



ADB Working Paper Series

**ACCELERATING THE NET ZERO
TRANSITION IN ASIA AND THE
PACIFIC: LOW-CARBON HYDROGEN
FOR INDUSTRIAL DECARBONIZATION**

Meng Yuan, Chunying Liu,
Bohong Wang, Wenlong Shang,
and Haoran Zhang

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Meng Yuan is an assistant professor at the Department of Planning, Aalborg University, Aalborg, Denmark. Chunying Liu is a master's student at the National Engineering Laboratory for Pipeline Safety/MOE Key Laboratory of Petroleum Engineering/Beijing Key Laboratory of Urban Oil and Gas Distribution Technology, China University of Petroleum, Beijing, People's Republic of China (PRC). Bohong Wang is a lecturer at the National and Local Joint Engineering Research Center of Harbor Oil and Gas Storage and Transportation Technology/Zhejiang Key Laboratory of Petrochemical Environmental Pollution Control, Zhejiang Ocean University, Zhoushan, PRC. Wenlong Shang is an assistant professor at the Beijing Key Laboratory of Traffic Engineering, College of Metropolitan Transportation, Beijing University of Technology and the School of Traffic and Transportation, Beijing, PRC; and at the Center for Transport Studies, Imperial College London, United Kingdom. Haoran Zhang is an assistant professor at the School of Urban Planning and Design, Peking University, Shenzhen, Guangdong, PRC.

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Please contact the authors for information about this paper.

Email: mengy@plan.aau.dk

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Asian Development Bank Institute
Kasumigaseki Building, 8th Floor
3-2-5 Kasumigaseki, Chiyoda-ku
Tokyo 100-6008, Japan

Tel: +81-3-3593-5500
Fax: +81-3-3593-5571
URL: www.adbi.org
E-mail: info@adbi.org

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Abstract

Hydrogen is regarded as one of the limited options for decarbonizing the hard-to-abate industrial sector. This work investigates the status and potential of green and blue hydrogen in some major industrial sectors, including oil refining, chemical production, iron and steel production, and high-temperature heat applications. The focus is put on the Asia and the Pacific (APAC) region, which accounts for half of the global industrial hydrogen demand. The status of the hydrogen market, the deployment actions of low-carbon hydrogen in industrial sectors in terms of national strategies, demonstration projects, and the regional hydrogen market of the APAC countries are summarized and analyzed. Perspectives are provided in support of accelerating the further decarbonization of the industrial sector in the APAC region with low-carbon hydrogen. Despite variations across countries in APAC in terms of low-carbon hydrogen production and application potentials due to different resource endowments, energy structures, and industrial structures, the region enjoys high potential overall, and in the ability for cross-border hydrogen trading in particular.

Keywords: green hydrogen, blue hydrogen, industry decarbonization, Asia and the Pacific, renewable energy

JEL Classification: Q40

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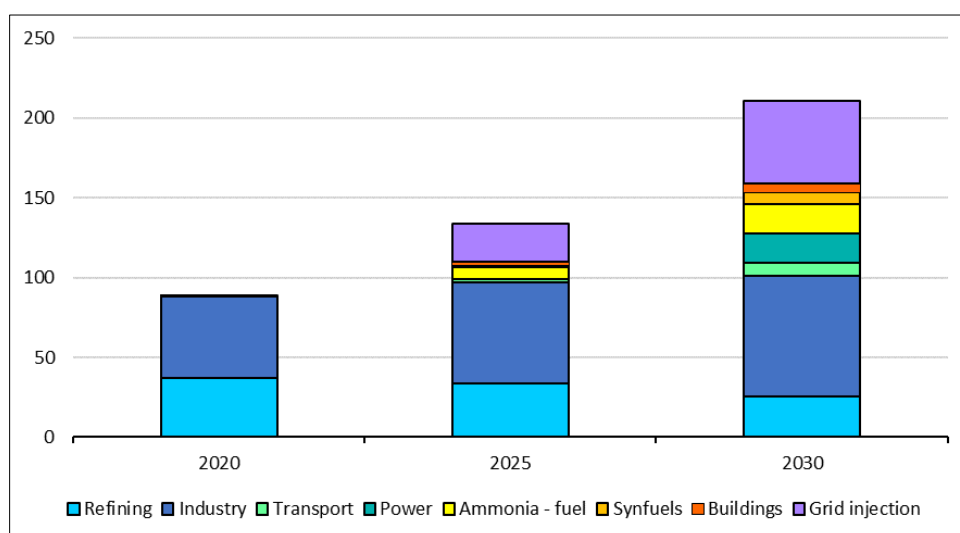
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1. INTRODUCTION

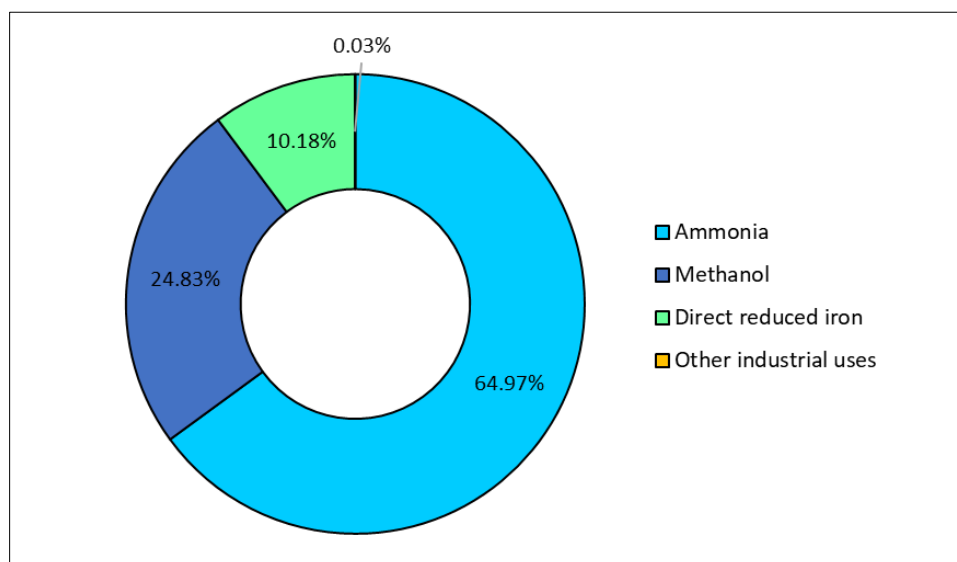
Decarbonizing the industry sector is crucial to global climate actions. As the largest energy end-use sector, the industry sector accounts for 38% of the global total final energy demand and emits 26% of the CO₂ emissions in the global energy system. Despite the knowledge that has been investigated on different decarbonization pathways (Johannsen et al. 2023), such as improvements in energy efficiency, renewable energy integrations, electrification of industrial processes, and shifting fuel with hydrogen and biomass, the understanding of industrial decarbonization is still inadequate due to the general heterogeneity of the industry sector. Among several promising pathways, hydrogen is one of the limited options for decarbonizing many industrial sectors, especially those that need chemical transformations and that it might not be possible to decarbonize with other clean energy sources (Griffiths et al. 2021). Figure 1 shows the global hydrogen demand by sector in the Net Zero Scenario of the IEA. As can be seen, hydrogen use today is dominated by industrial applications. The annual industry demand for hydrogen is 51 Mt, of which 46 Mt is used to produce chemicals (IEA 2021b). Figure 2 presents the share of global hydrogen demand in the industry in 2020. About three quarters were used for ammonia production and the remaining quarter for methanol. The direct reduced iron (DRI) process for steelmaking took the remaining 5 Mt.

