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# HYDROGEN IN DECARBONIZATION STRATEGIES IN ASIA AND THE PACIFIC

Edited by Dina Azhgaliyeva, KE Seetha Ram,
and Haoran Zhang

ASIAN DEVELOPMENT BANK INSTITUTE

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# Foreword 1

In a world that is acutely aware of the pressing need to address climate change and reduce carbon emissions, the search for sustainable and clean energy sources has become an urgent imperative. We find ourselves at a pivotal moment in history, where the urgency of reducing emissions in hard-to-abate sectors looms large. Out of the myriad of solutions, green hydrogen emerges as a beacon of hope in addressing this challenge, offering a pathway to cut emissions deeply and quickly. The economics looks robust, with the growing demand for green hydrogen in Asia and the Pacific, the question that looms before us now is how to bring this concept into fruition.

The heart of this transformation lies in a formidable barrier: cost. The development of green hydrogen, from production to transportation to utilization, presents significant financial challenges. These financial barriers are particularly burdensome for developing countries attempting to implement hydrogen infrastructure as many lack the financial capacity and expertise. This is where international institutions like the Asian Development Bank (ADB) and others must leverage their full arsenal of policy, technology, and expertise. These institutions must play a pivotal role in mobilizing the necessary financing to enable green hydrogen markets to flourish.

The *Strategy 2030 Energy Sector Directional Guide* released in July 2023 highlights ADB's commitment to promoting low-carbon energy sources, including hydrogen, and supporting initiatives that drive the global transition toward clean energy. The guide outlines a comprehensive roadmap for ADB to foster innovation, mobilize investments, and facilitate cooperation in the energy sector, making green hydrogen an integral part of the region's sustainable energy future.

ADB has already begun to realize this vision with technical assistance projects such as the Supporting Green Hydrogen Through High Technology project in India and the Preparing Energy Storage and Green Hydrogen Sector Development Program in Georgia. These projects assist developing member countries in paving the way for the hydrogen economy through policy assistance and capacity building. However, as these projects are still in their early stages, there is plenty of work ahead, and ADB is committed to expanding its efforts in this sector.

While the challenges ahead may seem daunting, this book is an invaluable source of information and insight that will help overcome these obstacles. It is a collective effort that brings together expertise in the field, offering a study of the opportunities and challenges ahead, and will help realize of the fullest potential of green hydrogen.

As we navigate the complexities of the challenges ahead, let us remember that these challenges are worth undertaking. The promise of green hydrogen is not just an abstract concept but a tangible reality that can redefine the way our world is powered. Together, we can seize this opportunity and usher in an era of sustainable energy that will benefit generations to come.

**Priyantha Wijayatunga**
Senior Director, Energy
Sectors Group (SG)
Asian Development Bank

# Foreword 2

It is my great pleasure to write this foreword for *Hydrogen in Decarbonization Strategies in Asia and the Pacific*. This timely book collects and explores the profound impact of hydrogen in the transition to a sustainable future, focused on its development and application in the Asia and Pacific region. It offers valuable insights into hydrogen policies, strategies and the establishment of a "hydrogen society" for decarbonization.

As the world urgently seeks solutions to reduce greenhouse gas emissions and address climate change, hydrogen has emerged as a crucial component of decarbonization strategies. This book provides a deep understanding of hydrogen's potential and its transformative role in achieving ambitious global climate targets. The authors examine the transition from gray and blue hydrogen to green hydrogen, offering policy makers, researchers, and industry leaders valuable insights and recommendations for the further development and utilization of low-carbon hydrogen energy.

The book is structured into two parts. Part I, "Sectoral Focus," explores hydrogen's role within hard-to-abate sectors, such as industry and transportation. It discusses low-emission or emission-free hydrogen, including blue hydrogen produced through carbon capture, utilization, and storage (CCUS) technologies, as well as green hydrogen produced from renewables. Part II, "Regional Focus," delves into the potential and challenges of hydrogen in Asia and the Pacific, with a specific emphasis on India, Japan, and Kazakhstan. The chapters provide insights into green hydrogen production, the transition pathways to a hydrogen society, and the development of hydrogen economies in these countries, offering invaluable policy implications for decision-making processes in the region.

I commend the authors for their expertise and dedication in addressing the complex issues surrounding hydrogen's role in decarbonization. Their thoughtful analysis, evidence-based approaches, and policy recommendations make this book an essential resource for anyone seeking a comprehensive understanding of hydrogen's potential in decarbonization strategies. The Executive Summary, with its concise overview of each chapter, ensures that readers can readily access key findings and policy recommendations.

I would also like to express my appreciation to the editors and contributors for their collective efforts in producing this valuable volume. Their commitment to advancing knowledge in the field of hydrogen energy is commendable, and their work will undoubtedly inspire further dialogue, collaboration, and innovation in the pursuit of sustainable development in Asia and the Pacific.

**Jerry Yan**
Chair Professor of Energy and Buildings,
The Hong Kong Polytechnic University
Editor in Chief of *Advances in Applied Energy* and *Nexus* journals

# Executive Summary

This book explores the pivotal role of hydrogen in decarbonization strategies. It provides an overview of the development and application of hydrogen energy across various sectors while analyzing hydrogen policies and strategies in Asia and the Pacific. The book addresses crucial and timely issues related to the development of a "hydrogen society" for decarbonization in the region with evidence-based approaches. The book is organized into two parts (sector and regional focus). This executive summary offers an overview of each chapter, highlighting key findings and policy recommendations.

## Part I: Sectoral Focus

The first part of the book explores the status and prospects of hydrogen energy in so-called hard-to-abate industry and transportation sectors where achieving net-zero emissions by replacing fossil fuels with electrification is difficult with currently available abatement technologies. These sectors are increasingly considering low- or zero-emission hydrogen energy solutions, such as blue hydrogen (produced from fossil fuel combined with carbon capture, utilization, and storage [CCUS] technologies) and green hydrogen (produced solely from renewables such as wind and solar combined with water electrolysis technologies) as decarbonization strategies. This part comprises the following three chapters:

**Chapter 1. Accelerating the Net-Zero Transition in Asia and the Pacific: Low-Carbon Hydrogen for Industrial Decarbonization** investigates the status and potential of blue and green hydrogen in hard-to-abate industry sectors, including crude oil refining, chemical production, and iron and steel production. The focus is on the Asia and Pacific region, which accounts for 50% of global industrial hydrogen demand. This chapter also provides findings based on the analysis of national hydrogen strategies and projects in selected countries: Australia, India, Japan, New Zealand, the People's Republic of China, and the Republic of Korea. Hydrogen policies and strategies vary across countries due to differences in resource endowment, industrial market structures, and national energy governance and climate targets. This chapter emphasizes the significance of specific stimulus policies and concrete road maps tailored to each country's economic and market conditions. It also highlights the integration of green hydrogen application in the industry sector into national environmental incentive schemes and the potential for cross-border hydrogen trading in the Asia and Pacific region.

**Chapter 2. History, Status, and Future Challenges of Hydrogen Energy in the Transportation Sector** provides an overview of preliminary studies on hydrogen energy deployment in the transportation sector based on a systematic literature review of 148 core papers published between 1996 and 2022. These studies primarily focus on issues related to hydrogen refueling station layouts, the impact of hydrogen fuel cells on greenhouse gas emissions, the use of fuel cell vehicles, and the environmental impact of hydrogen fuel cell vehicles. The review identifies future challenges for hydrogen energy in the transportation sector, particularly regarding cost reduction. The authors recommend priority locations for hydrogen refueling stations in urban and surrounding areas, the implementation of tax and/or financial incentives to encourage private sector participation and investment in station construction and research and development (R&D), the application of hydrogen energy in heavy vehicles, and subsidies to stimulate hydrogen-powered vehicle adoption. Additionally, the chapter stresses the importance of implementing laws, regulations, and safety standards for hydrogen and promoting environmental awareness and intellectual property protection to further advance hydrogen energy. It also highlights the need for international cooperation to establish an economic hydrogen energy ecosystem.

**Chapter 3. Role and Development Pathways of Green Hydrogen Energy Toward Carbon Neutrality Targets** offers a comprehensive review of the pivotal role of green hydrogen energy in the global energy transition toward carbon neutrality. The chapter synthesizes discourses on the status and development trends of green hydrogen production technologies and the role and applications of green hydrogen energy. Implications for future hydrogen development strategies are drawn based on a comparative analysis of hydrogen policies in Australia, the European Union, Japan, the People's Republic of China, the Republic of Korea, and the United States. The chapter indicates the main factors of national support for green hydrogen energy development by economy and demonstrates progress in deploying green hydrogen by sector. The total potential green hydrogen market is projected to reach $1 trillion by 2050, with global hydrogen energy demand estimated to reach 520 million tons by 2070. To promote green hydrogen development in line with global climate goals, the chapter highlights key principles, including creating an institutional and policy environment conducive to the hydrogen energy industry's development, transitioning policy incentives from direct support to scalable market mechanisms, and expanding hydrogen energy utilization in hard-to-abate sectors.

The following list summarizes the principles for development pathways of green hydrogen:

- To provide an institutional and policy environment conductive to the development of hydrogen energy industry and bring relatively mature hydrogen applications to market.
- To transition policy incentives from early direct support to scalable market mechanisms.
- To realize a large-scale application of hydrogen energy in areas that are difficult to achieve decarbonization through replacement of fossil fuel with electrification (sourced from renewable energy) to help achieve the goal of carbon neutrality.

## Part II: Regional Focus

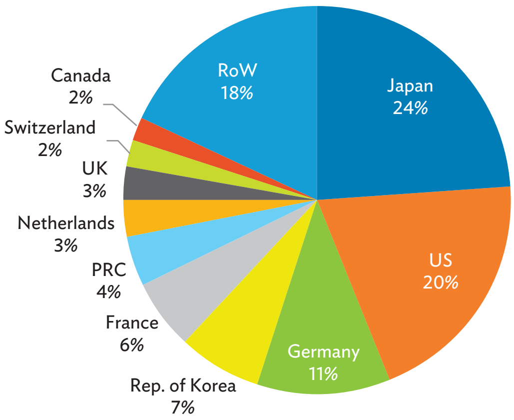
**Part II** delves into the prospects and challenges of hydrogen in the region, with particular emphasis on East, Central, South, and Southeast Asia. This part of the book investigates topics related to the potential of green hydrogen production and export in India, the transition pathways to a hydrogen society in Japan, and the development of a hydrogen economy in Kazakhstan, drawing policy implications. This part comprises the following five chapters:

**Chapter 4. Opportunities, Challenges, and Policy of Green Hydrogen in India** introduces insights into India's tremendous potential for green hydrogen production and utilization. It thoroughly investigates India's policies, investment, and production costs related to green hydrogen. The Indian government has set an ambitious target to supply 10% of global green hydrogen demand by 2030, producing 5 million tons with its renewable energy deployment capacities. Storage and transmission costs also influence hydrogen's competitiveness in the energy market. Large-scale hydrogen storage and long-distance transmission projects are encouraged to stimulate global demand for and utilization of green hydrogen. The chapter highlights the need to establish and sustain robust supply chain infrastructure and networks for green hydrogen through international cooperation among various stakeholders, including importing and exporting countries and technology leaders, to accelerate the global transition to green hydrogen.

**Chapter 5. Technology Foresight for Hydrogen Society Transition in Japan: A GTAP-E-Power Model Approach** conducts an impact assessment of the transition to a hydrogen society in Japan. It assesses the capital investment in hydrogen-related infrastructure in Japan using the GTAP-E-Power model, a detailed electricity-based economy-wide model. The simulation results indicate that carbon dioxide emissions in transportation, services, and power generation sectors will decline significantly, leading to economic growth (in terms of gross domestic product) and improved welfare. The chapter also discusses possible changes in output, price, employment, and supply chains. Establishing hydrogen production and infrastructure networks, a hydrogen society pilot zone, capacity building in hydrogen-related industries, policy dialogues on technology transfer, and stakeholder partnerships are vital for the hydrogen society transition.

**Chapter 6. How Can Japan Help Create a Sustainable Hydrogen Society in Asia?** highlights the importance of transitioning from blue and gray (fossil fuel-produced) hydrogen to green (renewables-produced) hydrogen to achieve net-zero climate goals. It analyzes Japan's current energy strategies and the barriers and benefits of green hydrogen transitions. Green hydrogen development has the potential to contribute to local revitalization, energy security, and regional and international cooperation for net-zero emissions. With Japan's commitment to carbon neutrality and a significant share of renewables in the power generation mix by 2050, domestic hydrogen demand is projected to rise substantially, while Japan currently produces only 2 million tons. The chapter highlights the ambiguity in Japan's national policies regarding the transition to green hydrogen and recommends strategic clarity, stronger connections between hydrogen policies and international climate and local revitalization strategies, and enhanced regional collaboration in R&D and capacity building.

**Share of All Hydrogen-Related International Patent Families**



PRC = People's Republic of China, RoW = rest of the world, UK = United Kingdom, US = United States.

Source: Authors using Chapter 6 analysis.

**Chapter 7. Toward a Hydrogen Economy in Kazakhstan** analyzes the role of hydrogen in Kazakhstan's long-term decarbonization strategy. Renewable energy sources have limited decarbonization capacity in hard-to-abate sectors such as heavy industry and transportation. Therefore, the development of low-carbon technologies such as hydrogen and CCUS is crucial. The chapter discusses drivers for Kazakhstan's pursuit of a hydrogen economy, including international agreements like the Paris Agreement and the Doctrine of Carbon Neutrality by 2060, as well as national and foreign carbon regulations. The chapter also addresses the geological, technological, and financial aspects of blue and green hydrogen value chains (production, storage, and transportation) and identifies near- and long-term hydrogen utilization areas. The authors propose stimulating local demand for hydrogen in various sectors and implementing technical standards and investment policies to mitigate financial challenges in hydrogen value chain development.

**Chapter 8. Green Hydrogen International Market: Barriers and Prospects for South and Southeast Asia** discusses the international green hydrogen market's prospects and significance due to limited production capacity in many countries to meet domestic demand for green hydrogen. The International Renewable Energy Agency predicts that over 30% of hydrogen will be traded across borders by 2050. The authors propose an action checklist for South and Southeast Asian countries seeking to enter the international green hydrogen market, based on a literature review and discussions related to the global green hydrogen value chain. The region possesses significant potential to become green hydrogen exporters because of its manufacturing components and materials for green hydrogen production. However, there are policy and legal barriers, including a lack of national policies supporting green hydrogen R&D, production, transportation, and material utilization. National and international legal frameworks to attract, protect, and profit from patents are also lacking. The chapter emphasizes the importance of developing policy and legal frameworks to incentivize R&D and hydrogen production while fostering international collaboration in the international green hydrogen market.

This book serves as a key knowledge source for understanding hydrogen's role in decarbonization strategies. It comprehensively analyzes the transition from gray and blue hydrogen to green hydrogen to accelerate decarbonization across various sectors and achieve ambitious global climate targets. The findings and discussions provide policymakers and researchers with forward-looking insights and policy recommendations for further developing and utilizing low-carbon hydrogen energy in Asia and the Pacific. Some chapters highlight the potential of low-carbon hydrogen application in hard-to-abate sectors, while others stress the need for specific road maps for transitioning to green hydrogen and a hydrogen society. To accelerate the hydrogen industry's development toward net-zero emissions, some authors recommend enhancing incentive schemes and international cooperation to mobilize various stakeholders for R&D in hydrogen technologies, infrastructure development, and cross-border supply chain networks. The following table provides a summary of all chapters.

## Summary of Chapters

| Ch. | Title | Theme | Coverage | Key Findings |
|---|---|---|---|---|
| **Part I: Sectoral Focus** | | | | |
| 1 | Accelerating the Net-Zero Transition in Asia and the Pacific: Low-Carbon Hydrogen for Industrial Decarbonization | Low-carbon hydrogen as industrial decarbonization strategy | Hard-to-abate industry sector in Asia and the Pacific | Region accounts for half of global industrial hydrogen demand (IEA 2019); policy recommendations for industry sector decarbonization through low-carbon hydrogen |
| 2 | History, Status, and Future Challenges of Hydrogen Energy in the Transportation Sector | Development and prospects of hydrogen in the transportation sector | Transportation sector | Trend in preliminary studies; future challenges for hydrogen energy in transportation; need for an economic ecosystem for hydrogen |
| 3 | Role and Development Pathways of Green Hydrogen Energy toward Carbon Neutrality Targets | Cross-economy analysis of hydrogen policies | European Union, United States, Japan, Republic of Korea, People's Republic of China, and Australia | Size of the potential green hydrogen market; key principles for green hydrogen development pathways |
| **Part II: Regional Focus** | | | | |
| 4 | Opportunities, Challenges, and Policy of Green Hydrogen in India | Potential for green hydrogen production and export | India | India's potential for green hydrogen owing to its renewable energy capacity; need for robust supply chain infrastructure |

*continued on next page*

**Summary of Chapters** *continued*

| Ch. | Title | Theme | Coverage | Key Findings |
|---|---|---|---|---|
| 5 | Technology Foresight for Hydrogen Society Transition in Japan: An Approach of GTAP-E-Power Model | Impact assessment of hydrogen society transition | Japan | Benefits of hydrogen society transition, including emission reduction, gross domestic product growth, and improved welfare |
| 6 | How Can Japan Help Create a Sustainable Hydrogen Society in Asia? | Role in promoting a hydrogen society in Asia | Japan | Significance of transitioning to green hydrogen as decarbonization strategy; benefits and barriers of green hydrogen transitions |
| 7 | Toward a Hydrogen Economy in Kazakhstan | Policy, technology, and economy aspects of hydrogen economy transition | Kazakhstan | Drivers for transitioning to a hydrogen economy; importance of stimulating local demand for hydrogen, especially in hard-to-abate sectors |
| 8 | Green Hydrogen International Market: Barriers and Prospects for South and Southeast Asia | International green hydrogen market | South and Southeast Asia | Prospects of the international green hydrogen market; policy and legal barriers to becoming green hydrogen exporters |

Source: Authors.

# Introduction: Promoting Hydrogen Society in Asia

*Wataru Kodama and Dina Azhgaliyeva*

The world is moving toward net-zero carbon emissions. As of the middle of 2023, 150 countries have committed to national carbon-neutral targets by 2030–2070 (Oxford Net Zero 2022). These countries make up 83% of global greenhouse gas (GHG) emissions and 90% of global gross domestic product (Oxford Net Zero 2022). However, relying solely on renewable energy is insufficient to achieve these targets, necessitating the exploration of alternative technologies. Many researchers and policymakers believe that hydrogen will play a transformative role in energy production and consumption, significantly contributing to the path to net-zero emissions. Hydrogen is a versatile "free energy carrier" that can be generated from various sources and applied across diverse sectors (IRENA 2019). Asia and the Pacific's ivestments in hydrogen hold the potential to transition toward a "hydrogen society" where hydrogen assumes a central role in daily life. As of mid-2023, seven countries in the region (Australia, India, Japan, the People's Republic of China [PRC], the Republic of Korea, Singapore, and Uzbekistan) have already developed national hydrogen strategies, with at least 11 other countries in the region in discussions or preparations for their own similar strategies (Bloomberg 2023). Despite the growing investments in hydrogen, the funding allocated to it remains relatively modest when compared to renewable energy.

In order to stimulate public interest and offer recommendations for policymakers in Asia and the Pacific, the Asian Development Bank Institute (ADBI) hosted three hydrogen-focused events in 2022: (i) Virtual Deep Dive Workshop on "Future Hydrogen Society in Asia and the Pacific" as part of the ADB Asia Clean Energy Forum;[1] (ii) ADBI

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[1] See event web page at https://www.adb.org/news/events/virtual-deep-dive-workshop-on-future-hydrogen-society-in-asia-and-the-pacific-and-regional-session-on-promoting-decarbonization-through-efficient-district-heating-and-cooling-solutions-in-east-asia-region.

Session on Green Hydrogen for Emission Mitigation as part of the 14th International Conference on Applied Energy;[2] and (iii) Virtual Workshop on Hydrogen in Decarbonization Strategies in Asia and the Pacific as part of the 8th Applied Energy Symposium on Low Carbon Cities & Urban Energy Systems 2022,[3] using an open call for papers. This concise introduction outlines key findings and recommendations from these workshops.

## Asia and the Pacific as a Future Leader in the Hydrogen Society

Asia and the Pacific stands out as one of the most promising regions to lead the global hydrogen ecosystem because of its considerable potential for both hydrogen production and consumption. This region accounts for approximately 60% of global carbon dioxide emissions in 2021 (Ritchie et al. 2020) and faces an urgent need to transition its energy mix by incorporating renewable energy and green hydrogen. Cost reduction is the most crucial challenge for scaling up hydrogen production and utilization in the region [4],[4] with discussions during the workshops focusing extensively on production and supply chain-related cost challenges.

