 and 11 million tons by 2050, with an additional 3 million tons and 10 million tons, respectively, of clean hydrogen production available for export.

In this case, the drivers that foster the entire clean hydrogen energy value chain in a cluster development model include industrial capacities, energy resources, and infrastructure. Additionally, the following five major foundational drivers created favorable conditions for cluster development:

(1) **Policy and financial incentives** at the federal and state designed to drive clean hydrogen development

(2) Enhanced **safety, code, standards, and permitting,** training for employees in relevant fields, and development of industry professionals

(3) **Integration of multiple stakeholders** including industry, companies, academic institutions, and national laboratories, covering all steps of research, development, demonstration, and go-to-market

(4) Encouraging public–private sector collaboration and spurring **private sector investment**

(5) **Justice and fairness,** by considering resettlement, compensation, reemployment opportunities, and other impacts for affected groups

4. Outlook and Recommendations

For industry, especially heavy industry, the large-scale utilization of green hydrogen is the key to deep carbon emissions reduction. To ensure the scalable, continuous, stable, and cost-effective supply of green hydrogen in industry, this study proposes a cluster development model. Under this model, the production, storage, transportation, and utilization of green hydrogen can organically combine and interact, delivering a systematic and optimized solution.

The region close to the supply and demand of green hydrogen is expected to be the first to have low/zero-carbon industrial clusters using green hydrogen as a deep carbon emissions reduction enabler, where requirements for storage and transportation are relatively limited and projects' implementation is more feasible in the near future. In the short to medium term, the industry cluster development model can effectively accelerate the green hydrogen utilization in regions where energy resources and utilization capacity match. Early industry cluster development practice could demonstrate the technical and economic feasibility of low/zero-carbon solutions represented by green hydrogen, and explore feasible business models. In regions where there is a resource mismatch between green hydrogen supply and hydrogen utilization, an integrated solution of hydrogen production, storage, transportation, and utilization could be considered. This integrated planning can help determine the optimal methods for acquiring green hydrogen in these regions.

To promote the development of the cluster model and accelerate the utilization of large-scale green hydrogen in industrial low/zero-carbon transition, this report presents the following five recommended actions:

The government, industry, academia, research, consumers, and finance should play an active role and collaborate closely, focusing on technological breakthroughs and advances in all aspects of green hydrogen production, storage, transportation, and utilization. Technical feasibility is the basis for cost comparability. At present, there are still bottlenecks to resolve all along the line from production to utilization of green hydrogen. Supports such as policy incentives and preference by financial institutions will greatly help the rapid breakthrough of green hydrogen–related technologies in the early stage of development, while encouraging industrial companies to incorporate green hydrogen and engage upstream and downstream partners. This will create a stable and reliable industrial chain and favorable market environment for the industrial utilization of green hydrogen. At the stage of implementation, the burden and long-term commitment of R&D are often too great for a single company, so it's important to draw in stakeholders to create synergies in the advancement of technology. Research institutes, universities, and industrial companies can collaborate in R&D of key technologies; industrial companies, industry associations, and downstream consumers can help promote the technology in industrial green hydrogen utilization for faster cost reduction.

Industrial companies, as the utilization side of green hydrogen, should pay close attention to the technological advancement and cost reduction of green hydrogen utilization, with timely and proactive deployment of improved green hydrogen technologies. Although the cost of green hydrogen–based production is still at a premium compared with the traditional fossil fuel routes, ongoing technological progress and wider adoption, along with potential carbon pricing and policy constraints, will gradually enhance the cost competitiveness of green hydrogen–based production routes. Feasibility studies, planning, and final investment decisions all require time, thus industrial companies can prepare in advance so as not to miss the best time window. In addition, in regions with advantageous renewable energy conditions, the timeline for achieving cost competitiveness in green hydrogen utilization will be further accelerated. Industrial companies should also pay close attention to and actively seek early opportunities to implement green hydrogen utilization that are commercially operable at scale as early as possible. This will enable them to benefit from low-carbon dividends before it is too late.

Regions should comprehensively assess the potential of green hydrogen for industrial production based on their own industrial capacity foundation and low/zero-carbon energy resources — and set up milestones and implementation routes. At present, the distribution of industrial production capacity in each region and province is mostly determined by fossil fuel resource endowment and market demand. Under the trend of low/zero-carbon transition, low/zero-carbon resources represented by green hydrogen have become new drivers for capacity layout. Each region should assess the potential for developing local renewable resources and green hydrogen to make comprehensive decisions based on local industrial demand. In addition, it is advisable to analyze the scale of hydrogen demand and deployable hydrogen sources from the bottom up, and gradually move hydrogen production from fossil fuel, by-product hydrogen to green hydrogen, to reduce the risk of stranding existing assets from transitioning too quickly.

At the macro level, it is essential to optimize and coordinate hydrogen supply and demand between different regions as well as the planning of storage and transportation infrastructure, while achieving comprehensive coordination and collaboration at the micro level. To meet the requirement for sustained and stable hydrogen supply in industrial hydrogen utilization, storage and transportation facilities should be properly equipped, regardless of whether hydrogen supply and demand are in the same location or in different locations. Hydrogen storage and transportation are bottlenecks in the hydrogen value chain at this stage. The construction of the required infrastructure necessitates large capital investment. To leverage the at-scale effect and to reduce the unit cost of storage and transportation calls for a unified plan for hydrogen storage and transportation infrastructure at the macro level. Such a plan can ensure that the positioning of the supply and demand of hydrogen in each region and the connection between the supply and demand can be optimized based on the resource endowment, industrial capacity foundation and other factors. At the micro level, collaboration between the hydrogen supply side and the demand side is required to jointly explore the storage and transportation solutions for hydrogen from production to utilization.

Renewables generation, electricity grid, hydrogen storage and transportation, and industry should be organically integrated to optimize the stability of large-scale hydrogen utilization in industry. Industrial utilizations demand a sustained and stable supply of green hydrogen due to the continuous, centralized and scaled industrial process. Given the intermittency of wind and solar, various technical solutions should be integrated to close the output gap in green hydrogen supply — such as grid electricity supplement, local hydrogen storage, and off-site hydrogen transportation. Based on resource differences in hydrogen utilization locations, the design of these integrated solutions can be optimized according to technical difficulties and cost-effectiveness. Therefore, stakeholders need to combine forces to explore and design the optimal hydrogen supply and utilization solutions.

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