Compared to other energy sectors, the industry sector might benefit from hydrogen in reducing the use of biomass at a lower cost (Korberg et al. 2023). But it should be noted that the direct use of hydrogen in the industrial process as an alternative fuel should be avoided from the energy efficiency and energy system perspective, unless there is no other option available or if the other option is biomass with unsustainable use (Sorknæs et al. 2022). Therefore, this paper will exclude the direct use of hydrogen as a fuel alternative in the scope of its discussion, focusing instead on the tough industries that are hard to abate through other solutions, i.e., oil refining, chemical production, and iron and steel production. The application of hydrogen for high-temperature heat will also be touched upon but will not be the focus.

Figure 1: Global Hydrogen Demand by Sector in the Net Zero Scenario of the IEA



Source: IEA 2021a.

Figure 2: Share of Global Hydrogen Demand in Industry in 2020

Source: IEA 2020.

A shift from traditional fossil fuel-based gray hydrogen to low-carbon hydrogen is essential to realize the global climate targets set in the Paris Agreement. This can be pursued by implementing green hydrogen based on renewable electricity and green hydrogen and blue hydrogen that are produced from natural gas combined with carbon capture, utilization, and storage (CCUS). The market for low-carbon hydrogen is still in its infancy. In the current industry sector, only 0.3 Mt out of the total 51 Mt is supplied with low-carbon hydrogen, and the rest is from gray hydrogen. Interest in the production of low-carbon hydrogen has been sparked among policymakers and industries around the world.

From the entire energy system point of view, the production of green and blue hydrogen could not only contribute to emission mitigation but could also provide benefits for the remaining sectors of the energy system in utilizing sector synergies. For example, green hydrogen helps integrate intermittent renewable energy sources (RES) such as solar and wind energy in the electricity sector, and electrolyzers can be regarded as an asset in providing flexibility. In addition, the excess heat from the process of green hydrogen production could also be utilized in district heating systems to diversify the heat sources. The production of blue hydrogen has many overlaps with existing industries, including the oil and gas industry, which provides the opportunity for a just energy transition given that the infrastructures, skills, and jobs needed can be transferred (Griffiths et al. 2021). Furthermore, the CO₂ captured can be utilized as the carbon point source naturally for other applications, such as the production of electrofuel via Power-to-X technology, enhanced oil recovery in field production, or in the food industry.

The Asia and the Pacific (APAC) region currently accounts for half of the global industrial hydrogen demand, with the People's Republic of China (PRC) alone taking 33% (17 MtH₂) for producing ammonia and methanol (IEA 2019a). In 2017, Japan announced its national hydrogen strategy for multiple fields, which makes it the first country in the world to establish a national hydrogen framework. Following Japan, other APAC countries, including the PRC, the Republic of Korea, New Zealand, and Australia, have also established their own strategies in support of the hydrogen

industry. The industrial applications of hydrogen are also covered in some of the national policies in these APAC countries.

Existing literature reviews various applications and prospects of low-carbon hydrogen globally in various sectors; nevertheless, an overall review is lacking for the APAC region, especially for the industrial sector. Investigation of the industrial sector is important to understand what role low-carbon hydrogen plays in national frameworks as well as the cross-border trading in APAC. This paper contributes to the literature by providing a comprehensive summary and analysis of the technical and policy status, potential, and perspectives in promoting green and blue hydrogen applications in the industrial sector of the APAC countries, which could serve as decision-support material for stakeholders in the local region.

The paper is structured as follows: Section 2 presents the status and the future potential of decarbonizing the industrial sector by using low-carbon hydrogen. The national hydrogen strategies in APAC with a focus on the industrial sector are summarized in Section 3. Section 4 analyzes the hydrogen market in the APAC region. Lastly, Section 5 concludes the paper and presents perspectives.

2. STATUS AND POTENTIAL OF INDUSTRIAL DECARBONIZATION WITH LOW-CARBON HYDROGEN

Most hydrogen today is used in three industrial sectors: oil refining, chemical production, and iron and steel production. Applications in high-temperature heat are also considered here. This section illustrates the status and the future potential of low-carbon hydrogen applications.

2.1 Oil Refining

2.1.1 Current Role of Hydrogen in Oil Refining

The global oil refining industry consumes 38 Mt of hydrogen annually. Hydrogen serves as an important feedstock, reagent, and energy source for refineries. The primary utilization pathway of hydrogen in oil refining is removing sulfur from crude oil and upgrading to heavy crude; however, there are also some applications for upgrading oil sands and hydrotreating biofuels.

Currently, around two thirds of hydrogen in oil refining is supplied by on-site steam methane reformers (SMRs) at refineries and merchant suppliers globally, while the rest are mostly supplied by the by-product of refineries and a little by on-site coal (IEA 2019a). The PRC, the US, and Europe comprise half of the global hydrogen consumption in refineries. The share of different sources varies from region to region. In the PRC, 10% of hydrogen comes from on-site coal, while that is not the case in the US and Europe.

2.1.2 Future Potential of Hydrogen in Oil Refining

Even though the global average quality of crude oil is becoming lighter and sweeter due to the rise of tight oil from the US, the future demand for hydrogen in oil refining is still expected to grow as a result of the tight regulation of the sulfur content globally, especially in road transport and marine fuels. It is estimated that the hydrogen demand in refineries will grow to around 41 Mt/yr by 2030.