### Production Cost

The high production cost of green hydrogen poses a significant challenge to its adoption as a viable alternative to conventional energy sources. Green hydrogen, produced via water electrolysis using renewable energy such as wind and solar, is carbon-free. However, its production cost is substantially higher than that of conventional energy sources and other types of hydrogen (Table 1). Gray hydrogen, generated from fossil fuels, currently dominates the market because of its price competitiveness. Blue hydrogen, another type, is produced from fossil fuels but emits fewer GHGs, thanks to carbon capture and storage (CCS) technology.

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[2] See event web page at https://www.adb.org/news/events/adbi-session-on-green-hydrogen-for-emission-mitigation-14th-international-conference-on-applied-energy.

[3] See event web page at https://www.adb.org/news/events/virtual-workshop-on-hydrogen-in-decarbonization-strategies-in-asia-and-the-pacific.

[4] For references made to presenters and panel discussants during the workshops, see References section.

## Table 1: Hydrogen Color Code

| Color Code | Energy Source | Related Technology | Clean Hydrogen |
|---|---|---|---|
| Green | Renewable | Water electrolysis | Yes |
| Blue | Fossil fuel | CCS | Yes/No |
| Gray | Fossil fuel | | No |

Source: Based on IRENA (2019).

With the declining prices of renewable electricity, green hydrogen is expected to become cost-competitive with gray hydrogen and other conventional energy sources (IRENA 2019). Some countries in Asia and the Pacific with substantial renewable energy capacities, such as Australia, India, and the PRC, have significant potential for green hydrogen production.[5] For instance, by 2030, green hydrogen costs in India could plummet to around $2 per kilogram, achieving parity with gray hydrogen and other fossil fuels across various applications [1, 9]. Blue hydrogen, while offering some advantages, is neither inherently carbon-free nor expected to experience the cost reductions projected for green hydrogen (IRENA 2019). Therefore, considering the regional environmental and economic conditions, Asia should prioritize investments in green hydrogen production over gray and blue hydrogen [4].

Synergies exist between green hydrogen and renewable energy production, as hydrogen, serving as an energy carrier, can provide demand-side flexibility by smoothing out the intermittencies of renewable energy production (IRENA 2019). For instance, in the southwest of England, locally produced green hydrogen from offshore wind energy is projected to cost half as much as the region's natural gas by 2050. Combined with offshore wind, green hydrogen could potentially satisfy the region's entire energy demand [2]. Given the geographical features of the Asia and Pacific region, similar scenarios can be envisioned for certain countries with high offshore wind energy potential (e.g., Australia) [2].

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[5] See, for example, report by the International Energy Agency (2019, p. 49) for the geographical distribution of green hydrogen costs in the long term.

## Supply Chain

Even if production costs decrease, hydrogen will not be a viable option without a robust supply chain. Developing supply chain networks is of particular importance to Asia and the Pacific, where both potential hydrogen exporters and importers coexist (KMPG 2021). Key considerations for supply chain development include (i) where to produce hydrogen and (ii) how to transport hydrogen. Concerning the first, local green hydrogen production in the power sector can enhance grid stability, maximizing the integration of intermittent renewable energy [5]. Such projects can be financially viable in the short term since the energy sector typically already possesses supply chain networks, obviating the need for extensive infrastructure development [5]. Alternatively, local hydrogen production for local consumption is another approach. For instance, Shikaoi town in Hokkaido, Japan, reliant on dairy and upland farming, initiated a biogas-based hydrogen supply chain in 2015, encompassing local production, storage, transportation, and consumption of hydrogen, making effective use of the substantial livestock manure produced annually [8].

Various methods are available for hydrogen transportation, but in the long term, pipeline transportation and maritime shipping are cost-effective modes for medium- and long-distance transport (IEA 2019). In Europe and the United States, hydrogen is already transported through natural gas pipelines as blended hydrogen and dedicated hydrogen pipelines as pure hydrogen. A case study from the PRC indicates that pipeline transportation is more cost-effective than using tube trailers and liquid hydrogen tankers for long-term carbon-neutral goals [10]. Given these distinct differences in technical requirements [10], and considering long-term carbon-neutral objectives, countries in Asia and the Pacific should prioritize investments in the latter technologies.

Shipping hydrogen in energy-intensive forms like ammonia or liquefied hydrogen is gaining attention. In the Hydrogen Energy Supply Chain Pilot Project between Australia and Japan, newly developed liquefaction and hydrogen transportation technologies facilitated the world's first international shipment of liquid hydrogen in January 2022 [3]. The Government of Japan aims to commercialize this supply chain network by the 2030s [3].

## Recommendations for Future Hydrogen Society

Countries in Asia and the Pacific are poised to assume various roles in the future hydrogen society: some will be technology leaders and/or exporters, some major hydrogen producers and/or exporters, and others major hydrogen consumers and/or importers (KPMG 2021). To maximize the region's potential in hydrogen production, utilization, and technology development, international collaboration among governments and private enterprises is particularly important for fostering a future hydrogen society.

Considering regional hydrogen supply and demand networks as an ecosystem is crucial. Comprehensive and multilateral measures should be taken to collectively boost hydrogen demand in the region [6]. Investments in hydrogen production, supply chain infrastructure, and related technologies should be optimally allocated based on the potential hydrogen demand and supply of each country. For example, countries like the PRC and India, with significant hydrogen production and consumption potential, may prioritize hydrogen production near consumption sites or the development of hydrogen pipelines. In contrast, countries like Japan, expected to be major importers because of their geographical characteristics (e.g., surrounded by sea), should focus on investment in shipment technologies. Moreover, given significant disparities in technology development and accessibility among countries in the region [9], regional collaboration in hydrogen technologies is of great importance.

Finally, while discussions on hydrogen often emphasize challenges, the co-benefits of hydrogen, including environmental, health (e.g., cleaner air), and economic (e.g., job creation), are often underemphasized [7]. Quantifying and monetizing these benefits are critical to making hydrogen politically and economically attractive to policymakers and investors [7].

## Conclusion

High production costs and a lack of hydrogen supply chain networks pose significant challenges to scaling up hydrogen production and utilization. However, Asia and the Pacific possesses unique potential and opportunities to address these challenges. To accelerate progress toward a future hydrogen society, the region must take comprehensive and multilateral measures to further stimulate and optimally allocate investments in hydrogen.

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## Presentations and Panel Discussions from Workshops

### Virtual Deep Dive Workshop on "Future Hydrogen Society in Asia and the Pacific"

(1) Mr. Nikhil Moghe. Partner Lead, Clean Fuels KPMG India. Green Hydrogen Opportunities.

(2) Dr. Mi Tian. Researcher, College of Engineering, Mathematics and Physical Sciences, University of Exeter. Wind to Hydrogen in Southwest England.

(3) Mr. Hiroki Yoshida. Deputy Director, Hydrogen and Fuel Cells Strategy Office, Ministry of Economy, Trade and Industry (METI), Japan. Panel discussion.

### ADBI Session on "Green Hydrogen in Emission Mitigation"

(4) Dr. Nandakumar Janardhanan. Research Manager, Climate and Energy Institute for Global Environmental Strategies. Making Hydrogen Society a Reality in Asia.

(5) Mr. Mathiew Geze. Director, Asia HDF Energy. Panel discussion.

(6) Dr. Victor Nian. CEO, Centre for Strategic Energy and Resources. Panel discussion.

(7) Dr. Eric Zusman. Senior Policy Researcher, Institute for Global Environmental Strategies. Panel discussion.

## ADBI Workshop on "Hydrogen in Decarbonization Strategies in Asia and the Pacific"

(8) Dr. Nandakumar Janardhanan. Research Manager, Climate and Energy, Institute for Global Environmental Strategies. How Can Japan Help Create a Sustainable Hydrogen Society in Asia?

(9) Dr. Ranjeeta Mishra. Economist, Reserve Bank of India. Future Hydrogen Society: India and the World.

(10) Ms. Zhu Zhu. China University of Petroleum. Techno-economic Analysis of Long-Distance Hydrogen Pipeline Transportation.

## PART I

# Sectoral Focus

# 1

# Accelerating the Net-Zero Transition in Asia and the Pacific: Low-Carbon Hydrogen for Industrial Decarbonization

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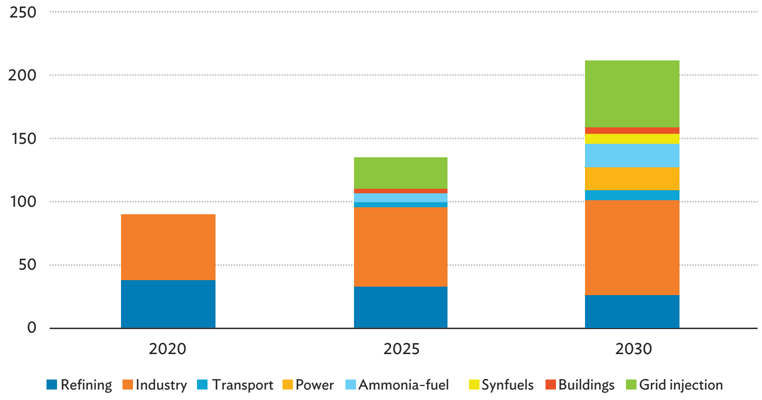
## 1.1 Introduction

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 $CO_2$ 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 1.1 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 1.2 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.

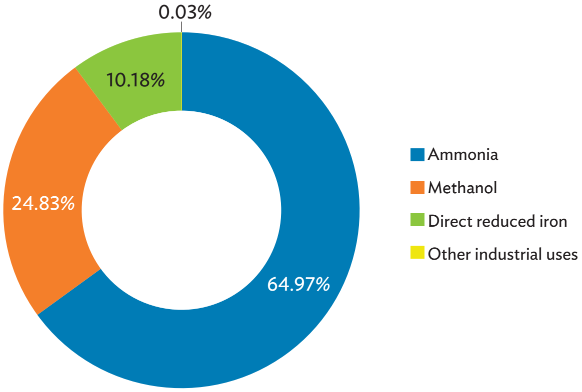
Compared to other energy sectors, the industry sector might benefit from hydrogen in reducing the use of biomass at a lower cost (Korberg et al. 2023). But it should be noted that the direct use of hydrogen in the industrial process as an alternative fuel should be avoided from the energy efficiency and energy system perspective, unless there is no other option available or if the other option is biomass with unsustainable use

**Figure 1.1: Global Hydrogen Demand by Sector in the Net Zero Scenario of the IEA**



Source: IEA 2021a.

**Figure 1.2: Share of Global Hydrogen Demand in Industry in 2020**



Source: IEA 2020.

(Sorknæs et al. 2022). Therefore, this chapter 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.

A shift from traditional fossil fuel-based grey 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 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 grey 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 $CO_2$ 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 $MtH_2$) 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 chapter 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.

## 1.2 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.

### 1.2.1 Oil Refining

#### 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.

### 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 $CO_2$ price is above USD50/$tCO_2$ compared to the traditional process without CCUS (IEA 2019a).

## 1.2.2 Chemical Production

### 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 $MtH_2$/yr and 12 $MtH_2$/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.

### 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.

## 1.2.3 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 $CO_2$ 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).

### 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 $MtH_2$/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 $MtH_2$/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.

### 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 $CO_2$ 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 grey/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).

### 1.2.4 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.

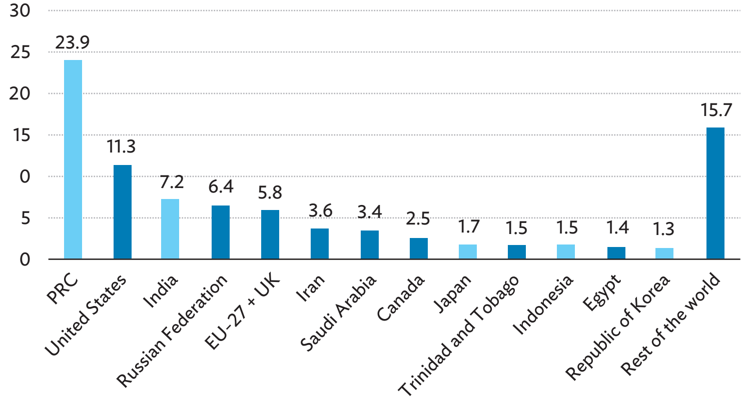
## 1.3 Status of Hydrogen Market in the APAC Region

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 carrier. 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 1.3 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 grey 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 1.3: Annual Hydrogen Consumption Worldwide in 2020 by Country (APAC Countries Marked in Light Blue)**

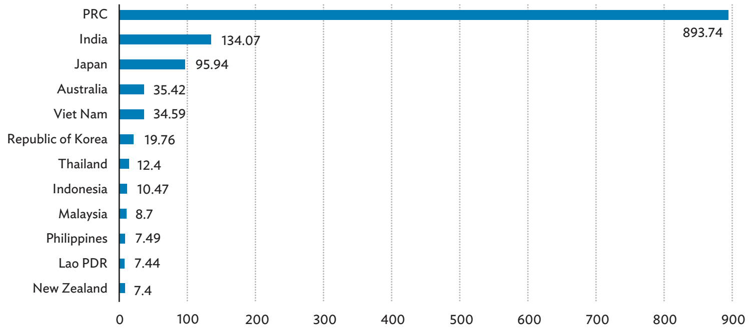


Source: International Renewable Energy Agency 2022.

Figure 1.4 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 1.4: Renewable Power Capacity in Selected APAC Countries in 2020**



Source: The Global Economy 2021.

## 1.4 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.

### 1.4.1 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 1.1 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 $MtH_2$/yr, of which 12 $MtH_2$/yr meet the industrial 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 way 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 the country. 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: *A Vision for Hydrogen in New Zealand: 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 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 1.1: 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 | - By 2025, the hydrogen production from renewable energy will reach 100,000–200,000 tons/year.<br>- 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 | - Explore hydrogen produced from renewable energy to replace fossil energy in refining and coal-to-oil gas industries. |
| | | Chemical production | - Expand the application scale of hydrogen to replace fossil energy in industrial fields such as synthetic ammonia and methanol. |
| | | Iron and steel | - Carry out research and application of hydrogen metallurgy technology utilizing hydrogen as reducing agent. |
| | | High-temperature heat | - 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 | - 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<br>Oil refining | - Encourage the production of green ammonia and methanol based on green hydrogen.<br>- Promote the replacement of hydrogen produced from fossil fuel sources with green hydrogen in ammonia production and petroleum refining.<br>- Ministry of Petroleum and Natural Gas will facilitate uptake of green hydrogen in refineries through both public and private sector entities. |
| | | Iron and steel | - Promote the production of steel with green hydrogen. |

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**Table 1.1** *continued*

| Country | Year | National Policies | |
|---|---|---|---|
| **Japan** (Nagashima 2018a; Ministry of Environment Government of Japan 2020) | 2017, 2019 | General | • Create a "Hydrogen Society" in which hydrogen is employed in both daily life and industrial activities.<br>• Fully diffuse hydrogen applications over the medium to long term through 2050.<br>• Relevant government agencies will work closely to discover promising seeds for fundamental research and industry needs.<br>• Consider the introduction of the various processes for using $CO_2$-free hydrogen in a sequential manner as the processes achieve economic rationality. |
| | | Oil refining and iron and steel production | • Consider transitioning from fossil fuel-based hydrogen to $CO_2$-free hydrogen to reduce carbon emissions in industrial processes such as steelmaking and oil refining. |
| | | Chemical production | • Develop technologies to combine CCS or hydrogen with ammonia production to eliminate $CO_2$ emissions. |
| **New Zealand** (Ministry of Business, Innovation & Employment 2019) | 2019 | Oil refining | • Actively explore the development of green hydrogen production to materially reduce the emissions from petroleum refining. |
| | | Chemical production | • Ammonia production: Use green hydrogen feedstock for chemical reactions.<br>• 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 | • Use green hydrogen as an alternative way of producing steel with zero-carbon emissions.<br>• Attempt to overcome the technological challenges that are currently impeding the widespread adoption of hydrogen to produce steel with a low-carbon footprint. |

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**Table 1.1** *continued*

| Country | Year | National Policies | |
|---|---|---|---|
| **Australia** (COAG Energy Council 2019; Australian Government Department of Industry, Science and Energy and Resources 2021) | 2019 | General | • Switch existing industrial hydrogen users to clean hydrogen.<br>• Investigate opportunities for clean hydrogen such as clean ammonia exports, clean fertilizer exports, industrial heating, iron ore processing, and steel production. |
| | | Steelmaking | • Steel production becomes a targeted application for hydrogen, with all new facilities producing steel from iron ore using hydrogen by 2030. |
| | | Industrial heat | • 2025: Hydrogen is being tested in at least niche applications, if not more broadly, and industry stakeholder acceptance of hydrogen is growing.<br>• 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 | • Increase domestic annual hydrogen consumption from 130,000 tons in 2018 to 5.26 million tons by 2040.<br>• 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, $CO_2$-free hydrogen by 2040. |

## 1.4.2 Low-Carbon Hydrogen Projects for Industrial Purposes in APAC

Table 1.2 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 $CO_2$ 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 1.2: 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 synthesize 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 CO2 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). |

*continued on next page*

**Table 1.1** *continued*

| Country | Industry | Hydrogen Type/ Year/Status | Projects |
|---|---|---|---|
| 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). |

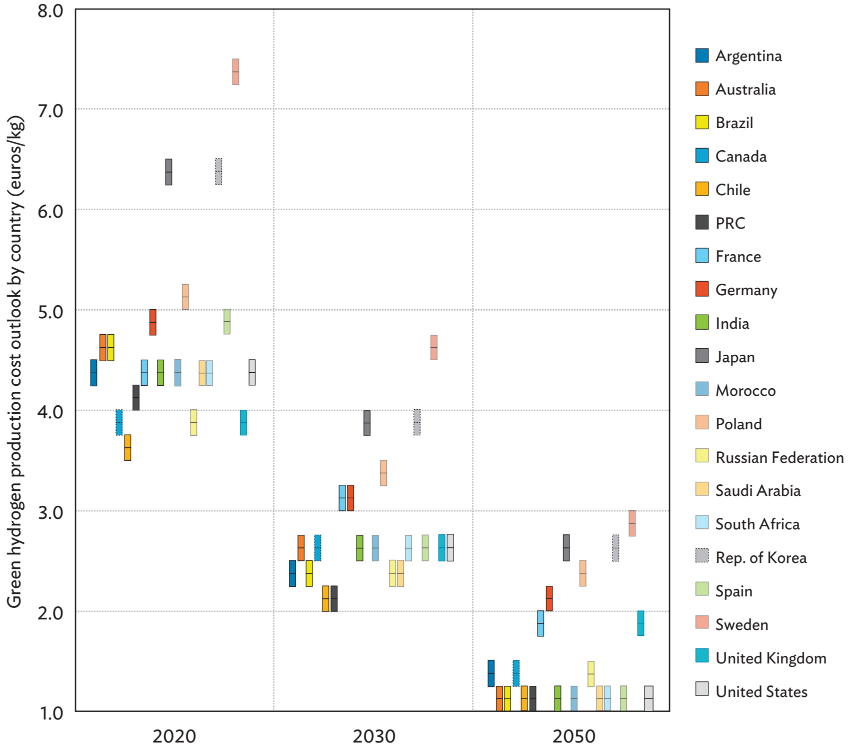
Source:

## 1.5 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, 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 1.5: Production Costs of Green Hydrogen Worldwide by Selected Country



Source: PwC 2021.

Figure 1.5 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 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.

## 1.6 Conclusions and Perspectives

With technological progress as well as strong support from government and investors, the development of low-carbon 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 chapter summarizes and analyzes the status, potential, and policies in the applications of low-carbon 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 low-carbon 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 low-carbon 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 low-carbon 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 $CO_2$. 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 low-carbon hydrogen application should be considered in the industrial sector in the national environmental incentive scheme.

Lastly, the APAC region enjoys both large potential for low-carbon hydrogen production and the ability to achieve local hydrogen consumption. In terms of hydrogen supply, there is the potential to export green 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 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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# 2

# History, Status, and Future Challenges of Hydrogen Energy in the Transportation Sector

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*Jie Yan, and Yamin Yan*

## 2.1 Introduction

### 2.1.1 Background

On 12 December 2015, the Paris Climate Conference reached an agreement on global climate change and set the goal to limit long-term global warming to less than 2 degrees Celsius, and preferably below 1.5 degrees Celsius, compared to preindustrial levels (Masson-Delmotte et al. 2018).

In order to achieve the targets for temperature control proposed in the Paris Agreement, many countries have proposed pathways for carbon neutrality, which has become a common vision and ongoing worldwide action plan. Among the emission reduction measures adopted by many countries and regions, encouraging the development and adoption of renewable energy has become a common choice (News 2022), and there is now a huge and historical opportunity to develop the latter. In the meantime, as a type of renewable and clean energy source, green hydrogen energy has received much attention, and it can play an important role in reducing carbon emissions in the transportation sector, in industrial power, and in other areas that generate large amounts of carbon emissions (Yu et al. 2022). In September 2020, at the 75th session of the United Nations General Assembly, President Xi Jinping announced that the People's Republic of China (PRC) would strive to peak its carbon dioxide ($CO_2$) emissions by 2030 and achieve carbon neutrality by 2060 (Xi 2020). Therefore, the research related to hydrogen energy is extremely important and of great significance, but also presents challenges (Zou et al. 2022).

As expected, the research and development of hydrogen energy in the field of transportation keeps increasing. The transportation industry is an important part of our society and underpins the prosperity of the different economies (Selvakkumaran and Limmeechokchai 2015). However, it is responsible for various types of energy consumption and greenhouse gas emissions, which account for 15% of total carbon emissions (Zhang 2022b). During the current period of the PRC's 14th Five-Year Plan, the Ministry of Transport has released a work plan that includes the implementation of 11 major projects, including the "Green Low Carbon Transport Sustainability Project." Around the overall goal of reducing the carbon intensity of transportation, it is necessary to support the large-scale use of new energy vehicles and ships. Therefore, hydrogen energy plays a more important role in the transportation sector and contributes to sustainable urban development (Bi et al. 2021).

Hydrogen fuel cell vehicles (HFCVs) have been developing rapidly in recent years, and many countries such as the PRC, Germany, and the United States are also accelerating the layout and construction of hydrogen refueling stations for HFCVs so as to vigorously promote the industrialization of hydrogen fuel cells. In addition to HFCVs, aviation and shipping are also actively exploring the application of hydrogen energy (Zhang 2022a). The development of hydrogen energy applications in the transportation sector will undoubtedly greatly facilitate extensive and deep decarbonization in this field.

### 2.1.2 Research Status

In order to obtain a general understanding of the research status of hydrogen, we searched the Web of Science database with "hydrogen" as the keyword, obtained more than one million related papers, and selected 8,000 from them. The keyword "co-occurrence analysis" was used by VOSviewer software for the above-listed papers. The analysis results are shown in Figures 2.1 and 2.2.

As can be seen in Figure 2.1, the terms "catalyst," "structure," "emission," "molecule," "formation," and "technology" appear most frequently, which indicates that scholars and researchers pay more attention to the production method, production efficiency, and energy structure of hydrogen. In addition, the pollution and emissions generated during the hydrogen production process are also the focus of researchers' attention.

**Figure 2.1: Keyword Co-Occurrence Analysis Based on Hydrogen**

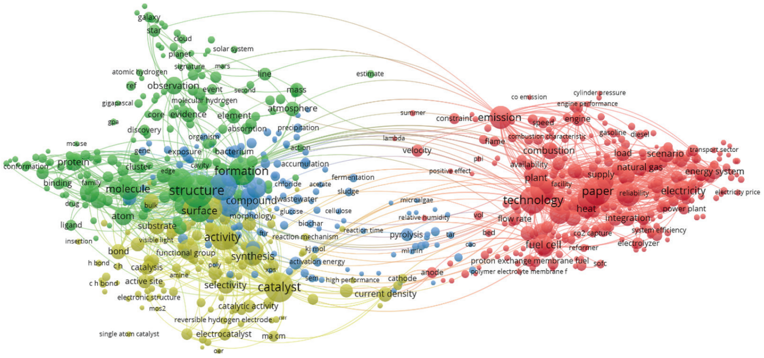
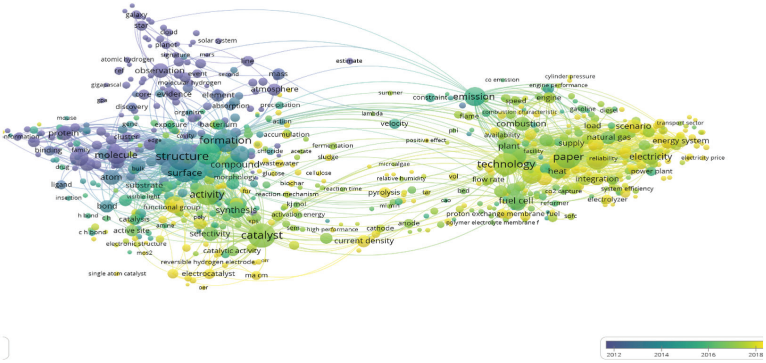


**Figure 2.2: Co-Occurrence Analysis of Keywords as Time Evolves**



The evolution of the research topics over time can be seen in Figure 2.2. According to the figure, the research topics in the previous years were mainly focused on structure, molecules, formation, catalysts, etc. In recent years, as research has intensified and more attention has been paid to environmental and climate issues, research topics have tended to focus on emissions, power, energy systems, cost, etc.

This study first analyzes and summarizes the research background and significance of hydrogen energy, then analyzes and summarizes the current situation and the hot topics of hydrogen energy research by setting keywords to search relevant papers, and, based on this, selects papers related to hydrogen energy in the field of transportation for further analysis. Through a review of the literature, this study briefly introduces the production and manufacturing process of hydrogen energy, the classification of hydrogen energy, and the technologies applied to the transportation field; in addition, the history, current situation, and controversies of its application in the transportation sector are also introduced. Following this, the searched papers are further classified and organized to analyze the application of hydrogen energy. Finally, the challenges of hydrogen energy in the field of transportation in the future are presented.

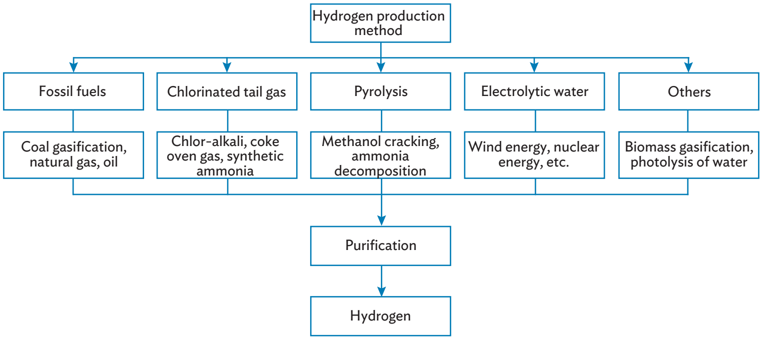
## 2.2 The Application of Hydrogen Energy

### 2.2.1 The Hydrogen Energy Production Process

The industry chain of hydrogen energy includes its production, storage, transportation, refueling, and use. Among these processes, hydrogen production technology includes its production from fossil energy, from electrolytic water, from industrial byproducts, and from renewable energy, as shown in Figure 2.3.

Hydrogen production from fossil energy sources mainly involves the use of fossil fuels to produce hydrogen by chemical pyrolysis or gasification. This technology is relatively mature and inexpensive, and

**Figure 2.3: Methods for Producing Hydrogen Gas**



it is currently the main method used for producing hydrogen. To date, hydrogen produced from fossil fuels has been employed mainly as a feedstock for industrial processes such as fertilizers and metallurgy. Since carbon dioxide is produced and emitted during the production of hydrogen, it is called "gray hydrogen" and can be combined with carbon capture and storage (CCS) technology to convert "gray hydrogen" into "blue hydrogen." The advantage of this technology is that it is suitable for large-scale hydrogen production, but the emissions are high and the gas impurities need to be purified (Zou et al. 2022).

Hydrogen production by electrolysis is the production of hydrogen by decomposing water. This technology allows the use of electricity from renewable sources without emitting carbon dioxide or other toxic substances, and is therefore known as "green hydrogen" in the true sense of the word. Electrolytic water has high theoretical conversion efficiency and the hydrogen obtained is extremely pure. Hydrogen production from electrolytic water can be classified into alkaline electrolytic water, acidic proton exchange membrane electrolytic water, high-temperature solid oxide electrolytic water, and other electrolytic water technologies (Zou et al. 2022). Lei et al. (2019) effectively increased the rate and purity of hydrogen production by developing a technique to produce hydrogen in acid-base two-phase solutions. Dossow et al. (2021) designed a process that can reduce greenhouse gas emissions by 76–78 %. Electrolytic hydrogen generated from offshore wind energy can also contribute to low-carbon systems and effectively reduce carbon emissions (Chen et al. 2021).

The industrial production process, such as in the chlor-alkali industry, will produce a large number of hydrogen byproducts, but the purity of these byproducts is not high, and the purification process requires high-end equipment and a large capital investment. With the continuous advance of the hydrogen energy industry and related scientific technologies, the advantages of industrial byproduct hydrogen gas are expanding. This method has significant advantages, such as its low cost, the wide range of sources, and low-carbon emissions in the recovery process, but the purification process is more complicated (Yang 2022).

Photocatalytic hydrogen production refers to a sustainable, clean, and renewable method of producing hydrogen, and one of the most widely studied and promising technologies is photolytic hydrogen production (Zou et al. 2022). The essence of photolytic hydrogen production technology is the use of semiconductor materials as catalysts to drive the decomposition of water. Microbial hydrogen production technology has emerged as a prospective way to produce hydrogen due to its convenient manufacturing technology and wide availability of sources. Common fermentative hydrogen production microorganisms include various types of hydrogen-producing Clostridium, thermophilic bacteria, and Escherichia coli (Vasconcelos, Leitão, and Santaella 2016; Pugazhendhi, Kumar, and Sivagurunathan 2019). Sadvakasova et al. (2020) investigated the process of producing hydrogen from cyanobacterial cells, and this process is the result of solar energy conversion. They concluded that cyanobacterial gene mutants with great potential for producing hydrogen should be constructed by genetic engineering in order to increase hydrogen production.

### 2.2.3 Classification of Hydrogen Energy Applications

The production, manufacture, and application of hydrogen energy is one of the important ways to achieve the goal of carbon neutrality, to guarantee national energy security, and to realize low-carbon transformation (Zhang 2022c). Currently, hydrogen energy is mainly used in energy, iron and steel metallurgy, the petrochemical industry, and so on. Along with the continuous adjustment of national economic policy and the continuous development of hydrogen energy industry technology, hydrogen energy will be applied to a wider range of fields.

#### Hydrogen Energy Storage

Today we should vigorously develop wind energy and solar photovoltaic power generation and complete the development of renewable energy by producing green hydrogen energy (Cope 2022). However, the intermittent and random nature of wind power and photovoltaic power generation affects the continuity and stability of their grid-connected power supply, and weakens the peak regulation of the power system (Zhou et al. 2022). With the continuous progress and improvement of green hydrogen energy technology, the use of renewable energy to generate electricity and produce green hydrogen is increasingly receiving attention. Meanwhile, the cost of manufacturing green hydrogen is decreasing, and it has further contributed to the pace of the energy transition.

#### Hydrogen Fuel

As the ultimate energy source for the electric power sector, hydrogen energy transforms chemical energy into electrical and kinetic energy through a series of reactions, providing power for vehicles. At the same time, green hydrogen also has advantages in terms of zero-carbon emissions, and the application in the vehicle industry of batteries based on green hydrogen has become very promising (Zou et al. 2022).

### Hydrogen Chemical Raw Materials

The current global demand for hydrogen is mainly used for ammonia synthesis, refinery hydrogenation production, methanol production, and so on (Zou et al. 2022). With the continuous development of relevant technologies, hydrogenation technology will be increasingly used in petroleum refinement and other petrochemical fields. Hydrogenation is also an important technological approach to the manufacture of green oil. Hydrogen is also commonly used for the synthesis of chemical products and compounds containing carbon, such as urea and industrial alcohols. These compounds can be easily stored and transported when liquefied, have high energy density, are less explosive, and can reach nearly zero-carbon emissions as liquid fuels, which makes them a suitable renewable energy source for storage and transportation other than electricity transmission.

## 2.2.3 Processes and Technologies for Hydrogen Energy in Transportation

The main application of hydrogen energy in transportation is using hydrogen as an energy source to power vehicles in order to reduce carbon emissions and air pollution caused by transportation vehicles. Since hydrogen energy can power transportation vehicles with zero greenhouse gas emissions (e.g., $CO_2$ and NOx), many countries are currently accelerating the speed with which they are deploying new energy vehicles such as hydrogen-powered ones. With the rapid development of fuel cell and renewable energy generation technologies, the application of green hydrogen energy in transportation is also gradually increasing (Greene, Ogden and Lin 2020; Bai et al. 2022; Bi et al. 2022; Yang et al. 2022). Rose and Neumann (2020) investigated a network of hydrogen refueling facilities for heavy-duty vehicles by combining an infrastructure location planning model with a power system optimization model that incorporates grid expansion options. The study discussed the interactions between hydrogen refueling stations and the electric power system, and shows that when both are considered systematically and in synergy with multiple sectors it can effectively reduce infrastructure construction costs, which can be a main consideration in building hydrogen refueling stations. Tao et al. (2020) explored the collaborative planning of a distribution network and transportation system for hydrogen fuel cell vehicles. Hydrogen fuel cell vehicles are introduced in the transportation network, and the simulation is performed by planning the location of hydrogen refueling stations, optimizing the ratio of internal combustion engine vehicles, electric vehicles, and fuel cell vehicles, and solving this optimization model using the mixed-integer linear programming and subgradient method. The simulation results show that the proposed model can achieve the lowest emissions due to the good coordination between the power and transportation systems. Pyza, Gołda, and Sendek-Matysiak (2022) studied strategies for the use of hydrogen energy in public transport systems. Through studying the method of hydrogen production and the impact on vehicle operating costs, it was found that the use of hydrogen energy vehicles in public transport systems can be effective in improving air quality as well as optimizing the mobility of the population due to the wide range of hydrogen energy sources. As an alternative energy source in public transportation systems, the use of hydrogen is reasonable and effective. Li and Taghizadeh-Hesary (2022) explored the economic feasibility of green hydrogen fuel cell electric vehicles for road transportation in the PRC and proposed a model to estimate the carbon emissions of the hydrogen supply chain and fuel cells. A balanced hydrogen cost model was also developed to analyze the total cost of supplying hydrogen from renewable energy sources to vehicle hydrogen filling stations, and the cost of fuel cell electric vehicles per kilometer. The results suggest that green hydrogen-fueled vehicles will become increasingly important in the PRC in the long run. Wickham, Hawkes, and Jalil-Vega (2022) studied the optimization of the hydrogen supply chain in the transportation sector. A spatially resolved optimization model was proposed to evaluate the optimal cost configurations of the hydrogen supply chain by 2050, including hydrogen grades and separation and purification technologies. The results show that under given techno-economic assumptions, an optimal configuration of the hydrogen supply chain includes using steam methane reforming with carbon capture and sequestration, the installation of new hydrogen transmission pipelines, modification of the natural gas distribution network to supply hydrogen, and the installation of localized VPS systems at refueling stations. The study found that it was important to include purification technologies in the model. Farahani et al. (2019) proposed an integrated hydrogen-based energy and transport model that facilitates the penetration of intermittent renewable energy sources without compromising the reliability of electricity, heat, and transport energy supplies, while also reducing the cost of the system.

### 2.2.4 History, Status, and Controversies of Hydrogen Energy in Transportation

Here, we try to investigate the research status of hydrogen energy in the transportation sector, and articles in transportation journals are searched, with the aim of concentrating on the research of hydrogen in the field of transportation. Research literature in the field of transportation was searched using the keywords “hydrogen” and “transport*”, and the keyword “co-occurrence analysis” was used through VOSviewer. The results are shown in Figures 2.4 and 2.5.

**Figure 2.4: Keywords Co-occurrence Analysis Based on Hydrogen and Transportation from the Content Dimension**

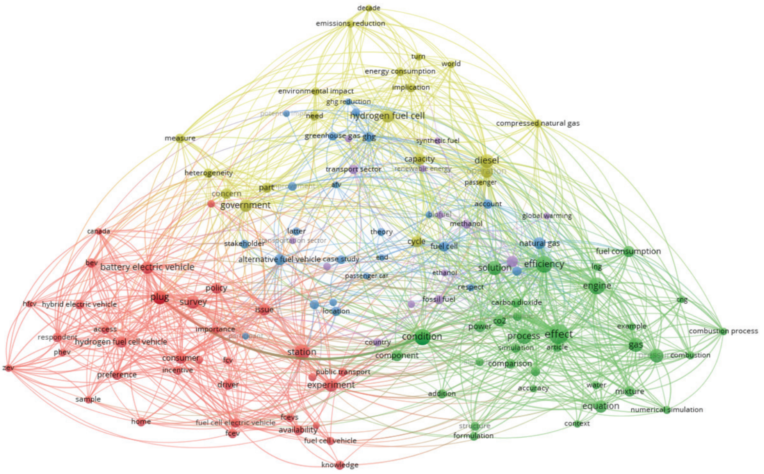
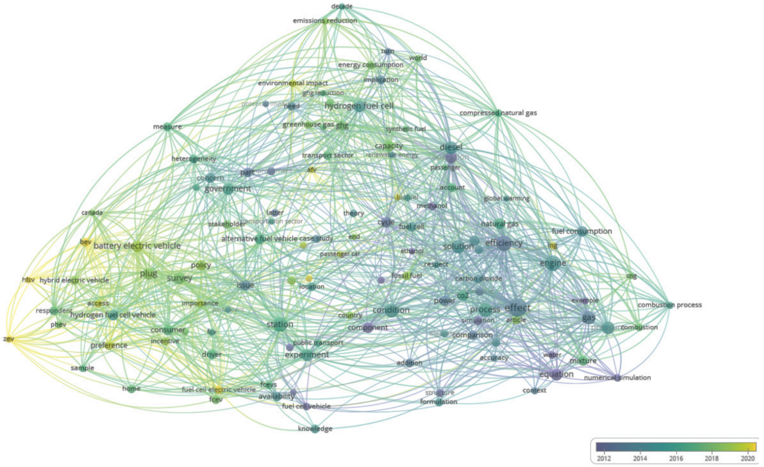


**Figure 2.5: Keywords Co-occurrence Analysis Based on Hydrogen and Transportation from the Time Dimension**



As shown in Figures 2.4 and 2.5, we can conclude that the hydrogen research in the field of transportation mainly focuses on hydrogen fuel cell vehicles, battery electric vehicles, fuel consumption, process, production, policy, efficiency, stations, and government. In the past few years, scholars have concentrated on the areas of efficiency, components, operation, and process, particularly focusing on the production of hydrogen fuel and the benefits of hydrogen vehicles. In recent years, research has been conducted in the areas of greenhouse gases, hydrogen fuel cell vehicles, battery electric vehicles, government, emission reduction, and preferences, with research directions falling mainly on government policies, fuel vehicles, hydrogen refueling station siting, energy conservation, and emission reduction.

## 2.3 Literature Search and Analysis

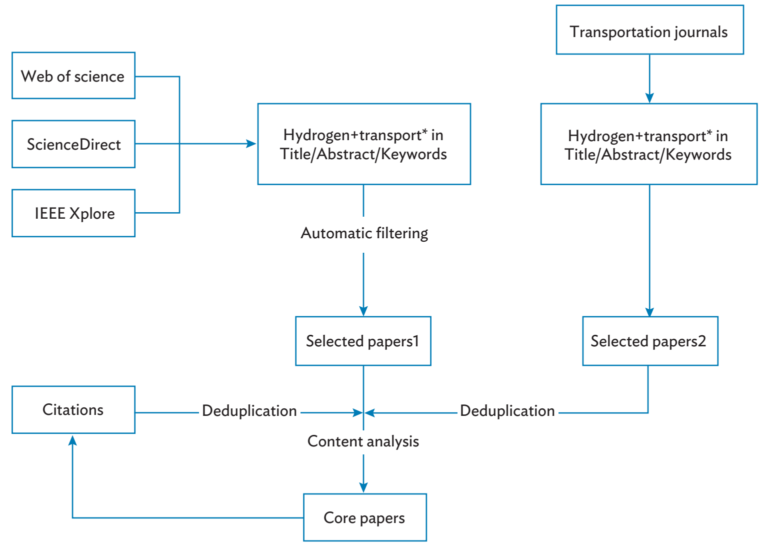
In this section, we mainly systematically investigated the literature related to hydrogen and transportation, and these selected papers are analyzed according to the classifications of their research direction.

### 2.3.1 Literature Search

In order to conduct a comprehensive review, we first systematically search for papers that concentrate on hydrogen and transportation systems. We conduct a literature search from specific databases and journals due to the difficulty in determining appropriate keywords. The literature search procedure is presented in Figure 2.6. In this review, Web of Science, ScienceDirect, and IEEE Xplore are selected as the search databases. The keywords "hydrogen" and "transport*" are searched in titles, abstracts, and keywords, and the time range is restricted to between 1996 and 2022. All the papers searched from the three databases are integrated together, and after deleting reduplicative and irrelevant papers, 190 papers are obtained.