It is important to produce hydrogen in a cleaner way to lower the overall emission intensity of the oil refining industry. There are two ways to realize this target: retrofitting the gas/coal-based hydrogen production facilities with CCUS (i.e., blue hydrogen), and replacing merchant hydrogen with cleaner hydrogen that is produced from electrolysis using renewable electricity (i.e., green hydrogen).

Yet, the economy of clean hydrogen is closely related to the price of carbon and the support for this policy. Take the PRC, for instance: The CCUS pathway for natural gas-based hydrogen production only becomes economically competitive when the CO₂ price is above USD50/tCO₂ compared to the traditional process without CCUS (IEA 2019a).

2.2 Chemical Production

2.2.1 Current Role of Hydrogen in Chemical Production

Almost all industrial chemicals have hydrogen as part of their molecular structure, although only a few primary chemicals require a large amount of hydrogen as feedstock in their production process. Ammonia and methanol are the biggest hydrogen consumers in the chemical industry, consuming 31 MtH₂/yr and 12 MtH₂/yr globally, respectively, with 65% of the hydrogen being sourced from natural gas and 30% from coal. The APAC region takes nearly half of the hydrogen consumption in the ammonia and methanol industry, of which 60% comes from coal. Almost all coal-based hydrogen is produced and used in the PRC.

2.2.2 Future Potential of Hydrogen in Chemical Production

The global demand for ammonia and methanol is expected to increase in the next decade, which will inevitably result in the growth of hydrogen. Similarly to the oil refining industry, a cleaner hydrogen deployment in the chemical industry also has the following two pathways: 1) retrofitting fossil fuel-based hydrogen with CCUS; and 2) using electrolysis-derived hydrogen from renewable electricity.

However, the cost of low-carbon production is much more expensive than that of fossil fuel-based production. Natural gas prices and electricity prices are the key factors affecting the economics of low-carbon hydrogen production. Electrolytic hydrogen is preferable for low-carbon production of ammonia and methanol in places where there is easy access to cheap renewable electricity, while natural gas with CCUS is competitive in places with high electricity prices.

2.3 Iron and Steel Production

The iron and steel industry (ISI) is regarded as one of the most hard-to-abate sectors and contributes to roughly 6% of global CO₂ emissions (IEA 2019a). The challenges of decarbonizing ISI derive from the following two processes: high-temperature heat required by specific processes like operating blast furnaces (BFs) and other production reactors, and the chemical reactions for iron ore refining (Ren et al. 2021).

2.3.1 Current Role of Hydrogen in the Iron and Steel Industry

The blast furnace-basic oxygen furnace (BF-BOF) and the direct reduction of iron-electric arc furnace (DRI-EAF) are the two primary production pathways of steel, accounting for around 90% and 7% of the total crude steel production, respectively. The BF-BOF pathway produces by-product hydrogen (9 MtH₂/yr) from coal consumption in the form of a mixture of gases, which are usually used on site.

The DRI-EAF pathway employs a mixture of dedicated hydrogen (4 MtH₂/yr) and carbon monoxide (synthesis gas) as the reducing agent (IEA 2019b), which is either made from coal or natural gas. India and Iran are the leading countries in DRI-EAF, adopting coal and gas as the feedstock, respectively.

2.3.2 Future Potential of Hydrogen in the Iron and Steel Industry

Compared to the BF-BOF pathway, the DRI-EAF pathway is considered to have better decarbonization potential as the synthesis gas used can be replaced with high-share or full hydrogen. The by-product hydrogen in the BF-BOF pathway is difficult to replace with other low-carbon hydrogen supplies as it is closely integrated with the operation (IEA 2019a). According to the projection of the IEA (IEA 2019b), employing the DRI-EAF pathway in all primary production of steel will lead to a 15-fold increase in hydrogen demand by 2050.

To further decarbonize the ISI, efforts from researchers, investors, and policymakers are underway. The focus is to utilize hydrogen as the primary reduction agent in steel production instead of the carbon monoxide obtained from coal and gas, which helps to lower the overall CO₂ intensity. From the technical perspective, without modifying the production process, up to 30% of natural gas can be replaced by hydrogen in the DRI pathway driven by natural gas. And only a minor retrofit of the equipment is needed to upgrade to a 100% hydrogen operation.

The carbon-abatement performance of hydrogen in the ISI greatly depends on the hydrogen sources, which further relies on the overall energy structure of the country. The green hydrogen from renewable electricity or the gray/blue hydrogen combined with CCUS can be considered (Ren et al. 2021). It has been found that the hydrogen-driven DRI-EAF pathway can be 10%~90% more expensive than the natural gas-driven system. Such a wide range is caused by the sensitivity to the electricity price (IEA 2019b; Gielen et al. 2020).

2.4 High-Temperature Heat

The application of high-temperature heat is rarely used in industrial processes today. Blending hydrogen into the existing natural gas pipeline network is a straightforward and feasible method of industrial application but is less environmentally beneficial. Hydrogen for heating purposes may face the challenge of competition from other clean heating pathways, such as biomass and direct CCUS.

3. STATUS OF HYDROGEN MARKET IN THE APAC REGION

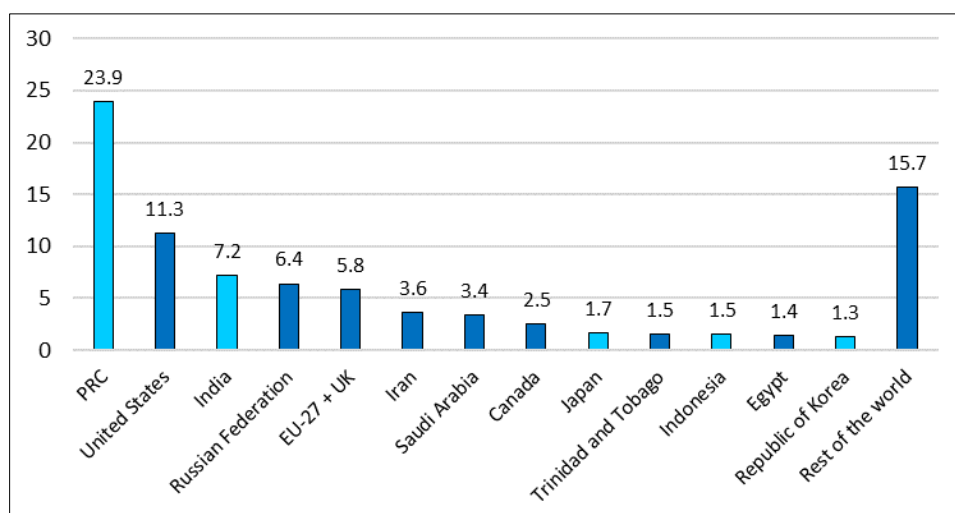
The APAC region is one of the fastest-growing markets for low-carbon hydrogen, with many countries investing in the development and use of this clean energy source. The demand for hydrogen in the APAC region is driven by a combination of factors, including the need to reduce GHG emissions, improve energy security, and support economic growth.