In addition, the keyword "transport*" is used for searching in three databases, and some papers with the name of specific transportation modes such as "railway," "road network," or "aviation" are possibly missed. To cope with this situation, a journal-based literature search is conducted. The search scope is limited to academic journals in the field of transportation. The same selection rules as in the dataset search are applied. Eventually, after the abstract review, 65 more papers are added. Therefore, 148 core papers based on database and journal-based search are obtained.

**Figure 2.6: Literature Search Procedure**



Source: Authors.

## 2.3.2 Literature Analysis

After a comprehensive analysis of the searched literature, the main topics on hydrogen energy in transportation are the problem of locating hydrogen refueling stations, the impacts of hydrogen fuel cells on greenhouse gas emissions, the use of fuel cell vehicles, and the environmental impact on hydrogen fuel cell vehicles. Based on the research focus of selected papers, we divide them into several categories for analyses and discussions.

### Problem of Locating Hydrogen Refueling Stations

A reasonable layout of hydrogen refueling stations can reduce users' refueling time and improve travel convenience (Shang et al. 2022). Scholars have conducted a considerable number of studies on the problem of locating hydrogen refueling stations.

Penev, Zuboy, and Hunter (2019) conducted an economic analysis of high-pressure pipelines within urban areas, and they concluded that pipeline delivery is more advantageous than vehicle transport when the hydrogen demand for fuel cell vehicles in a given area is sufficiently high.

In considering the time problem, Fang and Torres (2011) and Brey et al. (2016) conducted optimization studies of the hydrogen refueling station siting and layout problem with a view to reducing travel time. Following this, Zhao et al. (2019) investigated a modeling framework for alternative fuel station system locations based on path and multi-scale scenario planning. It provides effective information for planning hydrogen refueling station infrastructure. Meanwhile, Rose et al. (2020) studied the optimal development of alternative fueling station networks by considering node capacity constraints. Station capacity constraints were found to have a relatively large impact on the number and utilization of stations, and the diversity of station combinations. Coppitters et al. (2022) investigated the optimal design of hydrogen refueling stations under techno-economic and environmental uncertainties. The results show that it achieves good environmental performance but increases the cost of fuel in a hydrogen refueling station for fuel cell electric buses, which could be studied in the future in regard to integration technology with fully electric buses. After this, Tabandeh, Hossain, and Li (2022) studied the planning of hydrogen refueling stations for fuel cell vehicles in combination with renewable energy sources, and established a green model considering on-site hydrogen production capability. The location and size of hydrogen refueling stations can be well determined, and the green production of green hydrogen is also ensured. Bezrodniy, Rezchikov, and Dranko (2021) proposed an algorithm to optimize hydrogen refueling services at hydrogen refueling stations. Kelley et al. (2020) studied the geographic perceptions of early users of hydrogen fuel cells in evaluating a network of gas stations in California. The study suggests that in selecting sites, other factors should also be considered such as land use, population density, and traffic patterns. Reuß et al. (2017) conducted a spatial resolution-based infrastructure assessment by comparing the infrastructure of the hydrogen energy supply chain in Germany. The results show that salt caverns and gas transmission pipelines are the key technologies for future hydrogen infrastructure systems.

Following this, d'Amore-Domenech, Leo, and Pollet (2021) conducted a cost comparison between electrical energy and hydrogen, which considered the scenario of an energy source for large-scale power transmission at sea. The results of the study showed that the transmission of hydrogen by pipeline is cheaper than using electricity in deep-water areas at distances of more than 1000 km, and that transporting liquefied hydrogen by ship is the best option among the various hydrogen transport methods. Alazemi and Andrews (2015) summarized the current status and deployment of hydrogen fueling station networks. They concluded that from an economic, social, and environmental perspective, it is very reasonable to plan a network of hydrogen stations while hydrogen-fueled sales are growing. Chen et al.

(2021) used an optimal design and techno-economic evaluation method to assess a low-carbon hydrogen supply chain for refueling stations in Shanghai. The results showed that grid-connected green hydrogen production via a PV-wind hybrid system in a renewable energy-rich area (Qinghai Province, PRC) and delivering to refueling stations in the eastern coastal region of the PRC (Shanghai) via a liquid hydrogen truck are feasible solutions. Xu, Wu, and Dai (2020) analyzed the key barriers to the development of hydrogen refueling stations in the PRC. The high initial capital cost, limited financing channels, immature hydrogen storage technology, imperfect hydrogen transportation technology, a lack of relevant standards, and an imperfect subsidy mechanism were considered the six key factors. Sun and Harrison (2021) proposed a scheme to operate hydrogen fueling stations in renewable energy-rich areas. The electrolyte of the hydrogen fueling stations can be adaptively increased to produce excess electricity, which can convert low-carbon electricity into green hydrogen fuel. Zhao et al. (2021) proposed an optimal scheduling framework for cross-energy systems to evaluate the advantages of the supply chain from water electrolysis, compressed storage, and transportation to the utilization of green hydrogen for fuel cell vehicles. Dijkstra's algorithm is used to search for the shortest path for green hydrogen transportation, and the study shows that it can reduce the operation cost of the trans-energy system and promote the use of renewable energy. Cao et al. (2021) studied the hydrogen-based network microgrid planning problem and proposed an optimal planning model for electro-hydrogen microgrids with renewable green hydrogen production, storage, and refueling facilities. The results show that the computational time can be greatly reduced, and this planning method can also be applied to decarbonization of energy and transportation systems in the future. Bezrodniy and Rezchikov (2021) explored the control of hydrogen supply networks in the transport sector, considering relevant aspects of the hydrogen transport system and providing a method for the optimization of hydrogen supply networks.

Some scholars integrate hydrogen refueling stations with the power grid to study the feasibility of the layout, while others plan hydrogen refueling stations by considering the reduction of travel time. Different scholars take into account the various factors, but all of them tend to resolve the problem concerning the layout of hydrogen refueling stations.

## The Impact of Hydrogen Energy on Greenhouse Gas Emissions

The transportation industry has a significant impact on greenhouse gas emissions, and applying hydrogen energy to this sector will have a profound effect on energy conservation and emission reduction in the field of transportation (Liu et al. 2022a).

The application of hydrogen energy in transportation can effectively reduce greenhouse gas emissions (McKenzie and Durango-Cohen 2012; McDonagh et al. 2019; Logan et al. 2020; Navas-Anguita et al. 2020; Benitez et al. 2021). Low-emission alternative fuels are of importance for the low-carbon development of the transport sector, and in their study, Fernández-Dacosta et al. (2019) compared and evaluated alternative fuels in the transport sector. The results showed that green hydrogen production from steam methane reforming is the most economical option, and green hydrogen production from electrolysis using renewable energy sources is the most environmentally friendly one. Moreover, He et al. (2021) analyzed the greenhouse gas, air pollutant emission standards for light-duty fuel cell vehicles in the PRC. The greenhouse gas, volatile organic compound emissions of all fuel cell vehicles were lower than, or comparable to, those of gasoline vehicles, except for the grid electric electrolysis or liquefied hydrogen pathways. Yeh et al. (2006) analyzed the impact of hydrogen energy on transportation, energy use, and air emissions, concluding that although carbon capture and sequestration technologies for their production and renewable technologies for green hydrogen production have the ability to achieve greater $CO_2$ emission reductions, they are not economically competitive based on their modeling framework. In addition, Sun et al. (2022) proposed and modeled a control strategy based on a hydrogen refueling service charge for the smart city sector to guide the selection of hydrogen refueling stations for hydrogen fuel cell electric vehicles. The results show that promoting hydrogen fuel cell vehicles can help reduce emissions. Li et al. (2022) explored the prospect of applying hydrogen electric-to-gas technology in power and transportation systems and proposed a regional-scale integrated power and transportation system long-term coordination planning model. The results show that the system can effectively reduce $CO_2$ emissions.

Furthermore, Booto, Aamodt Espegren, and Hancke (2021) explored the environmental impacts of conventional diesel trucks, battery electric trucks, and fuel cell electric trucks in their respective life cycles in terms of energy type, energy source, and production route. The results show that hydrogen fuel cell electric trucks can reduce greenhouse gas emissions by 48% under the same conditions. The application of hydrogen energy as a fuel to vehicles can also significantly increase emission reductions (Frey et al. 2007; Janic 2008; Tittle and Qu 2013; Yazdanie et al. 2016; Booto, Aamodt Espegren, and Hancke 2021; Mingolla and Lu 2021; Chen and Lam 2022). Sundvor et al. (2021) studied alternative ways of powering high-speed passenger ships under a zero-emissions scenario in the context of Norwegian high-speed passenger ships, developing a model based on AIS data. The results suggest that further route optimization and infrastructure improvements are needed to better address greenhouse gas emissions. Following this, Hensher (2021) studied the process of transitioning to a green bus fleet. Along with the increasing demand for energy efficiency and green travel (Liu et al. 2022a), the cost of buses providing green travel is unknown, not only in relation to vehicle technology (especially hydrogen fuel cell technology), but also in terms of the infrastructure for hydrogen energy. The use of clean and renewable energy sources as feedstock for green hydrogen production has become particularly important. Following this, Frey et al. (2007) compared the actual fuel consumption and impact on emissions of diesel- and hydrogen-fueled buses. The effects of speed, acceleration, and road gradient were integrated into a single parameter using the VSP method to analyze fuel consumption changes. The results show that replacing diesel with methane steam reforming to hydrogen increases the fuel cycle and will significantly reduce CO, NOx, and HC emissions.

Janic (2008) explored the potential of liquid hydrogen in "carbon-neutral" air transport and argued that the infrastructure in air transport should be increased. Zhang et al. (2020) studied the cost and greenhouse gas emissions of grid-based electrolytic hydrogen fuel cell vehicles, simulating the time-varying hydrogen fuel replenishment demand for these vehicles. The results show that increasing the flexibility of hydrogen production can reduce the cost of hydrogen and power generation as well as $CO_2$ emissions. Meanwhile, Liu et al. (2022b) studied the economic and environmental benefits generated by green supply chains. The results showed that under regulation, green supply chains can drive upstream and downstream firms to reduce emissions faster. In addition, Longden et al. (2022) compared the emissions and costs of green hydrogen production from fossil fuels with those from renewable electricity. Comparing the two, the production of green hydrogen using electrolysis and zero-emission electricity does not produce greenhouse gas emissions. Using fossil fuels to produce green hydrogen, even with carbon capture and storage technology, the greenhouse gas emissions would be high. Doll and Wietschel (2008) analyzed the role of hydrogen energy in a sustainable transport vision, concluding that the use of hydrogen can significantly reduce $CO_2$ emissions in the transport sector, even when tailpipe and upstream emissions and the development of alternative technologies are taken into account.

Kim, Kim, and Lee (2020) studied the issue of greenhouse gas emissions from electric and hydrogen-fueled vehicles and their market share changes. The analysis showed that hydrogen fuel cell vehicles help to reduce greenhouse gas emissions, but affect the market share of electric vehicles, and require optimization of efficient infrastructure.

Edwards et al. (2008) analyzed the development of hydrogen energy and fuel cell technologies, concluding that hydrogen fuel cells possess the ability to eliminate $CO_2$ emissions and trigger a green revolution in transportation. After this, Salvi and Subramanian (2015) proposed measures to control transportation fuel pollution using hydrogen energy systems. The use of hydrogen as a fuel in vehicles was considered to improve energy security and reduce greenhouse gas emissions. Janić (2014) studied the application of hydrogen energy in the aviation sector. Using liquid hydrogen as an aviation fuel, its potential for green commercial air transport to solve problems and the impact of using liquid hydrogen as a fuel on greenhouse gas emissions, especially carbon dioxide, were explored. The results show that the use of liquid hydrogen as aviation transportation fuel can reduce greenhouse gas emissions in the future and that the goal of green commercial air transportation is achievable.

A lot of research on hydrogen energy in terms of greenhouse gas emissions has been conducted, and green hydrogen energy is a good alternative fuel as a clean and renewable energy source. Various transport modes such as highways, water transportation, and aviation can save energy consumption and reduce greenhouse gas emissions significantly if hydrogen energy is used as fuel for transportation (Shang et al. 2021).

## Application of Hydrogen Energy in Transportation

Transportation is the main application for hydrogen energy, while the main application of hydrogen energy in transportation is new energy vehicles with fuel cells as power.

There is also a lot of research in this area. Mabit and Fosgerau (2011) studied the demand for alternative fuel vehicles when registration taxes are high, using the example of Denmark, and developed a mixed logistic regression model. Using this model, it was concluded that people would be more likely to choose a more environmentally friendly alternative fuel vehicle over a conventional fuel vehicle, all else being equal. Alavi et al. (2017) proposed a community microgrid for providing car-to-grid power in the case of a scarcity of renewable energy generation, and the remaining renewable energy generation from the microgrid is stored in the form of green hydrogen. By using green hydrogen for transportation and re-electrification, the use of fuel cell vehicles can reduce carbon emissions in the transportation system. Following this, Zhou et al. (2022) investigated the performance of photovoltaic cells and proposed an adaptive differential evolution algorithm based on a dynamic backward learning strategy to effectively improve the identification of photovoltaic cell parameters. Hardman et al. (2017) summarized the barriers to the use of hydrogen fuel cell vehicles through a survey of consumers and suggested corresponding countermeasures, such as pre-deployment of optimized infrastructure. At the same time, they also found that consumers value the range of hydrogen fuel cell vehicles and the ability to provide emergency backup power. Ouchi and Henzie (2017) investigated the feasibility of marine sailboats as energy-harvesting devices to support the production of hydrogen. The results showed that low-cost hydrogen energy can be generated and transported simultaneously, providing a new pathway for the eventual replacement of fossil fuels. After this, Wu et al. (2021) performed an analysis of the application of hydrogen fuel cell vehicles under the carbon neutrality goal according to the characteristics of the PRC. Based on the results, inadequate supporting facilities, hydrogen fuel safety issues, and an insufficient number of manufacturers are the most important issues. Yu, Wang and Chen (2021) proposed the application of a new electric-hydrogen integrated hybrid DC traction power system to a future metro system. Simulation results show that it can effectively utilize renewable energy and regenerative braking energy to achieve energy savings. Moreover, Yi, Jang, and Lee (2021) designed a system for monitoring hydrogen fuel characteristics information on hydrogen fuel buses to respond to the hydrogen consumption and temperature of each component, etc., to determine the safe operation of hydrogen fuel cell buses.

Long et al. (2019) studied the demand for zero-emission vehicles using Canada as an example. The results showed that most people preferred plug-in hybrid and hydrogen fuel cell vehicles as their first choice and conventional or hybrid vehicles as their second choice. After this, Morrison, Stevens, and Joseck (2018) predicted the cost and potential market size issues for battery electric vehicles and hydrogen fuel cell electric vehicles by 2040. The results indicate that hydrogen fuel cell vehicles will cost approximately 71% to 88% less than pure electric vehicles in light vehicle fleets by 2040, and that fuel cell vehicles will have a significant cost advantage for larger models and drivers with longer daily driving ranges. Irdmousa et al. (2010) analyzed energy alternatives in the United States and, under optimistic assumptions, hydrogen energy ranked highest. Melo, Ribau, and Silva (2014) developed an optimized power system for the conversion of city buses to hybrid fuel cells and analyzed the possibility of replacing conventional bus fleets with efficient bus fleets equipped with batteries and hydrogen fuel cells. Subsequently, Durango-Cohen and McKenzie (2018) developed an optimization model applied to the design of bus fleets with different fuel propulsion technologies, taking into account energy consumption, greenhouse gas emissions, particulate matter, etc.

Fan et al. (2022) investigated the operational strategy of hydrogen energy in low-carbon marine transportation. A hybrid propulsion system was proposed, which enables the lowest cost of operation throughout under the greenhouse gas emission limit and further reduces the greenhouse gas emissions. Meanwhile, Ajanovic and Haas (2018) studied the economic prospects and policy framework for hydrogen fuels in the transport sector. It is argued that the prospects of hydrogen energy application in future bus transportation depend on the policy framework, among other things. Ramesohl and Merten (2006) investigated the role of hydrogen energy as an alternative transport fuel in terms of energy systems. They argued that while giving priority to the production of clean hydrogen from renewable energy sources, it is also important to consider how to improve the efficiency of hydrogen fuel cell vehicles. Fu et al. (2019) evaluated two strategies aimed at decarbonizing the transportation sector, electrification, and the use of hydrogen fuel. It was concluded that integrating hydrogen with electric power systems could provide a low-cost alternative energy source, and that the use of advanced hydrogen production technologies could further reduce costs. Singh et al. (2015) analyzed future applications of hydrogen energy in transportation. One of the potential uses of hydrogen is for integrated circuit generators and fuel cell technology in the transportation sector. They concluded that in the future, the energy demand should be adjusted to increase the use of hydrogen as a transportation fuel to provide a clean and green environment for people. Verhelst et al. (2012) studied the use of hydrogen engines and concluded that conversion to hydrogen-powered internal combustion engines could reduce emissions and increase the output power. Rinaldi and Veca (2007) conducted a study on innovative technologies for hydrogen storage using chemical hydrides. The study aimed to evaluate the suitability of polypropylene and low-density polyethene as optimal materials for this purpose. The results indicated that these materials possess exceptional characteristics, including easy recoverability during the hydrogen storage process. Moreover, due to their inherent safety features, these technologies are highly suitable for H2 refuelling stations. Abdelrahman et al. (2016) conducted a feasibility study of hybrid fuel cell and battery railcars. A future hybrid metro system developed in Canada was presented, providing a solution for a hybrid fuel cell train completely independent of grid power, which could save most of the costs and benefit the passengers. Borbujo et al. (2021) reviewed the European legislation and standardization on hydrogen and purely electric buses and heavy-duty trucks. They concluded that the current international safety standards applicable to fuel cells are mainly focused on light-duty vehicles and recommendations were made. Ren and Liang (2017) developed a fuzzy group multicriteria decision-making method to study the sustainability of marine bunker fuels. It was found that green hydrogen is the most sustainable alternative fuel and that it is more socially acceptable as a clean energy carrier without any emissions during the oxidation process.

In the transportation sector, hydrogen fuel cells are increasingly being studied as power facilities. However, there is still a gap between the range of hydrogen fuel cells and other batteries, and further research is needed.

## Application of Hydrogen Energy in Policy

The development of an industry is inseparable from the need for necessary support policies, and will in turn provide a scientific basis for policy adjustments.

It has been argued that more comprehensive policies should be developed to stimulate sales of zero-emission vehicles, rather than focusing on charging and refueling infrastructure (Miele et al. 2020). However, Bach et al. (2020) argued that the application of hydrogen technology in the marine sector is currently immature, and therefore priority needs to be given to supporting the research and development of hydrogen production technologies and infrastructure development, etc. Chen and Melaina (2019) and Jones, Genovese, and Tob-Ogu (2020) argued that more attention should be paid to cost policies. Similarly, Gallas and Stobnicki (2022) argued that the main limitation of hydrogen energy applications is the relative cost of hydrogen fuel and that hydrogen production technologies need to be developed to reduce the cost of hydrogen production or that hydrogen production needs to be subsidized. After this, Rottoli et al. (2021) studied alternative pathways for the electrification of light vehicles in the European transport sector. They found that a stronger policy push for fuel cell vehicles is needed, along with the development of good infrastructure. Pinchasik and Hovi (2017) studied $CO_2$ funds in the transport sector, using Norway as an example, and argued that funds should consider subsidizing renewable technologies such as biogas, electricity, or green hydrogen to promote market demand.

Hydrogen energy should be considered as the direction towards which the energy transition is aiming and its application can become a reality in shipping when hydrogen energy production and demand increase and costs decrease, and it can also achieve carbon emission reduction climate goals. Pomaska and Acciaro (2022) investigated the use of fuel cells and liquefied hydrogen as alternative fuels for ships, with the results of the study suggesting that government policymakers can implement financial incentives to accelerate the development of hydrogen fuels. In addition, Ibrahim et al. (2022) studied three coupled types of dedicated large offshore floating wind farms for hydrogen production. Offshore hydrogen pipelines were considered to be economical for large and remote farms. Their analysis concluded that the decentralized offshore electrolysis approach is a very modular system and provides flexibility while also improving dynamic operation. Mubenga and Stuart (2011) analyzed the feasibility of hydrogen fuel cell electric vehicles transported by hydrogen generated from solar energy. A system was designed to produce hydrogen using solar energy, demonstrating the feasibility of producing hydrogen for transportation using alternative energy technologies. Ehrenstein et al. (2020) studied the optimization of fuel supply chains on a global scale using the case of hydrogen in road transport in the UK. It was found that the generation of hydrogen from electrolytic water powered by wind and nuclear energy and stored in compressed form for distribution by rail is the least impactful for a sustainable fuel supply chain and is a sustainable solution in line with the carrying capacity of the earth.

The application of hydrogen energy requires policy support in terms of infrastructure development, tax incentives, technological advancement, and so on. Hydrogen energy can only work in various fields when there is more support from all sides.

## Other Studies Related to Hydrogen Energy

Lakhera, Rajan, and Bernaurdshaw (2021) analyzed the subsurface hydrogen storage capacity of salt mounds and proposed a method for evaluating the hydrogen storage potential of such mounds, taking into account several characteristics such as reservoir size and depth. According to their research method, the hydrogen storage capacity of rock salt can be predicted more accurately. Lee et al. (2022) compared different overseas hydrogen transportation methods from techno-economic and environmental perspectives. The results showed that operation conditions and the use of renewable energy are the main factors in reducing the cost and carbon emissions of the hydrogen supply chain. Liquid hydrogen storage is considered favorable, and improving the energy efficiency of the liquefaction cycle is essential to achieve efficient hydrogen transportation. Robledo et al. (2018) evaluated the application potential of fuel cell vehicles by combining integrated photovoltaic solar panels, residential buildings, and hydrogen fuel cell electric vehicles for power generation to achieve net-zero energy residential building goals. Menanteau et al. (2011) conducted an economic analysis of hydrogen produced by wind power in the transportation industry. The study showed that the variation in hydrogen production costs depends to some extent on the demand involved and that the storage technology of hydrogen is a key variable. In the future, with the development of large geological hydrogen storage facilities in wind farms or small hydrogen storage systems near gas stations, the cost of hydrogen storage may significantly decrease, which will eventually lower the cost of hydrogen for users.

## 2.4 Future Challenges

At present, the global hydrogen energy industry is generally in the primary stage of development. Since the energy transition is imminent, many countries in the world are increasing their investment in hydrogen energy. Currently, Europe and the United States are leading in wind power technology, the photovoltaic industry in the PRC is leading the world, and Japan is focused on hydrogen energy (Fastmarkets Team 2021). Compared with other energy sources, green hydrogen energy has several significant advantages. First, hydrogen is the most abundant element in the universe, it is easy to obtain, and thus it has great advantages in terms of sustainability. In addition, hydrogen can be produced from water and releases chemical energy through its reaction with oxygen reaction. The whole process only generates water, and no other pollutants are produced, so it is a recyclable closed-loop system (Stock 2021). Second, the high calorific value of hydrogen makes it an ideal substitute for existing fossil fuels. The calorific value of hydrogen is the highest among common fuels, i.e., about three times that of oil and 3.5 times higher than coal. As well as this, with the rapid development of the electric vehicle industry globally and the strong demand for energy storage based on lithium batteries in wind and PV power generation in the future, lithium resources will become a constraint to the development of a new energy industry in the future . Compared with the scarcity of lithium in lithium batteries, a long-term advantage of hydrogen energy can be expected. Hydrogen energy batteries and related technologies can purify the air (Hexun 2022), which is good news for cities with poor air quality. Hydrogen energy will be everywhere in the future owing to its wide range of uses, and it can be used in industrial raw materials, as well as various hydrogen energy vehicles for energy storage.

The largest application of hydrogen energy is in the transportation sector, and the most mature application technology of hydrogen energy and the most promising development in the future are hydrogen fuel cell vehicles in the field of transportation (Agency 2019). The industry chain of hydrogen energy in the transportation sector is extremely complicated, and its potential economic value is huge. The hydrogen energy industry chain in the transportation sector includes hydrogen production, storage and transportation, hydrogen refueling stations, hydrogen fuel cell applications and vehicle integration, and other procedures. Accordingly, the challenges exist in the production, compression, storage, transportation, distribution, and end use of hydrogen (Furfari 2021). The first challenge is how to reduce the cost of green hydrogen production significantly. The development trend of hydrogen energy is from gray to blue hydrogen, and finally to green hydrogen. Although gray hydrogen has pollutants, its cost is low, and it is the main means of hydrogen production in the medium and long term. Hydrogen production by electrolysis of water is an effective way to achieve large-scale production of green hydrogen, but the cost is high, and complete substitution of fossil energy cannot be fully achieved in the short term. In recent years, a lot of work concerning hydrogen production from electrolytic water has been conducted, and very good progress has been made in many aspects. In the future, it will be necessary to continuously improve the hydrogen production process and reduce the cost of green hydrogen production from electrolytic water.

Following this, the second challenge is to decrease the cost of storage and transportation in the most effective way. Hydrogen is chemically active and unstable: If there was a leak, it would be very easy for it to burn and explode, so safety should also be considered. However, compared with security challenges, its cost is the key to hindering the development of hydrogen energy in transportation. There are three main ways to store hydrogen, including gas, liquid, and solid. High-pressure gas-liquid technology has been widely used, and the storage and transportation of liquid hydrogen is technically mature, but the cost of transportation is high, and the risk of leakage and explosion exists, while cryogenic liquid hydrogen storage is costly. Solid-state hydrogen storage is still in the research and development stage. At present, gas transportation for hydrogen is mainly used, supplemented by transportation in a liquid state. Pipeline transportation is suitable for large-scale and long-distance hydrogen transportation with high efficiency, but it requires the construction of pipelines and lots of capital investment at the early stage; liquid transportation also consumes more energy. In the process of storage and transportation, the requirements for materials are very high.

Third, it is a challenge to reduce the cost of key equipment in hydrogen refueling stations and critical components in fuel cells. The core equipment of a hydrogen refueling station includes a hydrogen storage device, compression equipment, and filling equipment, with the compressor being the most costly. Currently, the technical pathways of a hydrogen refueling station can be divided into hydrogen production within the station and external hydrogen supply. Hydrogen production from electrolytic water within stations is the future development direction. In addition, the hydrogen fuel cell is the core component of new energy vehicles based on hydrogen. At the initial stage of industrialization, support policies from government are very much required. The most core part of the hydrogen fuel cell system is the fuel cell, including the fuel cell stack and the air compressor, which are costly and restrict the development of hydrogen fuel cells. The cost of the fuel cell stack accounts for 50% of the hydrogen fuel cell, and the membrane electrode is the core of the stack, accounting for 60% of the cost. Here platinum catalysts have to be mentioned, which are very expensive, and we need to develop low-platinum or platinum-free catalytic technology. Cost reduction is the focus of future development for hydrogen energy in the transportation field.

On top of this, a major challenge for the application of hydrogen energy in the transportation sector lies in whether countries and organizations across the world can cooperate and support each other so as to jointly establish an economic ecosystem of hydrogen energy. Human beings are facing the common problem of global warming, and it is urgent to achieve the goals of carbon neutralization and carbon peak. Some countries have begun to attach great importance to hydrogen energy, and put forward a strategy for the development of hydrogen energy. For example, Japan proposed the 2050 carbon neutrality green growth strategy in December 2020, and the European Union issued the European Green Deal in December 2019, both of them stating clear requirements and expectations for hydrogen energy. As the largest developing country, the PRC is developing hydrogen energy late, but it is expected to account for 10% of the total energy consumption in 2050. The government work report in the PRC in 2019 clearly proposed promoting the construction of infrastructure such as hydrogen refueling stations. In the "14th Five-Year Plan," the development of hydrogen energy has also been arranged accordingly. In the context of carbon neutrality, all countries and organizations have to work together to negotiate intellectual property rights and patent-sharing mechanisms, establish a market entry mechanism, and jointly promote the establishment of an economic ecosystem based on hydrogen energy that combines hydrogen production, storage, transportation, hydrogenation, hydrogen fuel cell applications, and other procedures into an efficient and low-cost sustainable industry chain system.

The future application of hydrogen has to be studied and developed, the technology for hydrogen production needs to be improved, key equipment and materials are required to reduce the cost, and the safety of hydrogen is also a concern. How to produce hydrogen extremely efficiently, safely, and at low cost is still to be resolved, and the related technical standards also need to be developed with other countries. Only when the technology is mature, the cost is low, and the market tends to accept hydrogen on a large scale can hydrogen energy be widely used in various fields, and then it can promote energy conservation and decarbonization of transportation systems, so as to contribute to the vision of carbon neutrality.

## 2.5 Conclusion and Policy Recommendations

Climate change is one of the biggest challenges of our time (Nations 2022), and promoting green and low-carbon transportation is an important way to cope with this situation. The transportation sector is a major source of greenhouse gas emissions, and there is a growing consensus in many countries to promote green transportation. Based on this, hydrogen energy has received great attention due to its unique advantages, such as zero emissions and high calorific value.

To understand the history, status, and future challenges of hydrogen energy in the transportation sector, we are conducting this review. First, we quickly recap on the background of hydrogen energy in the transportation sector and the research status of hydrogen energy. Following this, the applications of hydrogen energy are reviewed, the production process, processes and technologies for hydrogen energy are introduced, and the history, status, and controversies of hydrogen energy in transportation are also discussed here. Afterward, we conduct a literature search and analysis, and 148 core papers are obtained. The main topics on hydrogen energy in transportation are summarized, that is, the problem of locating hydrogen refueling stations, the impacts of hydrogen fuel cells on greenhouse gas emissions, the use of fuel cell vehicles, and the environmental impact of hydrogen fuel cell vehicles. Based on this, the main challenges are extracted, including reducing the cost of green hydrogen production, decreasing the cost of storage and transportation, reducing the cost of key equipment in hydrogen refueling stations and critical components in fuel cells, and whether countries and organizations across the world can cooperate and support each other.

Compared with new energy vehicles based on lithium batteries, hydrogen fuel cell vehicles have several advantages, such as being free from temperature restrictions, longer mileage, and rapid fuel replenishment. Compared with security challenges, their cost is the key issue hindering the development of hydrogen energy. Today, many scholars are devoted to the study of hydrogen energy applications and development in the transportation sector. All aspects of hydrogen production, storage, transportation, and use have received attention. Currently, the application of hydrogen energy in transportation is mainly in fuel cells, replacing fossil energy with hydrogen energy to play its role in energy conservation and emission reduction. However, the application of hydrogen energy in transportation is also limited by the cost of hydrogen production, transportation efficiency, safety of use, and so on.

Based on current hydrogen technologies and market conditions, urban and surrounding areas are recommended as the priority locations for the deployment of hydrogen refueling stations. These regions are more likely to have a relatively high traffic volume and well-developed public transportation systems, and residents in these regions tend to be more environmentally aware, all of which are conducive to the practical use of hydrogen energy in transportation. In addition, appropriate subsidies should be provided to encourage enterprises or organizations to participate in the construction of hydrogen refueling stations. The government may offer tax reductions or financial grants to encourage investment in station construction as well. Furthermore, hydrogen fuel cell vehicles should be promoted to facilitate the use of hydrogen energy in heavy vehicles such as trucks and buses. Through subsidies, exemption from vehicle purchase taxes, and free tolls, the government can play an important role in promoting the consumption of hydrogen-powered vehicles. Additionally, enterprises/academic organizations should be encouraged to engage in the research and development (R&D) of hydrogen energy technology and promote the industrialization of hydrogen fuel cell vehicles and related equipment, so as to establish a hydrogen energy vehicle industry chain.

In order to ensure the safe use of hydrogen energy in the transportation sector, it is imperative to establish relevant laws, regulations, and safety standards for hydrogen energy. For example, the certification and testing of hydrogen fuel cell vehicles should be strengthened, while the transportation and refueling processes of hydrogen gas need to be regulated. Finally, to better promote the applications of hydrogen energy, publicity and education efforts are also essential, and enhancing intellectual property protection and the environmental awareness of the public will also effectively facilitate the development of hydrogen energy technology in the transportation field.

Although the cost of each aspect is relatively high and the development of hydrogen energy is relatively slow at present, given the abundance of hydrogen and the green characteristics of hydrogen energy, the development of hydrogen energy will be beyond people's imagination. As a result of this review, we now understand more clearly that the obstacles encountered in the development of hydrogen energy in the transportation sector are not insurmountable. In the context of carbon neutrality, governments and institutions from all countries really need to work together to establish an economic ecosystem that is most suitable for the development of hydrogen energy. In brief, hydrogen energy is on the brink of flourishing.

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# Appendix 2

| | 2024 | 2025 | 2030 | 2035 | 2050 | 2060 |
|---|---|---|---|---|---|---|
| **European Union** | • Hydrogen production equipment by water electrolysis from renewable energy at least reaches 6 GW<br>• Annual green hydrogen production reaches 1 million tons | | • Hydrogen production equipment by water electrolysis from renewable energy at least reaches 40 GW<br>• Annual green hydrogen production reaches 10 million tons | | | |
| **United States** | | • Annual hydrogen demand reaches 13 million tons | • Annual hydrogen demand reaches 17 million tons<br>• Annual investment in hydrogen energy reaches $8 billion | | • Annual revenue of the hydrogen energy industry reaches $750 billion | |
| **PRC** | | • Annual green hydrogen production reaches 0.1–0.2 million tons | • Hydrogen production equipemnt from renewable energy reaches 100 GW | | | • Hydrogen production equipment from renewable energy reaches 500–750 GW<br>• Annual green hydrogen production reaches 75 million–100 million tons, accounting for 75%–80% of all hydrogen energy production |
| **Russia Federation** | • Export of hydrogen energy of 0.2 million tons | | | • Export of hydrogen energy of 2 million tons (maximum target of 12 million tons) | • Export of hydrogen energy of 15 million tons (maximum target of 50 million tons) | |
| **Japan** | | | • Commercial supply of hydrogen energy reaches 3 million tons<br>• Cost of hydrogen energy falls to ¥30/$m^3$ | | • Commercial supply of hydrogen energy reaches 20 million tons<br>• Cost of hydrogen energy falls to ¥20/$m^3$ | |
| **Rep. of Korea** | | | • Total hydrogen energy demand reaches 3.9 million tons, 50% from overseas | | • Total hydrogen energy demand reaches 27.9 million tons, 82% from overseas | |

# 3

# Role and Development Pathways of Green Hydrogen Energy Toward Carbon Neutrality Targets

*Han Wang, Jie Yan, and Wen-Long Shang*

## 3.1 Introduction

According to the United Kingdom (UK) Energy and Climate Intelligence Unit (ECIU) and other organizations, 137 countries had proposed carbon neutrality or net-zero emission targets by early June 2021 (Energy and Climate Intelligence Unit, Carbon Neutrality Coalition and Climate Action Tracker 2021). Hydrogen energy plays a pivotal role in the global pathway toward carbon neutrality. Recently, a series of major hydrogen energy projects have made significant progress, and hydrogen energy's footprint has spread across the globe. According to a study by Frost and Sullivan, with the support of government sustainability goals, the global hydrogen energy market will more than double in the next decade. By 2030, global hydrogen energy production will increase from the current 71 million tons to 168 million tons; and the industry's market revenue will increase from $177.3 billion in 2020 to $420 billion in 2030 (Frost and Sullivan 2020). Countries worldwide have considered the hydrogen-based economy to address growing concerns about carbon emissions, energy security, and climate change. The International Energy Agency predicts that the global demand for hydrogen energy will reach 520 million tons by 2070 (International Energy Agency 2020). As an essential step to address climate change and accelerate the energy transition, an increasing number of economies are giving more attention to developing hydrogen energy.

Depending on whether there are carbon emissions in the process of hydrogen production, hydrogen can be classified as gray hydrogen, blue hydrogen, or green hydrogen. Gray hydrogen is produced through fossil fuel combustion and produces carbon dioxide emissions during the process. The vast majority of hydrogen is gray hydrogen at present, accounting for about 95% of the global hydrogen production. Blue hydrogen is made from natural gas through steam methane reforming or autothermal steam reforming. It uses advanced technologies such as carbon capture, utilization, and storage (CCUS) to capture greenhouse gases to reduce carbon emissions in the production process. Green hydrogen is made from renewable energy, such as by electrolyzing water through renewable power generation, with no carbon emissions in the production process. Green hydrogen will be the dominant trend in developing hydrogen energy in a renewable-dominated energy system. According to a recent report by Frost and Sullivan, green hydrogen will grow at a compound annual growth rate of 57% to 5.7 million tons by 2030 (Frost and Sullivan 2020). According to Goldman Sachs, the total potential green hydrogen market will probably reach $250 billion by 2030 and $1 trillion by 2050 (Goldman Sachs 2022).

Hydrogen could play a crucial role in achieving the goal of carbon neutrality, and many countries and regions have already released their hydrogen development strategies. However, there is currently no comprehensive review on future hydrogen development strategies. This study can provide a reference for countries and regions that have not yet published their hydrogen development strategies. This paper starts with policies and related documents on hydrogen energy development in major countries and regions worldwide. It then describes the role and development pathway of hydrogen energy in a renewable-dominated energy system with respect to the aspects of renewable energy hydrogen production technology and the development trend, the role and application fields of hydrogen energy, and the development pathways of hydrogen energy in different countries under the goal of carbon neutrality.

## 3.2 Current Status and Development Trend of Green Hydrogen Production Technologies

Currently, hydrogen produced from fossil fuels is still the main source of the global hydrogen supply. However, under the temperature control target of the “Paris Agreement,” renewable energy will gradually replace traditional fossil energy and occupy the dominant position in the energy system. The main carriers of renewable energy are electricity and hydrogen, and as a carbon-free industrial raw material, green hydrogen energy is irreplaceable in some applications. So using renewable energy to produce green hydrogen and promote the development of green hydrogen has become a meaningful way to achieve carbon neutrality.

### 3.2.1 Green Hydrogen Production Technologies by Water Electrolysis

The main technologies used in green hydrogen production include water electrolysis, photoelectrochemistry, cycle coupling of solar energy and thermochemistry, biomass gasification and steam conversion, and biomass pyrolysis (Wan 2022). Among them, water electrolysis is the most commonly used technology. Green hydrogen production technology by water electrolysis can be divided into three categories: alkaline, proton exchange membrane, and solid oxide, depending on the electrolyte material. A parameter comparison of three green hydrogen production technologies by water electrolysis is shown in Table 3.1 (Cheng 2022).

#### (1) Green hydrogen production by alkaline water electrolysis

Alkaline water electrolysis uses the alkaline solution as the electrolyte. It is a mature technology and is the most economical way to produce hydrogen by water electrolysis. The electrolyte material is 20%–30% KOH solution or NaOH solution. The advantages of this hydrogen production are the long service life of its equipment (about 60,000 h) and the low cost (500–1500 $/kW). However, the electrolysis efficiency is relatively low (60%–75%), and the unit energy consumption is high (4.5–5.5 kWh/m$^3$). Moreover, corrosive liquid exists during the production, thereby complicating later operation and maintenance.

#### (2) Green hydrogen production by water electrolysis with proton exchange membrane

Compared with alkaline water electrolysis, the electrolytic current density of this hydrogen production technology can be increased to 10000–30000 A/m$^2$, the electrolytic efficiency can reach 70%–90%, and the unit energy consumption can be reduced to 3.8–5.0 kWh/m$^3$. It has the advantages of a small size and fast response time, which is more suitable for the new energy generation scenarios with fluctuating, intermittent, and random characteristics. So it is seen as a promising approach in the field of green hydrogen production (European Commission 2014). However, most of the proton exchange membrane is made of precious metals, resulting in high equipment costs ($1,100–$1,800/kW) and a degradation problem in the use process. The current technology has not yet achieved a breakthrough, making it difficult to achieve large-scale commercial applications.

### (3) Green hydrogen production by water electrolysis with solid oxide

Compared with the water electrolysis with a proton exchange membrane, this hydrogen production technology requires no precious metal catalyst and has the advantages of low energy consumption (2.6–3.6 kWh/m$^3$) and high energy conversion efficiency (85%–100%). However, this technology needs to decompose water vapor at a high temperature (700–800 °C) to produce hydrogen, which is still in the laboratory stage.

**Table 3.1: Parameters Comparison of Three Green Hydrogen Production Technologies by Water Electrolysis**

| | Alkaline Water Electrolysis | Water Electrolysis with Proton Exchange Membrane | Water Electrolysis with Solid Oxide |
|---|---|---|---|
| Electrolyte material | 20%–30% KOH or NaOH solution | Proton exchange membrane | Ceramic ($Y_2O_3$ /$ZrO_2$) |
| Operating temperature (°C) | 60–90 | 30–80 | 700–1000 |
| Electrolytic efficiency | 60%–75% | 70%–90% | 85%–100% |
| Energy consumption (kWh/m$^3$) | 4.5–5.5 | 3.8–5.0 | 2.6–3.6 |
| Response speed | ++ | +++ | + |
| Lifetime (h) | 60000 | 5000–8000 | – |
| Equipment cost ($/kW) | 500–1500 | 1100–1800 | – |
| Hydrogen purity | > 99% | ≥ 99.9995% | > 99% |
| Requirements of operation and maintenance | Complicated | Simple | – |
| Technology stage | Practical | Verification | Eevelopment |

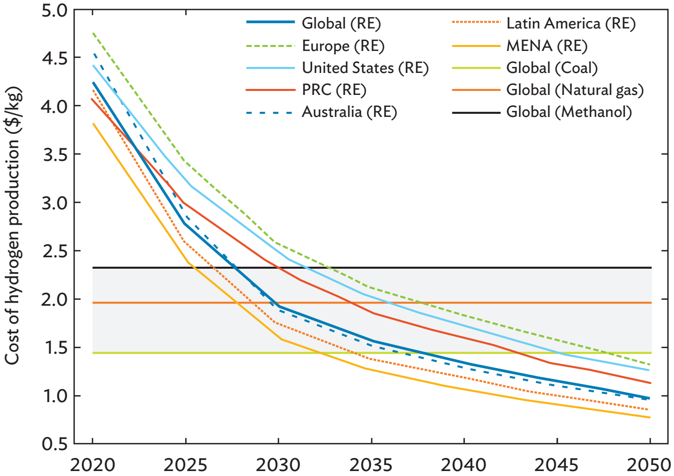
Source: Authors' compilation.