Figure 3 shows the annual hydrogen consumption of some selected countries in the world in 2020, with the light blue bar marking the countries from the APAC region. The data come from the current production of ammonia and methanol, the refining as well as the DRI process (International Renewable Energy Agency 2022). As can be seen from the figure, the APAC region stands in an important position in the global hydrogen

market. Within the APAC region, the PRC is the largest consumer with an annual consumption of 23.9 Mt, followed by India, the Russian Federation, Japan, Indonesia, and the Republic of Korea.

The majority of the hydrogen generated in the PRC is used as feedstock in oil refineries and chemical production, which comes from fossil fuels with around 60% from coal and 25% from natural gas. In India, about 99% of the gray hydrogen is utilized in petroleum refining and the manufacture of ammonia for fertilizers (Ministry of New and Renewable Energy 2023). Two giant refiners, Reliance Industries Limited and Indian Oil Corporation Limited, contribute to more than 70% of the national hydrogen production in India (Kar, Sinha, Harichandan et al. 2023). Japan has been a pioneer of hydrogen technology as well as a leader in the development of the hydrogen industry (Panchenko et al. 2023).

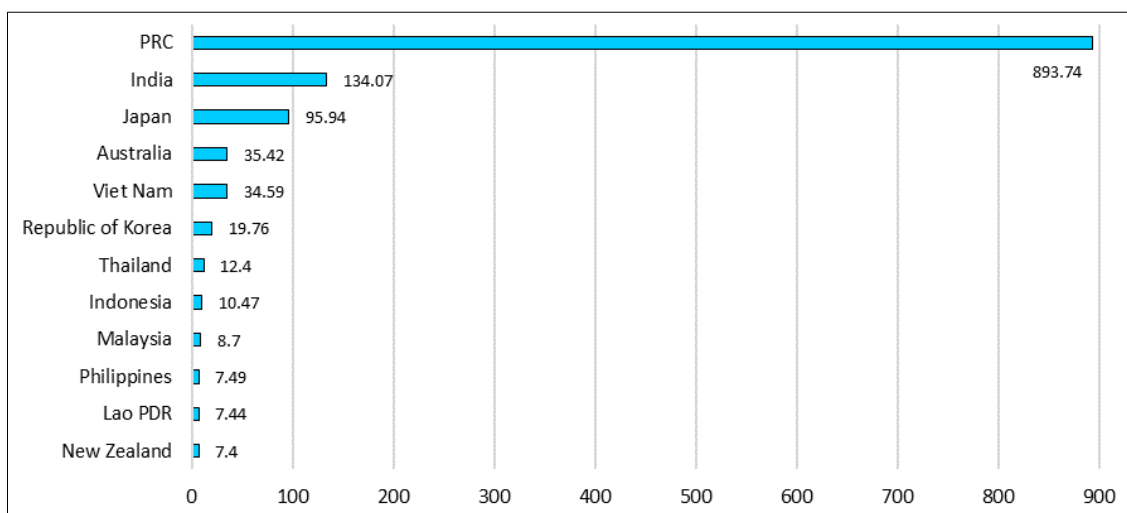
Figure 3: Annual Hydrogen Consumption Worldwide in 2020 by Country. APAC Countries Marked in Light Blue



Source: International Renewable Energy Agency 2022.

Figure 4 presents the renewable power capacity installed in several selected APAC countries in 2020 (The Global Economy 2021). It can be seen that the PRC, India, Japan, Australia, and Viet Nam are the top five countries in having the greatest ability to produce more RE electricity. Although the potential of RES is more convincing when looking into the future, the existing data on RE capacity still reveal the possibility of green hydrogen production based on renewable electricity and distribution within the APAC region.

In light of the existing hydrogen consumption, renewable power production, geography, and industry structure of each country, it can be concluded that the PRC, India, Japan, the Republic of Korea, and Australia will naturally play key roles in the hydrogen value chain in APAC. Therefore, in the following sections, several key countries in the APAC region in terms of low-carbon hydrogen production and consumption will be studied from the perspectives of national hydrogen strategies and project development.

Figure 4: Renewable Power Capacity in Selected APAC Countries in 2020

Source: The Global Economy 2021.

4. NATIONAL HYDROGEN STRATEGIES ON THE INDUSTRIAL SECTOR IN APAC

This section reviews the current national hydrogen strategies as well as the major low-carbon hydrogen projects in the selected APAC countries with a focus on the industrial sector.

4.1 National Hydrogen Strategies of APAC Countries

The governments in the APAC region are investing in hydrogen projects and infrastructure, promoting the development of hydrogen technologies, and creating favorable regulatory environments for the growth of the hydrogen market. Table 1 summarizes the national hydrogen strategies released in APAC countries related to industrial use purposes. Due to the differences in resource endowment, industrial structure, and the national climate governance and energy development goals, the hydrogen strategies vary across countries.

- **PRC**

The PRC is the largest hydrogen producer in the world with around 33 MtH₂/yr, of which 12 MtH₂/yr meet the quality standard (National Development and Reform Commission 2022). Most hydrogen used today is produced from fossil fuels as feedstocks in refineries or chemical facilities. In March 2022, the Chinese government released the first long-term development plan for hydrogen in the PRC, covering the period 2021–2035. The plan put forward a phased approach to developing a domestic hydrogen industry, technologies, and production capabilities (Nakano 2022).

In terms of the industrial sector, the plan is to expand the scale of application of hydrogen in replacing fossil fuels, promote the transformation of synthetic ammonia, synthetic methanol, refining, coal-to-gas and other industries from high-carbon to low-carbon processes, and carry out R&D in the DRI pathway of the iron and steel industry. Moreover, the existing huge natural gas pipeline network in the PRC also serves as an important method of hydrogen

transportation. The policy also supports pilot demonstrations of blending hydrogen into the existing gas pipeline networks (Wang et al. 2018, 2020).

- **India**

The National Hydrogen Energy Board (NHEB) in India approved the National Hydrogen Energy Road Map (NHERM) in 2006, which aims to fill the technology gaps in different aspects of hydrogen and set the targets for 2020. However, unfortunately, the goal of 2020 wasn't accomplished since hydrogen still cannot compete with fossil fuels.