## 3.2.2 Future Cost of Green Hydrogen Production

The cost of hydrogen production by water electrolysis from renewable energy includes the costs of energy generation, water electrolysis equipment, and raw material (water), along with other operation and maintenance costs. The cost of renewable energy generation is the most critical factor affecting the cost of green hydrogen, and for every 0.1 $/kWh reduction in generation cost, the cost of hydrogen can be reduced by 5.5 $/kg (European Commission 2020). According to Hemado Green Energy, the average electricity cost of green hydrogen production in 2020 was 44 $/MWh, accounting for 56% of the total cost; the electricity cost to produce green hydrogen in 2050 is estimated at 17 $/MWh, which will account for 70% of the total cost. Moreover, the lower cost of water electrolysis equipment cannot compensate for the impact of high electricity prices (Government of Germany 2020).

Future costs of green hydrogen production globally and in several regions are shown in Figure 3.1. The global cost of green hydrogen production will decrease yearly from 4.2 $/kg (2020) to 1 $/kg (2050). It will be lower than the cost of hydrogen production from methane, almost the same as the cost of hydrogen production from natural gas in 2030, and lower than the cost of hydrogen production from thermal power in 2040. The cost of green hydrogen production is highest in Europe and lowest in the Middle East and North Africa. The difference in electricity cost directly contributes to the regional disparity in green hydrogen cost.

**Figure 3.1: Future Costs of Green Hydrogen Production Globally and in Several Regions**



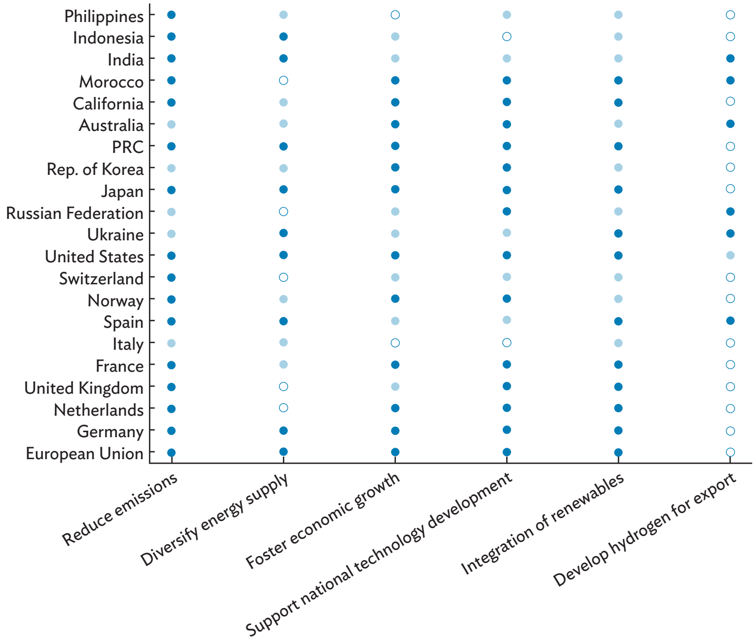
Source: Authors.

# 3.3 The Role and Application Areas of Green Hydrogen Energy

## 3.3.1 The Role of Green Hydrogen Energy

On the one hand, green hydrogen energy can reasonably cooperate with renewable energy with the characteristics of randomness and volatility; the hydrogen can be used as long-term energy storage to improve the utilization rate of renewable energy and grid reliability. On the other hand, green hydrogen energy can help industries in which it is difficult to achieve deep decarbonization through electrification, such as logistics and industries, supporting the goal of carbon neutrality. In addition, hydrogen energy can provide more options for energy and fuel sources to ensure national energy security, provide more employment opportunities, and create economic benefits.

**Figure 3.2: Main Factors of National Support for Green Hydrogen Energy Development**



Source: Authors.

The main factors of national support for green hydrogen energy development include reducing emissions, diversifying the energy supply, fostering economic growth, supporting national technology development, integrating renewables, and exporting, as shown in Figure 3.2 (The US Department of Energy 2002).

## 3.3.2 Applications of Green Hydrogen Energy

The main applications of green hydrogen energy include industry, energy, transportation, construction, and export. The deployment of hydrogen energy applications varies in different countries, as depicted in Figure 3.3 (The US Department of Energy 2002).

### (1) Industry

Green hydrogen is used in areas where it is difficult to achieve deep decarbonization through electrification in the industry field. It is applied in the following areas: 1) oil refining, where hydrotreating and hydrocracking are used to remove impurities and improve the efficiency of intermediate recycled oil; 2) chemicals, where green hydrogen is used as industrial feedstock and as fuel to synthesize ammonia, methanol, methane, etc.; 3) steel, where green hydrogen is used to replace coke and natural gas. Most countries have deployed green hydrogen energy applications in the industry field.

### (2) Power

With the further increase in deep decarbonization requirements in the power field, the main applications of green hydrogen energy are as follows: (1) using hydrogen energy as long-term energy storage to balance the volatility of renewable energy and electricity demand. It is a flexible resource in the power system; (2) using hydrogen energy as a fuel for gas turbines or fuel cells to provide electricity for essential facilities such as hospitals and communication infrastructures during power outages, thereby improving the reliability of the electricity system; (3) hydrogen can be converted into ammonia and co-fired with pulverized coal to reduce the carbon intensity of traditional coal-fired power stations. Fifteen countries and regions have deployed hydrogen energy applications in the power field, not including Italy, Norway, and Switzerland.

### (3) Transport

Hydrogen has long been seen as a potential transportation fuel and as a clean alternative to oil and natural gas. The hydrogen power system is one of the few options for achieving rapid emission reductions in transportation due to its zero carbon emissions and wide adaptability. The main applications of hydrogen fuel cells in transportation include: 1) road transportation, such as small cars, buses, trucks, and other vans; 2) maritime transportation, such as ships and ports; 3) rail transportation and air transportation. Using hydrogen as a fuel for vehicles has the advantages of a short refueling time and long endurance mileage compared with pure electric vehicles. Transportation is the main application field of hydrogen energy; 18 countries and regions have deployed hydrogen energy applications in the transport field.

## (4) Buildings

The heating of buildings is basically provided by traditional energy at present. On the one hand, hydrogen energy can be used to heat buildings and communities; on the other hand, it can be used as a backup power source to realize the interconnection and complementation with electricity and other energy varieties to improve the utilization efficiency of energy.

Compared with natural gas, hydrogen has the advantages of being less dense, easier to ignite, and having greater combustion heat per unit mass. Furthermore, since hydrogen is easy to diffuse in the air, it has a

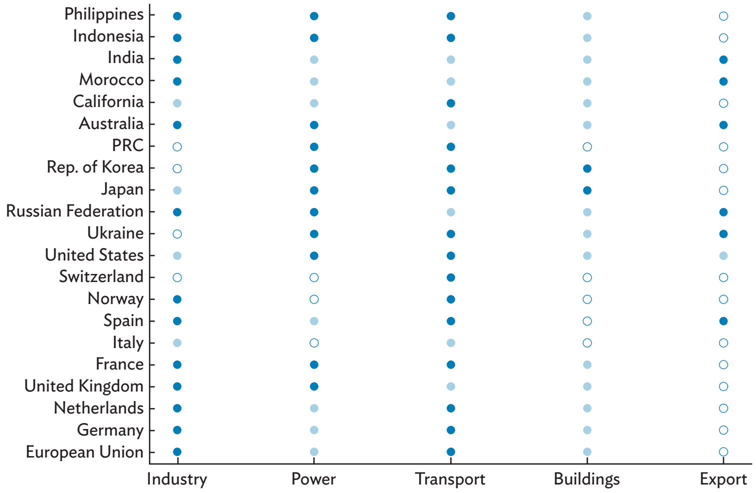


**Figure 3.3: Deployment of Green Hydrogen Energy Applications in Different Countries and Regions**

Source: Authors.

low aggregation risk. The application of hydrogen energy for building heating can change the way of heating from being centralized in thermal power plants to distributed and can solve the problem of high investment in infrastructure construction, such as heat pipe networks and power grids. Among the aforementioned 21 countries and regions, most have less hydrogen energy deployment in the building field.

**(5) Export**

Countries such as India and Australia have deployed strategic plans to export hydrogen energy to maintain their status as energy exporters.

## 3.4 Policies and Related Documents on Green Hydrogen Energy Development in Several Countries and Regions

To date, more than 40 countries and regions have released hydrogen energy development strategies, treating hydrogen energy as an important part of promoting the new climate and energy policy. Many countries and regions are actively laying out the hydrogen energy industry. They promote hydrogen energy development by developing a specific roadmap, strengthening policy support, increasing infrastructure investment, establishing industrial development alliances, strengthening international cooperation, etc. (Fuel Cell and Hydrogen Energy Association (FCHEA) 2019; US Department of Energy 2020). This section focuses on the policies and related documents of hydrogen energy development in jurisdictions with sufficient progress in policy support and investments in green hydrogen, namely the European Union, the United States, the PRC, Japan, the Republic of Korea, and Australia), as shown in Table 3.2.

### 3.4.1 European Union

In December 2011, the EU formulated “Energy Roadmap 2050” (Government of Japan 2017), which prioritized the development of hydrogen and fuel cells as one of the ten elements that would influence the change of the energy system in the future. The European Commission released “A Hydrogen Strategy for a Climate-Neutral Europe” (Government of Japan 2021) on 8 July 2020, which described the development plan for hydrogen energy in Europe over the next 30 years, making green hydrogen a priority for future development in the EU. Hydrogen from renewable energy will be expanded for large-scale applications in challenging industries to decarbonize by lowering the cost of renewable power and accelerating the development of related technologies, ultimately contributing to the goal of being "Climate Neutral" by 2050. Germany is the most representative country for hydrogen energy development in the EU. In 2020, the German government released "The National Hydrogen Strategy" (Agency for Natural Resources and Energy 2022), which defined the strategic position of green hydrogen as it aimed to become the global leader in the field of green hydrogen.

### 3.4.2 United States

The United States was the first to incorporate hydrogen energy into its national energy strategy. In November 2002, the US Department of Energy (DOE) released the "National Hydrogen Energy Roadmap" (Ministry of Economy, Trade and Industry 2022), which clarified the traditional approach to building a hydrogen energy system. On 6 November 2019, the Fuel Cell and Hydrogen Energy Association (FCHEA) released the "Road Map to a US Hydrogen Economy – Reducing Emissions and Driving Growth Across the Nation" (Government of the Republic of Korea 2019). On 12 November 2020, the US DOE released the "Hydrogen Program Plan" (Government of the Republic of Korea 2020), which proposed an overarching strategic framework for hydrogen energy research, development, and demonstration over the next decade and beyond. In March 2022, the US DOE announced an investment of $28 million for the Front End Engineering Design (FEED) program for clean hydrogen energy, which aimed to develop the next-generation hydrogen production technologies; produce clean hydrogen at low cost from municipal solid waste, residual coal waste, waste plastics, and biomass feedstocks; and promote the realization of the "Hydrogen Energy Research Plan."

### 3.4.3 Japan

After the Fukushima nuclear disaster, Shinzo Abe proposed the goal of building a "hydrogen energy-based society." In December 2017, Japan became the first country to release a basic hydrogen energy strategy with the "Hydrogen Basic Strategy" (Government of the Republic of Korea 2021) . The "strategy" proposed to establish a commercial-scale supply chain around 2030, purchase about three million tons of hydrogen every year, and realize a hydrogen cost of about 30 JPY ¥/m3. In November 2021, the Japanese government updated "The Sixth Basic Energy Plan" (The National Development and Reform Commission and the National Energy Administration 2016), which proposed that the share of hydrogen energy in the energy structure should reach 11% by 2030. In 2022, the Agency for Natural Resources and Energy (ANRE) released "Building a Large-scale Hydrogen Energy Supply Chain with the Goal of Achieving a Hydrogen Energy Society" (State Council of the People's Republic of China 2016), and the Ministry of Economy, Trade, and Industry (METI) released the "Current Status and Future Research Directions of Hydrogen/Ammonia" (National Energy Administration 2019), both of which elaborated on the future development of hydrogen energy in Japan. In addition, Japan has reached cooperation agreements with Australia, Brunei Darussalam, Norway, and Saudi Arabia on procuring hydrogen fuel.

## 3.4.4 Republic of Korea

Hydrogen energy has been positioned by the Republic of Korea government as an important intermediary for improving energy efficiency and optimizing the renewable energy power system. In order to achieve the strategic goal of hydrogen energy, the Republic of Korea government took the "Hydrogen Economy" as one of the three strategic investment areas in 2018, along with artificial intelligence and big data. In 2019, the Republic of Korea released the more sophisticated "A Blueprint for the Development of Hydrogen Economy" (National Development and Reform Commission and the National Energy Administration 2022), which specified the main goals and sector targets regarding hydrogen and fuel cell technology. On 4 February 2020, the Government of the Republic of Korea officially enacted the first law on hydrogen energy, the "Law on the Promotion of Hydrogen Economy and Hydrogen Safety Management" (Ministry for Energy and Emission Reduction and Ministry for Resources and Northern Australia 2019), laying the legal foundation for the government's commitment to hydrogen energy and the implementation of facility safety standards. In 2021, Prime Minister Kim Boo-kyum chaired the fourth meeting of the Hydrogen Economy Council and released the Republic of Korea's first "Basic Plan for Hydrogen Economy Development" (Luo 2017), which elaborated on the future development of hydrogen energy in the Republic of Korea.

## 3.4.5 PRC

The PRC is the largest hydrogen energy producer and has the world's biggest installed renewable energy capacity. It has great potential to supply clean and low-carbon hydrogen energy. In 2016, the PRC released the "Roadmap of Key Innovation Actions for the Energy Technology Revolution" (Li et al. 2021), which proposed to achieve large-scale, low-cost production, storage, transportation, and application of hydrogen. In the same year, the “13th Five-year Plan on Technology and Innovation” (Ma 2022) proposed to focus on developing hydrogen energy and other disruptive technologies that could lead to an industrial revolution. Hydrogen energy was first included in the national government report in 2019, and the National Energy Administration issued the “Green Industry Guidance Catalogue” (Deng 2020) to encourage the development of hydrogen energy. In March 2022, the National Development and Reform Commission (NDRC) and the National Energy Administration (NEA) jointly issued the “Medium and Long-term Plan for the Development of Hydrogen Energy Industry (2021–2035)” (Hemado Green Energy 2021). This plan clarified the energy attribute of hydrogen and made clear that hydrogen energy is an integral part of the future national energy system. Green hydrogen energy should be fully exploited to promote the green and low-carbon transformation of terminal energy (such as transportation and industry) and other high-consumption and high-emission industries. Furthermore, it is clear that hydrogen energy is the key direction of strategic emerging industries and is the new growth point for building green and low-carbon industrial systems.

### 3.4.6 Australia

In 2018, the Australian Energy Council officially recognized the economic and environmental benefits of hydrogen and formulated a vision for the hydrogen industry. In November 2019, the Australian government published “Australia’s National Hydrogen Strategy” (Ludwig-Bölkow-Systemtechnik GmbH 2020), which identified 15 development goals and 57 joint actions, with a view to becoming a major participant in the global hydrogen energy industry by 2030 and reaching 30 million tons per year of green hydrogen production capacity by 2050.

## Table 3.2: Policies and Related Documents of Hydrogen Energy Development in Several Countries and Regions

| Country/ Region | Released year | Policies and Related Documents | Source |
|---|---|---|---|
| European Union | 2011 | Energy Roadmap 2050 | European Commission |
| | 2020 | A Hydrogen Strategy for a Climate - Neutral Europe | European Commission |
| United States | 2002 | National Hydrogen Energy Roadmap | US DOE |
| | 2019 | Road Map to a US Hydrogen Economy – Reducing Emissions and Driving Growth Across the Nation | FCHEA |
| | 2020 | Hydrogen Program Plan | US DOE |
| Japan | 2017 | Hydrogen Basic Strategy | Government of Japan |
| | 2021 | The Sixth Basic Energy Plan | Government of Japan |
| | 2022 | Building a Large-scale Hydrogen Energy Supply Chain with the Goal of Achieving a Hydrogen Energy Society | ANRE |
| | 2022 | Current Status and Future Research Directions of Hydrogen/Ammonia | MEIT |
| Rep. of Korea | 2019 | A Blueprint for the Development of Hydrogen Economy | Government of the Rep. of Korea |
| | 2020 | Law on the Promotion of Hydrogen Economy and Hydrogen Safety Management | Government of the Rep. of Korea |
| | 2021 | Basic Plan for Hydrogen Economy Development | Government of the Rep. of Korea |
| PRC | 2016 | Roadmap of Key Innovation Actions for the Energy Technology Revolution | NDRC and NEA |
| | 2016 | 13th Five-year Plan on Technology and Innovation | State Council of the PRC |
| | 2019 | Green Industry Guidance Catalogue | NEA |
| | 2022 | Medium- and Long-term Plan for the Development of Hydrogen Energy Industry (2021–2035) | NDRC and NEA |
| Australia | 2019 | Australia's National Hydrogen Strategy | Government of Australia |

Source: Authors' compilation.

## 3.5 Development Pathways of Green Hydrogen Energy under Carbon Neutrality Target

### 3.5.1 European Union

According to "A Hydrogen Strategy for a Climate-Neutral Europe" (Government of Japan 2021) published by the European Commission, there are three phases in developing a clean hydrogen economy in the EU.

#### (1) Phase I (2020–2024)

This phase is aimed at reducing the carbon emissions of existing hydrogen production processes and expanding the application areas of hydrogen energy. The installed capacity of hydrogen production equipment by water electrolysis from renewable energy should reach at least 6 GW, and the annual green hydrogen production should reach one million tons in 2024.

#### (2) Phase II (2025–2030)

This phase is aimed at making hydrogen energy an important component of an integrated energy system. The installed capacity of hydrogen production equipment from renewable energy should reach at least 40 GW, and the annual green hydrogen production should reach 10 million tons in 2030. The applications of hydrogen energy will gradually extend to industry and transportation. At this stage, hydrogen energy will still be produced close to the application terminals or in areas with rich renewable energy resources to realize a regional eco-energy system.

#### (3) Phase III (2031–2050)

The aim of this phase is to realize the large-scale application of hydrogen energy. The technology for producing hydrogen from renewable energy will gradually mature; hydrogen energy will be deployed on a large scale to replace industries that struggle to decarbonize and help to achieve carbon neutrality.

### 3.5.2 United States

The US Fuel Cell and Hydrogen Energy Association (FCHEA) released a report on the "Road Map to a US Hydrogen Economy" at the 2019 Fuel Cell International Symposium and Energy Show. According to this report, the hydrogen economy development pathway in the US can be divided into four phases (Fuel Cell and Hydrogen Energy Association 2019).

## (1) Phase I (2020–2022)

The development goals in this phase are to identify reliable and technology-neutral decarbonization targets at more state and federal levels, bring relatively mature hydrogen applications to market, increase the public awareness and acceptance of hydrogen and continue to experiment with other applications of hydrogen, expand mature applications (such as forklifts) and near break-even applications (such as backup power), and drive market demand growth to match the production capacity of hydrogen.

## (2) Phase II (2023–2025)

This stage is the initial scale development stage, aimed at achieving large-scale hydrogen production and building the first large-scale, low-carbon, or zero-carbon hydrogen production facilities. With the expansion of hydrogen production, the scale of hydrogen-related equipment (especially automotive fuel cell production equipment and fuel station equipment) will be expanded simultaneously to reduce costs and improve performance. This phase requires clear regulatory guidelines to coordinate market participants and attract investment, transitioning policy incentives from early direct support to scalable market mechanisms. The hydrogen demand in the US will reach 13 million tons in 2025.