In 2021, a new National Hydrogen Energy Mission (NHM) (Ministry of New and Renewable Energy 2021) was released in India to develop a roadmap for the use of hydrogen as an energy source, which gives equal attention to long-term and short-term targets. A framework will be designed in order to achieve the goal of creating a worldwide hub for the manufacture of hydrogen technology. The application of hydrogen in specific areas will be promoted, including the mandatory use of green hydrogen in industries such as steelmaking as well as petrochemical and fertilizer production, and the demonstration of transportation purposes. The NHM is an important step towards India's transition to clean energy and a reduction of its dependence on fossil fuels.

In January 2023, the Indian government launched another new strategy for green hydrogen, called the National Green Hydrogen Mission (Ministry of New and Renewable Energy 2023). The mission aims to replace fossil fuel sources with green hydrogen in some major industries, including ammonia production and oil refining, steelmaking, and synthetic fuel production, which is derived from green hydrogen such as green ammonia and methanol. The mission aims to build the capability of green hydrogen production to at least 5 Mt annually by 2030.

- **Japan**

Japan issued its "Basic Hydrogen Strategy" in 2017, becoming the first country in the world to adopt a national hydrogen framework (Nakano 2021a). The strategy describes the hydrogen and fuel cell policies as well as introducing the targets of the applications. Based on this strategy, the "Strategic Roadmap for Hydrogen and Fuel Cells" and the "Strategy for Developing Hydrogen and Fuel-Cell Technologies" were released in 2019, setting the technological target of the hydrogen supply chain. In October 2020, Japan declared that the country will aim to reduce greenhouse gas emissions to net zero by 2050 and achieve a fully decarbonized society.

Hydrogen is regarded as a key component of Japan's decarbonization target. The country aims to expand its hydrogen market from the current level of 2 Mt per year to 3 Mt per year by 2030 and to 20 Mt per year by 2050. Meanwhile, the nation seeks to reduce the cost of hydrogen to around a third of the current level by 2030. Even though the strategy mentioned a wide range of end-use sectors, such as electricity, transportation, residential, heavy industry, and potentially refining, the government focused on mobility because Japan is the leading country in fuel cell vehicles and seeks to export this technology to the rest of the world.

- **New Zealand**

New Zealand aims to achieve a net zero carbon economy by the year 2050. Currently the hydrogen market is still quite limited in New Zealand. The emphasis is on industrial products (hydrogen carriers) and feedstocks utilized in the chemical and oil refining industries. The hydrogen strategy in New Zealand consists of two components: the hydrogen vision Green Paper (Ministry of Business, Innovation & Employment 2019) published in 2019 and a hydrogen roadmap that is under development. Renewable energy is plentiful in New Zealand. The government believes there is a greater opportunity to explore the use of renewable energy to produce green hydrogen as an alternative fuel for both domestic and international use.

- **Australia**

The Australian government released the National Hydrogen Strategy (the Strategy) in November 2019, which aims to put Australia in a position to seize the hydrogen opportunity and take the lead in the expanding global market (COAG Energy Council 2019). The Strategy identifies 57 actions for building Australia's hydrogen industry with a focus on clean hydrogen, including both clean "renewable hydrogen" and clean "CCS hydrogen." The Strategy focuses on initiatives that bring down market barriers, boost hydrogen production, increase demand efficiency, and enhance the competitiveness of cost. A key element of the strategy is the development of hydrogen hubs (or large-scale demand clusters), which will act as a launchpad for expansion of the hydrogen industry as well as important infrastructure to promote a cost-effective hydrogen supply chain (Kar, Sinha, Bansal et al. 2023). Another main objective of the Strategy is to make Australia a hydrogen exporter (Longden 2020). The goal of industrial application of clean hydrogen is mainly in industrial feedstocks and heating.

- **Republic of Korea**

The Republic of Korea has committed to net zero carbon emissions by 2050. In 2019, the government announced the Hydrogen Economy Roadmap, which aims to create a sustainable hydrogen economy in the Republic of Korea by 2040, with hydrogen playing a major role in the country's energy mix and contributing to economic growth, job creation, and the reduction of GHG emissions (Ministry of Trade and Industry and Energy 2019). The roadmap outlines the steps and measures that the government and private sector will take to increase the production, distribution, and use of hydrogen in various sectors, including transportation, power generation, and industry. The roadmap sets targets for the growth of the hydrogen market and the expansion of hydrogen infrastructure, as well as the development of new technologies and the promotion of international cooperation. The major focus of this roadmap is on the use of hydrogen in mobility, such as producing 6.2 million fuel cell electric vehicles and rolling out 41,000 hydrogen buses on the street by 2040 (Ministry of Trade and Industry and Energy 2019). Although the Republic of Korea has competitive heavy industrial sectors, including shipbuilding and steelmaking, the use of hydrogen in these hard-to-abate sectors has not yet been regarded as the priority of the government in its pursuit of a hydrogen economy (Nakano 2021b).

The accessibility and availability of hydrogen in a country, as well as its level of industrialization and energy dependence, are crucial factors that determine the potential opportunities and challenges in hydrogen development. This also includes the country's potential as an energy exporter or importer. A number of countries within APAC have issued their own national hydrogen strategies, which have been adopted widely and affected the actions of the domestic public and private sectors. The APAC region includes several countries that import energy, export technology, and possess favorable conditions for hydrogen production, making them strong candidates for energy exportation. As a result, APAC has set ambitious overall goals comparable to those of the EU and developed a diverse range of strategies and priorities.

In terms of the application of hydrogen in the industry sector, there is a need to translate the national ambitions and strategies into more concrete policy initiatives. Most APAC countries have delivered policies on hydrogen technology R&D and boosting the scale of hydrogen production and applications in the industrial sectors, which are mostly on a qualitative basis instead of clear goals and solid strategies relating to the pathways.

Table 1: Summary of the National Hydrogen Strategies in the Industrial Sector in APAC

Country	Year		National Policies
PRC (National Development and Reform Commission 2022)	2022	General	<ul style="list-style-type: none"> By 2025, the hydrogen production from renewable energy will reach 100,000–200,000 tons/year. By 2035, a hydrogen energy industry system will be formed, and a diversified hydrogen energy application ecology covering transportation, energy storage, and industry will be built.
		Oil refining	<ul style="list-style-type: none"> Explore hydrogen produced from renewable energy to replace fossil energy in refining and coal-to-oil gas industries.
		Chemical production	<ul style="list-style-type: none"> Expand the application scale of hydrogen to replace fossil energy in industrial fields such as synthetic ammonia and methanol.
		Iron and steel	<ul style="list-style-type: none"> Carry out research and application of hydrogen metallurgy technology utilizing hydrogen as reducing agent.
		High-temperature heat	<ul style="list-style-type: none"> Explore the application of hydrogen energy as a high-quality heat source in industrial production.
India (Ministry of New and Renewable Energy 2023)	2023	General	<ul style="list-style-type: none"> By 2030, the capacity of green hydrogen production will exceed 5 Mt, with potential to research 10 Mt for potential export markets.
		Chemical production and oil refining	<ul style="list-style-type: none"> Encourage the production of green ammonia and methanol based on green hydrogen. Promote the replacement of hydrogen produced from fossil fuel sources with green hydrogen in ammonia production and petroleum refining.
		Oil refining	<ul style="list-style-type: none"> Ministry of Petroleum and Natural Gas will facilitate uptake of green hydrogen in refineries through both public and private sector entities.
		Iron and steel	<ul style="list-style-type: none"> Promote the production of steel with green hydrogen.

continued on next page

Table 1 *continued*

Country	Year		National Policies
Japan (Nagashima 2018a; Ministry of Environment Government of Japan 2020)	2017, 2019	General	<ul style="list-style-type: none"> • Create a “Hydrogen Society” in which hydrogen is employed in both daily life and industrial activities. • Fully diffuse hydrogen applications over the medium to long term through 2050. • Relevant government agencies will work closely to discover promising seeds for fundamental research and industry needs. • Consider the introduction of the various processes for using CO₂-free hydrogen in a sequential manner as the processes achieve economic rationality.
		Oil refining and iron and steel production	<ul style="list-style-type: none"> • Consider transitioning from fossil fuel-based hydrogen to CO₂-free hydrogen to reduce carbon emissions in industrial processes such as steelmaking and oil refining.
		Chemical production	<ul style="list-style-type: none"> • Develop technologies to combine CCS or hydrogen with ammonia production to eliminate CO₂ emissions.
New Zealand (Ministry of Business, Innovation & Employment 2019)	2019	Oil refining	<ul style="list-style-type: none"> • Actively explore the development of green hydrogen production to materially reduce the emissions from petroleum refining.
		Chemical production	<ul style="list-style-type: none"> • Ammonia production: Use green hydrogen feedstock for chemical reactions. • Synthetic gas production: Hydrogen can serve as a post-combustion feedstock if it is added to carbon monoxide and carbon dioxide after the combustion of coking coal.
		Iron and steel production	<ul style="list-style-type: none"> • Use green hydrogen as an alternative way of producing steel with zero-carbon emissions. • Attempt to overcome the technological challenges that are currently impeding the widespread adoption of hydrogen to produce steel with a low-carbon footprint.
Australia (COAG Energy Council 2019; Australian Government Department of Industry, Science and Resources 2021)	2019	General	<ul style="list-style-type: none"> • Switch existing industrial hydrogen users to clean hydrogen. • Investigate opportunities for clean hydrogen such as clean ammonia exports, clean fertilizer exports, industrial heating, iron ore processing, and steel production.
		Steelmaking	<ul style="list-style-type: none"> • Steel production becomes a targeted application for hydrogen, with all new facilities producing steel from iron ore using hydrogen by 2030.
		Industrial heat	<ul style="list-style-type: none"> • 2025: Hydrogen is being tested in at least niche applications, if not more broadly, and industry stakeholder acceptance of hydrogen is growing. • 2030: Hydrogen is being implemented in at least niche applications, if not more extensively, and manufacturers are developing equipment that can accept 100% hydrogen.
Rep. of Korea (Ministry of Trade and Industry and Energy 2019)	2019	General	<ul style="list-style-type: none"> • Increase domestic annual hydrogen consumption from 130,000 tons in 2018 to 5.26 million tons by 2040. • Overseas hydrogen produced with renewable energy and brown coal in an eco-friendly way will be imported from 2030, with 70% of demand for hydrogen met with eco-friendly, CO₂-free hydrogen by 2040.

4.2 Low-Carbon Hydrogen Projects for Industrial Purposes in APAC

Table 2 lists the selected low-carbon hydrogen projects for industrial purposes in the APAC region. Green hydrogen-based industrial projects are rising in the PRC, especially in the field of chemical production and DRI-based iron and steel production. Ningxia Baofeng Energy Group has launched the largest green hydrogen project in the world to date using a 150 MW alkaline electrolyzer fueled by a 200 MW solar array, making use of the renewable energy resources in the north-west of the PRC. Using pure hydrogen as reducing gas in the DRI process is still in the trial and experimental stage in the PRC. With Baosteel and Hebei Iron and Steel Group as the two primary trailblazers, it is anticipated that the PRC will have at least 8.2 million Mt/yr of low- or zero-carbon DRI capacity in the pipeline between 2021 and 2025. The third-largest steel producer in the world, Hebei Iron and Steel, is a subsidiary of the Baowu Group, which also owns Baosteel (Zhang 2022).

India is exploring the use of green hydrogen in oil refining as part of its efforts to promote clean energy and reduce GHG emissions. One example of a green hydrogen project for oil refining in India is the partnership between the Indian Oil Corporation and the Institute of Chemical Technology to develop a pilot project to produce green hydrogen from RE sources and use it in the refining process. The project aims to demonstrate the viability of using green hydrogen in the oil refining industry and to encourage the wider adoption of this technology.

Australia is expected to produce the lowest levelized costs for green hydrogen by 2050 among the countries due to its abundant low-cost RE potential of wind and solar resources. Photovoltaics (PV) is the largest contributor to its national electricity production in the country. By 2022, Australia had the largest number of green hydrogen plants in the world with a total number of 96. Australia is also the largest iron ore producer in the world. Shifting to DRI exports could increase value added in Australia and reduce global CO₂ emissions greatly (Gielen et al. 2020). Both New Zealand and Australia are working on a feasibility study of low-carbon chemical production using green hydrogen. The two countries are looking to export hydrogen to other APAC countries such as Japan and the Republic of Korea.

Despite the lack of a national roadmap, Singapore is also promoting its investment in the hydrogen space and carrying out research and development activities on decarbonization technologies, such as CCUS and low-carbon hydrogen. The International Oceanic Administration has also identified some potential projects to explore the utilization of hydrogen in the marine industry.