## (3) Phase III (2026–2030)

This is a phase of diversified development. Various hydrogen production technologies will be widely used, and the scale of water electrolysis will continue to expand. Hydrogen will be closely linked to the power grid and renewable energy. In 2030, the hydrogen demand will exceed 17 million tons, while 4,300 hydrogen refueling stations will operate in the US; the annual investment in hydrogen energy will reach $8 billion.

## (4) Phase IV (2031–)

This is a phase of extensive promotion. Hydrogen energy will be deployed on a large scale across all regions and industries in the US, and the previously supportive policies will be phased out after 2030. At the same time, hydrogen production equipment based on fossil fuel will be retrofitted with carbon capture and storage technology. Various low-cost and low-carbon hydrogen production technologies will compete. In addition to manufacturing and producing for the domestic market, hydrogen energy and the related production technologies will be exported to Europe and Asia. The annual revenue of the hydrogen energy industry in the US will reach $750 billion in 2050.

### 3.5.3 Japan

The development pathways of hydrogen energy in Japan mainly include the following three aspects: (1) achieving low-cost and low-carbon emissions hydrogen production by using carbon capture and storage (CCS) technology or water electrolysis from renewable energy; (2) strengthening the infrastructure for importing and domestic hydrogen transportation; (3) promoting the extensive application of hydrogen in various sectors such as automobiles, combined heating and power in the household, and power generation.

Further, according to "Building a Large-scale Hydrogen Energy Supply Chain with the Goal of Achieving a Hydrogen Energy Society" (State Council of the People's Republic of China 2016)released by the Agency for Natural Resources and Energy in 2022 and "Current Status and Future Research Directions of Hydrogen/Ammonia" (National Energy Administration 2019) released by the Ministry of Economy, Trade and Industry, the hydrogen energy development pathway in Japan can be divided into the following three stages:

#### (1) Phase I (2022–2030)

Continuously expanding the application of hydrogen energy in power generation, transportation, industry, and livelihood, and researching hydrogen production technologies from renewable energy. Developing the international hydrogen energy import chain, establishing a large-scale overseas import mechanism after 2025, and developing the domestic green hydrogen supply capacity simultaneously. The commercial supply capacity of hydrogen energy should reach three million tons, and the cost of hydrogen energy is expected to fall from ¥100/$m^3$ to ¥30/$m^3$ in 2030.

#### (2) Phase II (2031–2050)

Vigorously developing low-carbon hydrogen production technologies, such as hydrogen production from renewable energy and hydrogen production from lignite combined with CCS. Hydrogen energy will be used in multiple fields and realize a large-scale application in power generation. The commercial supply capacity of hydrogen energy should reach 20 million tons, and the cost of hydrogen energy is expected to decrease to ¥20/$m^3$ in 2050.

#### (3) Phase III (2051–)

The aim of this phase is to realize a large-scale application of hydrogen energy in areas in which it is difficult to achieve deep decarbonization through electrification to help achieve the goal of carbon neutrality, and to diversify the supply sources of hydrogen energy to ensure national energy security.

### 3.5.4 Republic of Korea

According to the "Basic Plan for Hydrogen Economy Development" (Luo 2017) released in 2021 at the Fourth Hydrogen Economy Council Meeting, the development pathway of hydrogen energy in the Republic of Korea can be divided into two stages.

#### (1) Phase I (2021–2030)

Vigorously developing hydrogen-fueled vehicles and ensuring an annual increment of 100,000 hydrogen-fueled household vehicles and 2,000 hydrogen-fueled commercial vehicles. Realize the commercial application of CCUS technology and 10 MW hydrogen production equipment, providing strong support for green hydrogen production. The total hydrogen energy demand will reach 3.9 million tons, and the proportion of green hydrogen will reach 75% in 2030. The amount of self-produced hydrogen will be 1.94 million tons, and the amount of overseas-purchased hydrogen will be 1.96 million tons, accounting for about 50% of all demand.

#### (2) Phase II (2031–2050)

Building 40 overseas import chains and commercializing the hydrogen production equipment of GW grade. By 2050, the number of hydrogen-fueled household cars will reach 5.15 million, and the number of hydrogen-fueled commercial vehicles will reach 110,000. The total hydrogen energy demand will be 27.9 million tons, which needs to be composed entirely of green hydrogen and blue hydrogen with low carbon emissions. The amount of self-produced hydrogen will be five million tons, and the amount of overseas purchased hydrogen will be 22.9 million tons, accounting for 82% of all demand.

In 2050, hydrogen energy will account for 33% of terminal energy consumption and 23.8% of electricity generation in the Republic of Korea, surpassing oil to become the primary energy source. In addition, the Republic of Korea will generate $1 trillion, create 567,000 job opportunities, and reduce greenhouse gas emissions by more than 200 million tons through implementing this plan.

### 3.5.5 PRC

Generally analyzed with "China Hydrogen Energy Development Roadmap 1.0: How to Achieve a Green, Efficient and Economic Hydrogen Energy Supply System?" (China EV100 2020) released by China EV100 in 2020, "Mid-and-long-term Plan for the Development of Hydrogen Energy Industry (2021–2035)" (National Development and Reform Commission and the National Energy Administration 2022) jointly released by the National Development and Reform Commission and the National Energy Administration in 2022, and "Key to a New Era of Green Hydrogen Energy: China 'Renewable Hydrogen 100' Development Roadmap in 2030" (Rocky Mountain Institute and China Hydrogen Alliance Research Institute 2022) jointly released by the Rocky Mountain Institute and the China Hydrogen Alliance Research Institute, the hydrogen energy development pathway in the PRC can be divided into the following four stages.

### (1) Phase I (2020–2025)

Providing a fairly complete institutional and policy environment for development of the hydrogen energy industry and initially establishing a relatively complete supply chain and industrial system in 2025. The demonstration applications of hydrogen energy are expected to achieve apparent results, and the green hydrogen production technologies will make significant progress. In 2025, the number of fuel cell vehicles will reach 50,000, and the annual production of green hydrogen will reach 0.1–0.2 million tons, becoming an important part of hydrogen energy consumption and realizing the $CO_2$ emission reduction of one to two million tons per year. At this stage, the storage and transportation of hydrogen energy are mainly through high-pressure compressed gas vessels, and liquid hydrogen transportation is promoted as a pilot. The refilling mode of hydrogen energy is mainly based on joint stations, and integrated hydrogen production stations are promoted as a pilot.

### (2) Phase II (2026–2030)

By 2030, a relatively complete technological innovation system for the hydrogen industry and green hydrogen production system will be formed, and the hydrogen production technology from renewable energy will be widely applied. With the advantages of industrial agglomeration and a large-scale market, the installed capacity of hydrogen production facilities from renewable energy is expected to reach 100 GW, accelerating the scale effect.

### (3) Phase III (2031–2035)

This phase is for forming a hydrogen energy industry system and building a diversified hydrogen energy application ecology covering transportation, energy storage, industry, etc. The proportion of green hydrogen in the terminal energy consumption will obviously be increased, vigorously supporting the energy transformation. In this stage, the storage and transportation mode of hydrogen energy will mainly be through liquid hydrogen, supplemented by high-pressure compressed gas vessels. The refueling mode of hydrogen energy will develop toward diversification and networking.

### (4) Phase IV (2036–2060)

The supply pattern of hydrogen energy in the PRC will gradually shift to a clean and low-carbon route, with only a small amount of fossil energy hydrogen production for scenario-specific use in this phase. The installed capacity of hydrogen production from renewable energy will expand with an annual growth of 5%–10%, the cumulative installed capacity will reach 500 GW–750 GW, and the green hydrogen production will reach 75 million–100 million tons by 2060, accounting for 75%–80% of all hydrogen energy production. At this stage, hydrogen energy can be stored and transported in multiple ways, such as liquid hydrogen, high-pressure compressed gas vessels, and via pipeline.

## 3.6 Conclusion

Green hydrogen energy is still very expensive compared to non-green hydrogen and renewable energy; however, it is expected that the cost of green hydrogen will fall substantially in the period 2030–2050. Furthermore, green hydrogen has the potential to play a pivotal role in the global pathway towards the carbon neutrality target, for example via the following applications. Firstly, green hydrogen energy can be used as long-term energy storage to improve the utilization rate of renewable energy and grid reliability – for example, where seasonal storage is needed. Secondly, green hydrogen energy can help industries in which it is difficult to achieve deep decarbonization through electrification (renewable energy), such as logistics and industries. The total potential green hydrogen market will probably reach $250 billion by 2030 and $1 trillion by 2050 (Goldman Sachs 2022).

Therefore, a comprehensive review of the role and development pathways of green hydrogen energy towards carbon neutrality target is provided in this paper, including the current status and development trend of green hydrogen production technologies, the role and applications of green hydrogen energy, the policies and related documents of green hydrogen energy development in several countries and regions, and the development pathways of green hydrogen energy under the carbon neutrality target.

According to the above research content, for countries or regions with a need to formulate the development pathways of green hydrogen energy (for example, due to the need in green hydrogen to decarbonize hard-to-abate sectors, long-term storage in the power sector, or export revenue), the development of hydrogen energy is suggested to follow the following principles. First, providing an institutional and policy environment conducive to the development of hydrogen energy industry and bringing relatively mature hydrogen applications to market (where non-green hydrogen is already used for a long time) – for example, by incentivizing the replacement of non-green hydrogen with green hydrogen by industries.

Secondly, transitioning policy incentives from early direct support to scalable market mechanisms. Hydrogen energy should be closely linked to the power grid and renewable energy at this stage. Then, forming a hydrogen energy industry system and building diversified hydrogen energy applications covering transportation, energy storage, industry, etc.

Finally, realizing a large-scale application of hydrogen energy in areas where it is difficult to achieve deep decarbonization through replacing fossil fuel with electrification (sourced from renewable energy) to help achieve the goal of carbon neutrality, i.e. hard-to-abate sectors such as steel and cement. Hard-to-abate sectors will require incentives promoting the replacement of fossil fuels with green hydrogen in order to achieve decarbonization of such sectors.

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# PART II

# Regional Focus

# 4

# Opportunities, Challenges, and Policy of Green Hydrogen in India

*Wataru Kodama, Ranjeeta Mishra, and Dina Azhgaliyeva*

## 4.1 Introduction

Many researchers and policymakers believe that hydrogen will revolutionize energy production and consumption, making a significant contribution to a net-zero pathway. Hydrogen is often described as "a free energy carrier" and can be produced from various energy sources (IRENA 2019). It is not a new technology, but humans have been producing and using hydrogen since the 18th century. In fact, the first internal combustion engine ran on hydrogen more than 200 years ago. So, what is new about hydrogen? The expected rapid and unprecedented growth in the scale and applications of hydrogen raises important issues related to safety,[1] infrastructure, transportation, supply chain, taxonomy, and more.

Thanks to hydrogen's ability to be stored and transported on a large scale, it is expected to find applications in sectors beyond its traditional use, such as power generation, transportation, manufacturing, and related industries. *Green hydrogen*, hydrogen produced through water electrolysis using renewable energy sources, can particularly aid in decarbonizing hard-to-abate sectors like steel, cement, and petrochemicals, which are crucial for achieving net-zero emissions. Moreover, it can enhance the efficient use of intermittent renewable energy sources like solar and wind by storing energy, especially for long-term or seasonal storage. This helps balance variable energy output, reducing waste and curtailment of renewable energy when demand falls

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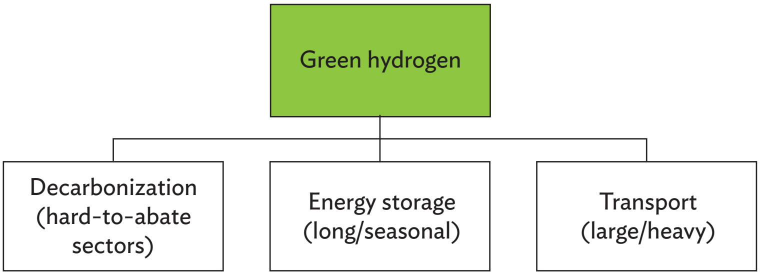
[1] Safety is outside the scope of this chapter.

below supply (Figure 4.1). Because of these factors, many governments have initiated national green hydrogen strategies with ambitious targets, envisioning a future hydrogen-based society with low or zero carbon emissions, where hydrogen plays a central role in daily life and economic activities. Policy support for green hydrogen is growing. Table 4.1 provides a summary of some (green) hydrogen initiatives, including those supporting the supply of green hydrogen and the demand for green hydrogen in several countries. Green hydrogen supporting policy instruments include investments, funds, public–private partnerships, subsidies, and targets. The implementation of policies supporting green hydrogen started to grow substantially from 2020, with most policies introduced in 2021 (Figure 4.2). The majority of green hydrogen policies are focused on a country's internal affairs, while approximately 20%–25% of these policies involve two countries or regional cooperation such as the Japan–Indonesia cooperation agreement on decarbonization technologies, the Australia–Japan cooperation agreement on hydrogen and fuel cells, and the Canada–Netherlands hydrogen memorandum of understanding.

**Figure 4.1: Examples of Green Hydrogen Use**



Source: Authors.

## Table 4.1: Illustrative Examples of Supply and Demand Side Initiatives of Hydrogen

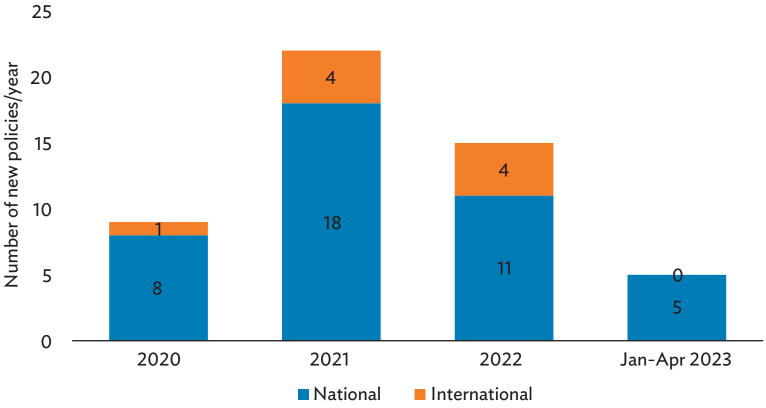
| | Supply-Side Initiative | Demand-Side Initiative |
|---|---|---|
| Japan | $150 million to establish a hydrogen supply chain; $91.7 million subsidies toward public hydrogen station development | Public–private partnership; investment subsidies |
| United Kingdom | Scaling up green hydrogen manufacturing capacity to 1 GW/year by 2025; £28 million for funding the hydrogen supply program;<br>£240 million Net Zero Hydrogen Fund | £40 million Hydrogen and Fuel Switching Innovation Fund |
| European Union | 40 GW electrolyzer capacity and up to 10 Mt/year of green hydrogen by 2030 | Industrial quotas of green hydrogen |
| Germany | 5 GW of annual green hydrogen generation capacity by 2030;<br>€700 million investment under the National Innovation Programme in Hydrogen | €0.9 billion purchase grants for utility vehicles and €0.6 billion for purchase of buses, both for alternate fuels |

GW= gigawatt, MT = million tons.

Note: Without any specification, all numbers are cumulative.

Source: Moghe (2022).

## Figure 4.2: Green Hydrogen Policy Implementation



Note: Hydrogen policies are included in the International Energy Agency's Policies Database (https://www.iea.org/policies?qs=hydrogen&technology%5B0%5D=Hydrogen). For other green hydrogen policy databases, please see Appendix 4.

Source: Authors' own using data from the International Energy Agency's Policies Database (2023).

While annual investments in the low-carbon energy transition grew significantly in 2022 compared with 2021 and reached a historic record in 2022 (BloombergNEF 2023a, 2023b), global investment in green hydrogen is very small compared with investments in renewable energy. Nevertheless, investments in green hydrogen are growing fast with signed agreements for more hydrogen production set for the coming years. Consequently, there exists a substantial gap in both the qualitative and quantitative utilization of hydrogen. Thus far, large-scale hydrogen use has been primarily limited to oil refining and chemical production, with almost all the hydrogen being generated from fossil fuels, often referred to as *gray hydrogen*. *Green hydrogen* currently lacks cost competitiveness when compared to hydrogen produced from fossil fuels, primarily due to its higher production costs. To realize a hydrogen-based future society, it is imperative to reduce the production costs of green hydrogen, maintain supply chain infrastructure, and expand its utilization across various sectors.

India, the world's fifth-largest economy and the third-largest GHG emitter, possesses significant potential for both the production and utilization of green hydrogen. The government has initiated ambitious plans to establish itself as a global "green hydrogen hub." The literature on hydrogen development in India is expanding (Kar et al. 2023; Sharma 2022; Medisetty et al. 2020; Sircar et al. 2022; Qureshi et al. 2022). The literature broadly agrees that the expansion and leadership in the field of green hydrogen from India is centered on hydrogen research, development, value chain expansion, and the commercialization of hydrogen technology. This chapter aims to provide an overview of the opportunities and challenges associated with green hydrogen in India.

The remainder of this chapter is structured as follows. Section 4.2 offers a foundational background by reviewing the current progress and challenges in hydrogen production, storage, transmission, and utilization. Section 4.3 delves into India's hydrogen policy, opportunities, and challenges. Finally, Section 4.4 concludes with a set of policy recommendations.

## 4.2 Opportunities and Challenges

### 4.2.1 Hydrogen Production

Hydrogen, due to its reactivity, is not naturally occurring and must be artificially produced. As summarized in Table 4.2, hydrogen is categorized by a color code based on its production process (hydrogen itself is colorless and emits no emissions when consumed). In addition to green and gray hydrogen, there is another type known as *blue* *hydrogen*, produced from fossil fuels (typically natural gas or coal) but with reduced GHG emissions achieved by capturing and permanently storing GHGs underground using carbon capture and storage (CCS) technology. Additionally, hydrogen produced from water electrolysis using nuclear energy is referred to as *pink hydrogen*. Determining which type of hydrogen should be considered "clean" (in addition to green hydrogen) is a subject of debate.

Definitions of low-carbon or clean hydrogen are not consistent across countries. For instance, the European Union considers only green hydrogen as clean hydrogen (European Commission 2021), while Japan implicitly includes green, blue, and pink hydrogen as clean hydrogen (Ministry of the Environment 2021). Although blue hydrogen may play a significant role during the transition from gray to green hydrogen, capturing 100% of GHGs with CCS technology is often considered impractical in practice. Therefore, in the long run, the production of green hydrogen should be prioritized over other types of hydrogen (Janardhanan 2022). IRENA (2022) defines low-carbon hydrogen as "[h]ydrogen produced from any technology pathway that has a carbon intensity below that of the incumbent fossil-based production pathway," including blue hydrogen.

The establishment of taxonomy and certification standards for clean hydrogen will be primarily driven by importing countries rather than exporting ones. Hydrogen certification plays a crucial role in hydrogen trade, which is why hydrogen-importing countries such as the European Union, the United Kingdom, and Japan have started introducing clean hydrogen certification initiatives.[2]

**Table 4.2: Hydrogen Color Code**

| Color Code | Source | Related Technology | Clean Hydrogen |
|---|---|---|---|
| Green | Renewable | Water electrolysis | Yes |
| Blue | Fossil fuel | Carbon capture and storage | Yes/No |
| Gray | Fossil fuel | | No |
| Pink/purple/red | Nuclear | Water electrolysis | Yes/No |

Note: Clean hydrogen taken from the discussed country cases, not authors' opinion.

Source: Authors' own.

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[2] For more detailed information on hydrogen certification, please refer to IRENA (2022) and IRENA and RMI (2023).

Presently, about 70 million tons (Mt) of hydrogen are produced annually, with 76% generated from natural gas and nearly all the remainder produced from coal. Consequently, hydrogen production contributes to approximately 830 Mt of annual carbon dioxide emissions (IEA 2019). The significant reliance on gray hydrogen is primarily driven by its price competitiveness compared to other hydrogen types, including green hydrogen (Table 4.2). The present production costs of green hydrogen stand at around $5 per kilogram ($/kg), significantly higher than gray hydrogen and other fossil fuels. To achieve price competitiveness for various end uses, the cost needs to be reduced to around $2/kg (Moghe 2022). However, the declining costs of water electrolysis and renewable energy, combined with the implementation of larger-scale hydrogen projects, are expected to decrease the production cost of green hydrogen. Notably, the price of renewable energy is a critical factor because the fuel used for water electrolysis constitutes the largest component of the overall production cost of green hydrogen, accounting for 45%–75% (IEA 2022a). A number of cost projections indicate that, by 2030–2050, the cost of green hydrogen will significantly decline because of lower costs for electrolyzers and renewable energy, enough for green hydrogen to be competitive with blue and gray hydrogen. According to PwC (2022), "[h]ydrogen production costs will decrease by around 50% by 2030 and then continue to fall steadily at a slightly slower rate until 2050." This cost trajectory suggests that green hydrogen could become cost-competitive with natural gas, potentially displacing imports and attracting investments across the value chains (IEA 2021).