Table 2: Selected Low-Carbon Hydrogen Projects in APAC

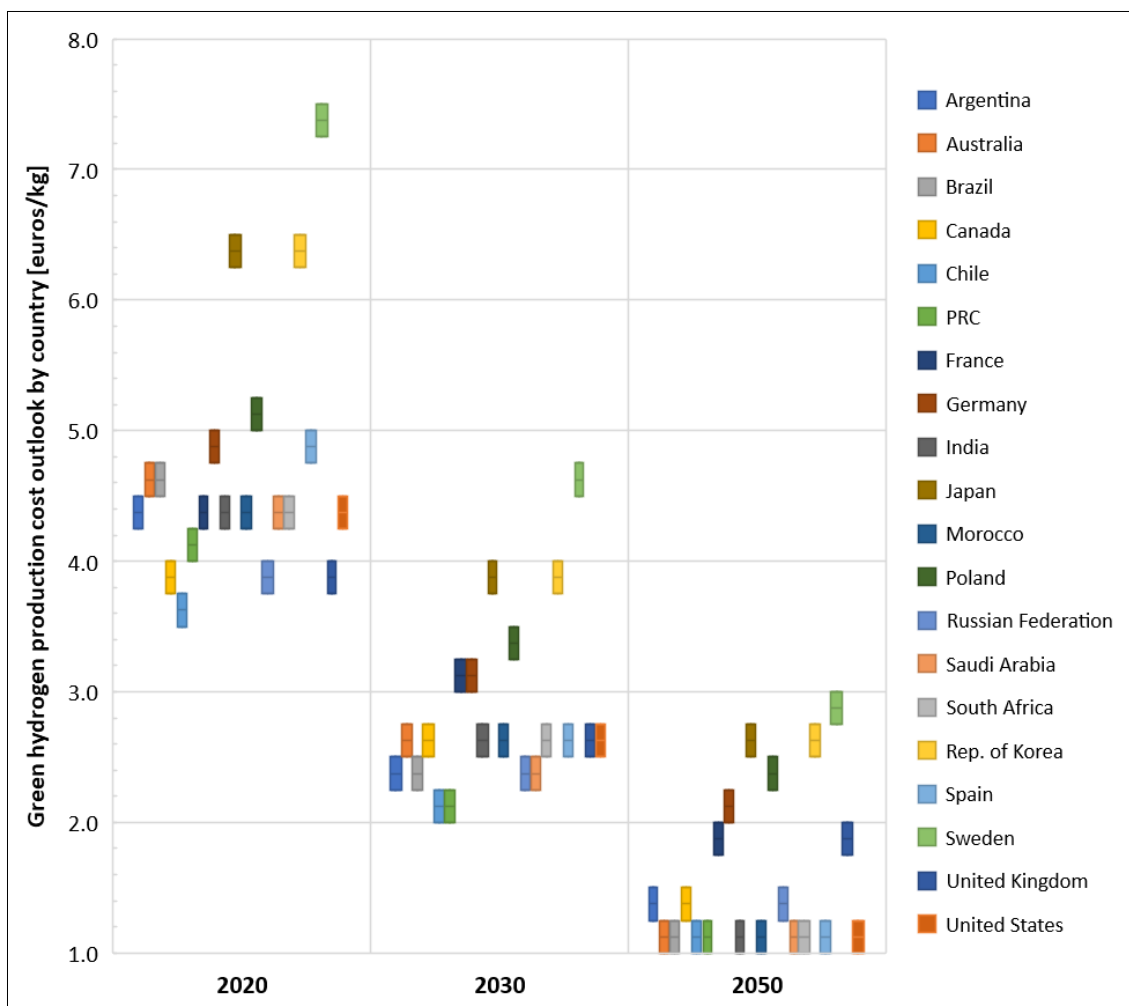
Country	Industry	Hydrogen Type/Year/Status	Projects
PRC	Chemical production	Green/2020/Ongoing	Lanzhou "Solar Methanol" Demonstration Project is the first demonstration project of solar fuel production in the PRC, with a total investment of 141 million yuan. Water electrolysis uses solar-generated electricity (20 MW) to generate hydrogen, and then carbon dioxide hydrogenation to produce synthesized methanol (1,440 tons/yr).
		Green/2021/Ongoing	Ningxia Baofeng Energy Group produces green hydrogen through solar power generation, and the green hydrogen produced is used to produce high-end materials such as methanol and olefins (Newenergy.in-en.com 2021).
	Iron and steel production	Green/2021/Planned	Angang Group signed an agreement to realize the process of wind power+PV-hydrogen production by electrolysis of water-hydrogen metallurgy (The Low-carbon Research Team 2021).
		Green/2022/Under construction	Baosteel Group subsidiary Baosteel Zhanjiang Iron and Steel is constructing the PRC's first self-integrated shaft furnace, and the world's first shaft furnace that directly adds hydrogen for the reduction process (1 Mt). The new facility will use green hydrogen powered by local wind and solar energy.
India	Oil refining	Green/2022/Commissioned	The first pure green hydrogen pilot plant is commissioned by Oil India Limited at Jorhat Pump Station in Assam, which produces green hydrogen from the electricity generated by the existing 500 kW solar plant using a 100 kW AEM electrolyzer array.
Japan	Oil refining	Blue/2019/Ongoing	The first full-chain CCS project in Japan, the Tomakomai CCS Demonstration Project, captured and stored CO ₂ from a coastal oil refinery on Hokkaido Island in Japan from 2016 to 2019. The hydrogen production unit in the refinery produces offgas that contains about 50% CO ₂ , which is captured in an active amine process (IEA 2021c).
	Hydrogen production	Green/2020/Ongoing	A demonstration pilot project "FH2R" to produce hydrogen from renewable energy in Fukushima Prefecture (10 MW) (Nagashima 2018b).
New Zealand	Oil refining	Green/2021/Feasibility study	The only oil refinery in New Zealand, Marsden Point, is engaged in the Refining NZ Green Hydrogen Project, which aims to investigate how solar energy and hydrogen might be used to reduce costs or serve as the foundation for low-carbon business lines in the future.
	Chemical production	Green/2022/Under construction	Hiringa Energy Limited and Ballance Agri-Nutrients Limited have applied to develop a renewable green hydrogen hub at Kapuni, Taranaki. Ballance Agri-Nutrients Kapuni, a nearby ammonia-urea manufacturing facility, will receive baseload power from wind turbines and green hydrogen from electrolyzers.
Australia	Chemical production	Green/2023/Under construction	Yara Pilbara and ENGIE will build a renewable hydrogen plant in the Pilbara to produce renewable ammonia using a 10 MW electrolyzer.
Rep. of Korea	Hydrogen production	Green/2022/Planned	Hyosung Group invested 1 trillion won to build green hydrogen production facilities (10 MW).

5. HYDROGEN MARKET IN THE APAC REGION

The APAC region is one of the fastest-growing markets for low-carbon hydrogen, with many countries investing in the development and use of this clean energy source, as can be seen from the above sections. The region has some of the largest hydrogen markets in the world, including Japan, the Republic of Korea, the PRC, and Australia, as well as rapidly growing markets in Southeast Asia and India.

The initial challenges posed by a country’s export/import potential have already influenced the development of national hydrogen policies in countries with significant industrialization and energy demands, such as Japan and the Republic of Korea, and those with a strong exporting foundation, such as Australia. This interplay between export and import strategies is reshaping the global energy landscape through new trade relationships and routes between countries.

Figure 5: Production Costs of Green Hydrogen Worldwide by Selected Country



Source: PwC 2021.

Figure 5 presents the current (2020) and future (2030 and 2050) production costs of green hydrogen worldwide in some selected countries (PwC 2021). Each box in the figure indicates the cost of one country with information on the maximum cost (upper

line of the boxes) and the minimum cost (lower line of the boxes). It can be seen that Chile currently has the lowest production cost of green hydrogen in the world, i.e., between 3.5 and 3.75 euros per kilogram. Over the next three decades, the number of countries that will be able to produce renewable-derived hydrogen for only one euro per kilogram is expected to increase significantly. The three countries with the lowest production cost in the APAC region are Australia, the PRC, and India, which will be between 1 and 1.25 euros per kilogram in 2050. Japan and the Republic of Korea will be relatively higher, i.e., between 2.50 and 2.75 euros per kilogram.

A fast development of RE-based green hydrogen is foreseeable in the PRC considering its massive renewable power capacity. However, taking into account the huge hydrogen demand in the country, the hydrogen produced in the PRC might be used for self-consumption, thus the PRC could become neither an exporter nor an importer. As demand for clean hydrogen sources continues to grow, some countries in the APAC region are expected to become major suppliers of hydrogen to other countries, both in the region and around the world.

In recent years, there has been growing interest in the export of hydrogen from Australia. Several Australian companies have already established partnerships and signed agreements to export hydrogen to countries in the APAC region, including Japan, the Republic of Korea, and the PRC. Given the significant natural gas and coal reserves as well as the RE potential in Australia, there are great opportunities for both green and blue hydrogen.

India aims to grow its hydrogen industry and become a major player in the global hydrogen market. On the export side, India is looking to leverage its experience in RE, particularly solar power, to produce green hydrogen. India has a significant advantage in terms of its large, low-cost workforce and its experience in the development and deployment of RE technologies, which could make it an attractive source of low-carbon hydrogen for other countries. On the import side, the country has already established partnerships with several countries in the APAC region, including Australia and Japan, to import low-carbon hydrogen.

Japan and the Republic of Korea are major importers of hydrogen in the APAC region. As countries that lack the natural resources for low-carbon hydrogen production, they are reliant on imports to meet their growing demand for clean energy. Both countries are looking to import low-carbon hydrogen from countries such as Australia and Malaysia, which have significant natural resources, including renewable energy and natural gas, which can be used to produce low-carbon blue and green hydrogen.

As the APAC region continues to invest in the development of the hydrogen economy, the growth of hydrogen trading is expected to accelerate, with increased demand for low-carbon hydrogen as a clean and sustainable energy source driving the growth of the hydrogen market.

6. CONCLUSIONS AND PERSPECTIVES

With technological progress as well as strong support from government and investors, the development of clean hydrogen energy in the APAC region enjoys broad prospects. Nevertheless, the development of clean hydrogen is still faced with major challenges before maturing, including high cost, technical barriers, and the lack of a market and sufficient ambitious policies. Also, in the short term, the further growth of low-carbon hydrogen as clean energy has to overcome the economic uncertainty brought by the COVID-19 pandemic.

This paper summarizes and analyzes the status, potential, and policies in the applications of clean hydrogen in the industry sector in the APAC region. Based on the analysis, the following perspectives are presented to help further decarbonize the industry with clean hydrogen.

Firstly, it is important to provide stronger policy support for the industry sector in the APAC countries. In the early stages, government policy, financial support for clean hydrogen, and infrastructure are essential for enhancing the commercial competitiveness of hydrogen relative to fossil fuels. The current national hydrogen strategies in some APAC countries are proposed in a rough and general way for the development of all related sectors. If there are any specific targets set, then most of them are for the mobility sector, such as in the Republic of Korea and Japan. However, there is a lack of clear targets and development pathways for clean hydrogen deployment in the industrial sector. The development of specific stimulus policies for clean hydrogen for different industries has been suggested to accelerate the deployment of decarbonization.

Secondly, it is essential to adapt the promotion measures to the local conditions of each country. The economic development and energy structure of the countries in the APAC region vary a lot, and it is important to understand the industries or sectors of each country that drive the existing hydrogen demand and costs from the demand-side perspective. Different strategies can be implemented for developed and middle-income countries. Countries that can bring leverage could share clear schemes such as FITs, grants, concessional loans, taxes, and exemptions. And countries that cannot bring financial leverage should implement friendly regulations to welcome innovative projects that can bring sustainable learning curves in the short run. The strengths and weaknesses of each country can be identified to elaborate a sort of regional strategy (Geze 2022).

Thirdly, low-carbon hydrogen is involved in various industrial processes from the technical perspective, while at the same time it also interacts with other sectors such as the power generation sector in the conversion process. The chemical industry, iron and steelmaking, and oil refining industries emit a large amount of CO₂. The hydrogen promotion schemes should also be coordinated with other environmental incentive schemes, such as carbon pricing and trading, to ensure that desired policies are carried out in an efficient way. This point is rarely mentioned in the current national strategies. It is suggested that clean hydrogen application should be considered in the industrial sector in the national environmental incentive scheme.

Lastly, the APAC region enjoys both large potential for clean hydrogen production and the ability to achieve local hydrogen consumption. In terms of hydrogen supply, there is the potential to export clean hydrogen from renewable resource-rich regions to high-demand centers in APAC. As mentioned earlier, Australia has the potential to be one of the major exporters of clean hydrogen due to its relatively mature infrastructure and abundant renewable energy resources. Additionally, New Zealand has expressed interest in maximizing its ability to export hydrogen. From the demand side, Japan is considered to be potentially one of the largest importers of green hydrogen in Asia due to its lack of renewable resources. Overall, even though it is still unclear whether clean hydrogen production and export can be realized on a commercial scale, there are already some possible candidates in the APAC region that might deliver green or blue hydrogen to consumers around the region.

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