The central question is how to accelerate this transition. In addition to expediting advancements in renewable energy sources such as solar and wind, public investments in research and development of green hydrogen technologies and facilities play a crucial role. Specifically, the costs associated with electrolyzers represent approximately one-third of the production costs, leaving ample room for improvement in hydrogen electrolyzer technology (IEA 2021). In the early stages of renewable energy production, like solar and wind, governments provided substantial support for the deployment of solar photovoltaic and wind turbines. Today, there has been a total investment of $472 billion in these energy sources, predominantly from private capital (IEA 2019, 2022a). Similar to the trajectory of other renewable energy, the anticipated growth in policy backing and the rising global enthusiasm for green hydrogen is poised to boost investments in the coming years.

### 4.2.2 Storage and Transmission

Hydrogen, as the lightest element, possesses a low energy density per unit volume, approximately one-third that of natural gas. This characteristic implies that a larger volume of hydrogen needs to be stored and transported to meet a given energy demand. Consequently, storage and transmission costs have a significant impact on the competitiveness of hydrogen in the energy market, especially as its production and usage scale up.

Currently, about 85% of hydrogen is either produced or consumed on-site, with the remaining 15% being transported by truck or pipeline (IEA 2019). As hydrogen production and demand continue to grow, larger volumes of hydrogen will need to be stored and delivered in the future. However, both compressed and liquefied hydrogen, the two typical forms of storage, present certain challenges and are relatively costly. Compressed hydrogen, used in fuel cell vehicles at pressures of 350–700 bar, has only 7.5%–15% of the energy density of gasoline. This means that the current technology requires significant storage space and results in higher delivery costs (IEA 2019; Langmi et al. 2022). Similarly, although liquefied hydrogen has a higher energy density, it must be cooled to –253 degrees Celsius. With current technology, the liquefaction process consumes about 25%–30% of the energy content of the stored hydrogen (Langmi et al. 2022). Without innovations in hydrogen storage technologies, transmitted hydrogen is unlikely to be an affordable energy option.

In the long run, transporting hydrogen gas via pipelines and shipping appears to be the most cost-effective method for delivering hydrogen to both industries and households. Currently, global hydrogen pipelines are only 5,000 kilometers in total length (IEA 2021), but it is possible to repurpose existing natural gas pipelines for hydrogen transportation. According to estimates by the IEA (2019), pipeline transmission is expected to become significantly cheaper than truck transportation in the near future, while shipping in the form of blended hydrogen (mixed with natural gas) may be a preferable option for long-distance transmission.

Several large-scale hydrogen storage and transmission projects are already underway. For example, Germany plans to invest in large-scale hydrogen transmission from Norway through pipelines by 2030. In the Hydrogen Energy Supply Chain (HESC) Project, Japan achieved the world’s first international shipment of liquid hydrogen from Australia and aims to commercialize this supply chain by the 2030s (Ministry of the Environment 2021). In Asia and the Pacific, countries with abundant renewable energy potential, such as Australia, India, and Southeast Asian countries, are expected to become hydrogen exporters, while major hydrogen consumers such as Japan and the Republic of Korea are expected to become importers. Maintaining supply chain infrastructure is particularly important for these countries.

### 4.2.3 Hydrogen Usage

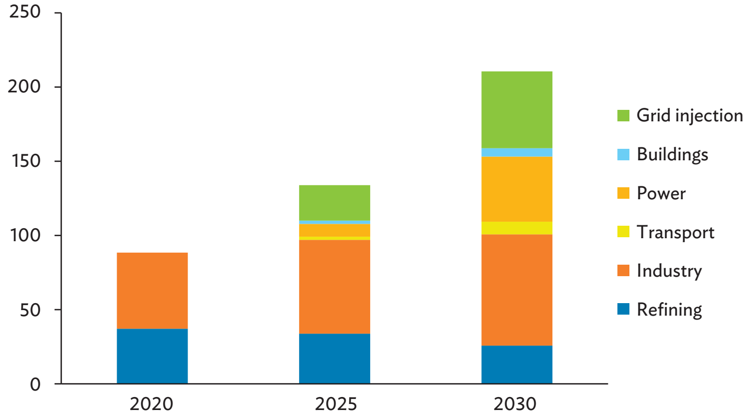
Hydrogen demand has experienced significant growth, more than tripling since 1975, and this upward trend is expected to continue (IEA 2022a; 2022b). One of the primary consumers of hydrogen is the oil refining industry, which typically relies on on-site hydrogen production through steam methane reforming. The use of green hydrogen in this context is not common because of its high production costs, although there are ongoing projects utilizing electrolytic hydrogen in the refining process. In the industry sector, hydrogen is predominantly used for chemical production, such as ammonia and methanol. Gray hydrogen is the prevalent choice in industry because of its relatively lower price (IEA 2021).

Hydrogen is anticipated to find applications across various sectors (Figure 4.3). Despite its long history, the use of hydrogen in fuel cell electric vehicles (FCEVs) has remained limited, accounting for less than 0.001% of the global vehicle stock. However, the FCEV market is starting to expand, particularly in Asian countries, including India, where the FCEV stock grew annually by 70% from 2017 to 2020 (IEA 2021). To further boost the FCEV market, Japan, for instance, aims to establish 1,000 hydrogen stations and operate 1,200 FCEV buses by 2030 (Ministry of the Environment 2021). As FCEV technology advances and hydrogen prices decline, the use of hydrogen in the transport sector is expected to continue growing.

The power sector is also projected to witness increased use of hydrogen (Figure 4.3). Some countries have set targets for utilizing hydrogen or hydrogen-based fuels (such as ammonia and synfuels) for energy generation. For example, the Republic of Korea aims to achieve 1.5 gigawatts (GW) of power capacity by 2022 and 15 GW by 2040 (IEA 2021), while Japan targets 1 GW by 2030. Moreover, India plans to add 175 GW of green hydrogen-based energy within the next decade.

According to the IEA (2022b), global hydrogen demand is expected to reach approximately 180 Mt, with around half of this demand stemming from new applications in sectors that have not traditionally used hydrogen, such as power generation. Achieving the objectives outlined in the Net Zero Scenario necessitates a significant increase in

**Figure 4.3: Global Hydrogen Demand by Sector in the International Energy Agency's Net Zero Scenario, 2020–2030**
(million tons)



Notes: 2025 and 2030 are projections. The Net Zero Emissions by 2050 Scenario refers to "a pathway for the global energy sector to achieve net zero CO2 emissions by 2050" (International Energy Agency 2022c).

Source: Authors' own using data from the International Energy Agency (2022b).

demand creation, especially in these new applications.[3] However, out of the projected 180 Mt of annual hydrogen production, it is estimated that 60 Mt will be green hydrogen and 70 Mt will be gray hydrogen production. To align with the Net Zero Scenario, it is imperative to accelerate the reduction in production costs of green hydrogen, coupled with robust policy support and investments in green hydrogen production and supply chain infrastructure.

## 4.3 Green Hydrogen in India

In this section, we examine India's hydrogen policies, the production costs of green hydrogen, and the supply chain network.

Low-carbon hydrogen, including green and blue hydrogen, holds significant promise within India's industry sector, where it can serve as a substitute for natural gas, coking coal, or oil products (IEA 2021).

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[3] Refer to note in Figure 4.3 about the Net Zero Emissions by 2050 Scenario.

This implies that industries like steel, ammonia-based fertilizers, and methanol, among others, could transition to production methods with lower GHG emissions (IEA 2021). Given India's relatively high natural gas prices and substantial potential for renewable energy deployment, as we will further discuss, green hydrogen stands as a highly promising option for India in the near future.

### 4.3.1 Hydrogen Policy

In response to the growing energy demand and the imperative to address climate change, India has established policy targets aimed at achieving energy independence by 2047 and net-zero emissions by 2070. To facilitate this transition away from fossil fuels, the government has set an ambitious target of producing 5 Mt of green hydrogen and adding 175 GW of green hydrogen-based energy capacity by 2030.

The first hydrogen road map was introduced in 2006 by the Ministry of New and Renewable Energy, marking the beginning of government investments in research and development through various public sector institutions (IEA 2021). In 2021, the government initiated the National Hydrogen Mission, with multiple objectives, including positioning India as a "Global Hub for production, usage, and export of green hydrogen and its derivatives" (Ministry of New and Renewable Energy 2023). Notably, the hydrogen policy is strongly oriented toward making India a leading global green hydrogen exporter, with a goal of supplying approximately 10% of the global green hydrogen demand by 2030 (Ministry of New and Renewable Energy 2023). The key policy attributes under the National Hydrogen Mission are:

1. **Demand creation**
    - Develop strategic international partnerships to enable export.
    - Enforce consumption targets ("minimum share") for green hydrogen and its derivatives for designated consumers, e.g., petroleum refiners, fertilizer producers, etc.
    - Support deployment of FCEV buses and trucks by covering capital costs of initial years.
2. **Incentives**
    - Support domestic electrolyzer manufacturing and green hydrogen production.
    - Supply incentives on green hydrogen production.
3. **Enabling systems**
    - Identify and develop "Green Hydrogen Hubs," regions capable of supporting large-scale production and/or utilization of hydrogen.

- Develop certification for green hydrogen and its derivatives.
- Provide public investment in research and development.

While India has set ambitious goals for green hydrogen production and usage, comprehensive hydrogen policies with detailed guidelines have not yet been announced. However, some initial policies have been declared to incentivize investment in green hydrogen manufacturing (Ministry of Power 2022), including the following:

- Manufacturers of green hydrogen and green ammonia are allowed to purchase renewable power from the power exchange or establish their renewable energy capacity independently or through other developers, regardless of location.
- Access to these incentives will be granted within 15 days of receiving an application.
- Manufacturers can store unconsumed renewable power with a distribution company for up to 30 days and retrieve it when needed.
- For projects commissioned before 30 June 2025, manufacturers will enjoy a 25-year waiver of interstate transmission charges.
- Green hydrogen and ammonia manufacturers and renewable energy plants will receive priority grid connectivity to minimize procedural delays.
- Both green hydrogen and ammonia manufacturers and distribution licensees will be incentivized for consuming renewable power through the Renewable Purchase Obligation (RPO) program.
- Priority grid connectivity will be granted at both the generation and green hydrogen and ammonia manufacturing ends for renewable energy capacity established for green hydrogen and ammonia production.
- Manufacturers of green hydrogen and ammonia will be permitted to establish bunkers near ports for storing green ammonia, which can be used for export or shipping.

In India, investments in hydrogen are currently quite limited. Nevertheless, under the National Hydrogen Mission, the government anticipates as much as $96 billion in investment in green hydrogen and its derivatives by 2030. India is expected to experience substantial cost reductions by 2030—and particularly by 2050. This trajectory positions India to potentially have the lowest green hydrogen costs in Asia and the Pacific and among the lowest globally. Consequently, India has the potential to emerge as one of the largest hydrogen producers and exporters in the region.

## 4.3.2 Green Hydrogen Production

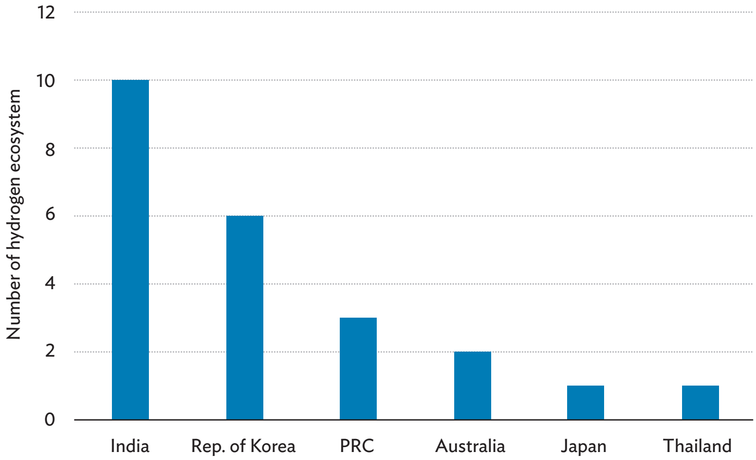
India emerges as one of the most promising countries to scale up green hydrogen production, owing to its substantial potential in renewable energy production. Thus far, the government has set a target to produce 5 Mt of green hydrogen by 2030 (Ministry of New and Renewable Energy 2023).

Countries around the globe are pinpointing potential "hydrogen valleys"—geographical areas such as a city, region, island, or industrial cluster—where multiple hydrogen applications are seamlessly integrated into a cohesive ecosystem. The aims is consolidate various hydrogen applications, ensure substantial hydrogen consumption, and cover the entire value chain within these hydrogen valleys. This approach provides a clear path for scaling up hydrogen technology, rendering it a practical and sustainable solution. Moreover, it demonstrates hydrogen's capability for sectoral integration.

India is expected to lead Asia and the Pacific in the number of hydrogen ecosystem units by 2033 (Figure 4.4). The country has identified 10 states as pivotal for green hydrogen production. These states were selected based on existing steel and fertilizer industries, refineries, ports, renewable energy operations, and potential power generation capacity.

Apart from the proposed capacity development plans showcasing the growing momentum in the green hydrogen sector, numerous large-scale green hydrogen projects are already in development in the country. While the existing pilot projects have relatively modest production capacities, typically around 10 megawatts, it has been announced that by 2025, there will be six green hydrogen gigafactories, as outlined in Table 4.3. These projects alone are expected to contribute up to 8 GW equivalent electrolyzer capacity by 2025, with production capacity projected to reach 1.8 Mt by 2030 (Gupta 2022). To achieve the national target of 5 Mt of green hydrogen production capacity by 2030, additional investments in green hydrogen projects will be essential.

## Figure 4.4: Projected Hydrogen Ecosystem Units in Asia and the Pacific by 2033



PRC = People's Republic of China.

Source: Authors' own using data from Enincon (2023), Hydrogen Valleys Across the Globe.

## Table 4.3: Electrolyzer Manufacturing Capacity of Major Green Hydrogen Projects in India

| | | Planned Capacity (gigawatt) | | |
|---|---|---|---|---|
| **Company/Project** | **Main Electrolyzers** | **2023** | **2024** | **2025** |
| Reliance-Stiesdal | Alkaline | | 0.5 | 1 |
| Larsen & Toubro | Alkaline | | 0.5 | 1 |
| L&T-HydrogenPro | Alkaline | | 0.5 | 1 |
| H2e Power | Solid-oxide | 0.5 | 1 | 1 |
| Greenko ZeroC-John Cockerill | Alkaline | | 1 | 2 |
| Ohmium | Polymer electrolyte membrane (PEM) | 2 | 2 | 2 |

Source: Authors' own based on Gupta (2022).

### 4.3.3 Supply Chain Network

India possesses significant potential for green hydrogen production, and the government has been actively pushing the country to become a major hydrogen exporter. In particular, the government expects global green hydrogen demand to reach 10 Mt by 2030 and aims to supply 10% of this projected global demand. These targets seem achievable, given that (i) production costs of green hydrogen are expected to be competitive with gray hydrogen in India by 2030, and (ii) several large-scale hydrogen projects are already in progress. However, uncertainties persist regarding global green hydrogen demand and the establishment of robust supply chain networks.

Projections indicate that global hydrogen demand will reach 180 Mt, with only one-third of that demand expected to be met by green hydrogen (IEA 2022b). This is primarily due to the limited number of countries capable of producing low-cost green hydrogen and transport to demand, such as India and the People's Republic of China. Therefore, for India, reducing costs for green hydrogen storage and transmission is crucial to scaling up green hydrogen demand. Despite the country's ambitions to become a green hydrogen hub, concrete large-scale and long-distance hydrogen transmission projects have yet to be announced in India. Unlike some major projects that encompass both hydrogen production and transmission (e.g., Australia and Japan's HESC Project, NEOM and Air Products's Green Hydrogen Project in Saudi Arabia), large-scale hydrogen projects in India have primarily focused on investments in production capacities. Consequently, the country faces challenges in establishing international hydrogen supply chain networks and creating an international green hydrogen market.

In May 2022, India signed a hydrogen cooperation agreement with Germany, a country aiming to reduce its dependence on Russian fuels, with plans for large-scale green hydrogen exports to Germany (Kurmayer 2022). Beyond technological cooperation, the agreement includes initiatives to invest in hydrogen production capacity and supply chain infrastructure. Therefore, there is considerable interest in whether any large-scale hydrogen transmission project between India and Germany will be announced.

In the pursuit of net-zero emissions, accelerating the transition from gray hydrogen to green hydrogen and expanding hydrogen utilization are critical goals, not only for India but also for other countries. Given that low-price green hydrogen production will be feasible in select countries at least in the short term, potential hydrogen exporters like India and the People's Republic of China, importers like Japan and the Republic of Korea, and technology leaders like Japan and Germany need to cooperate further to establish and maintain a robust supply chain infrastructure.

## 4.4 Conclusion and Way Forward

Green hydrogen is anticipated to play a pivotal role in achieving net-zero emissions. However, its current usage is severely limited due to its high production costs. To make green hydrogen competitive in the market, further reductions in renewable energy prices and advancements in green hydrogen technologies are imperative. This chapter has offered an overview of the opportunities and challenges associated with green hydrogen in India.

The country, with its substantial capacity for renewable energy deployment, holds immense potential for green hydrogen production. The production cost of green hydrogen in India is projected to decline significantly by 2030, potentially becoming one of the most cost-effective options globally. This opens up the possibility for India to emerge as a major exporter of green hydrogen in the near future.

In light of these prospects, the Government of India has established ambitious initiatives and targets to bolster green hydrogen production and utilization in the country, with a particular emphasis on green hydrogen exports. One of the goals is to supply 10% of the global green hydrogen demand by 2030. Several large-scale green hydrogen projects are already in the pipeline, with plans to collectively produce 1.8 Mt annually by 2030. However, while investments in production capacities are on the rise, large-scale and long-distance transmission projects have yet to be announced. The government is actively seeking international collaborations to establish supply chain infrastructure and create global demand for green hydrogen from India.

To facilitate the transition from gray hydrogen to green hydrogen and meet the growing hydrogen demand, it is crucial to recognize that low-cost green hydrogen can be produced effectively only in countries with significant renewable energy deployment capabilities. Thus, maintaining robust supply chain networks among exporting and importing countries is essential. International cooperation among hydrogen exporters, importers, and technology leaders is imperative to support the development of these networks and ensure the success of the green hydrogen transition.

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# Appendix 4: List of Hydrogen Policy Databases Used

| Organization | Database | Access |
|---|---|---|
| International Energy Agency | Policies database | Free |
| https://www.iea.org/policies?qs=hydrogen&technology%5B0%5D=Hydrogen | | |
| Baker McKenzie | Global Hydrogen Policy Tracker | Free |
| https://resourcehub.bakermckenzie.com/en/resources/hydrogen-heat-map | | |
| BloombergNEF | Hydrogen Subsidies Tracker | Subscription |
| BloombergNEF | Global Hydrogen Strategy Tracker | Subscription |

# 5

# Technology Foresight for Hydrogen Society Transition in Japan: A GTAP-E-Power Model Approach

*Michael C. Huang, Yoko Iwaki, and Ming-Huan Liou*

## 5.1 Introduction

Japan, a highly developed country with a critical shortage of hydrocarbon resources, sees multiple values in the use of hydrogen, including energy security, industrial competitiveness, and carbon emission reductions. In 2017, Japan was the first country to adopt a hydrogen framework with its Basic Hydrogen Strategy (METI 2020). The framework promotes an end-use approach that focuses on electricity, transportation, housing, heavy industry, and refining. Meanwhile, being a leader in fuel cell technology, particularly fuel cell vehicles (FCVs), manufacturing firms from the related fields are seeking to export this technology to the rest of the world. The main issue is to experiment with different options for sourcing hydrogen to adjust its industrial and energy policy for a society that utilizes the development of hydrogen energy.

### 5.1.1 Development of Hydrogen Technology

To achieve the medium- and long-term goals in the Basic Strategy, and to realize the "hydrogen society" that the Japanese have set out, the government has consistently allocated a budget of 98.9 billion yen (approx. $693 million) in FY2022 for research and development (R&D) related to fuel cells and water electrolyzer technology (METI 2021). To effectively reduce the risk and provide an incentive to encourage private firms towards this emerging field, public-private co-investment in R&D and pilot projects is essential to create synergy (Arque-Castells and Spulber 2022). The core concern is about the mobility sector applying hydrogen technologies, such as "power to gas," which is envisioned as a resolution to renewable power intermittency for stimulating domestic hydrogen production with co-benefits.

In the market application, hydrogen energy generation has matured with several methods categorized in Table 5.1 in different colors. Thanks to its feature of storable energy, the transition to a hydrogen society could be referred to as an additional accessory investment in the existing power generation sources. It is also foreseen that it will decrease hydrogen energy generation costs if the demands and R&D continue to increase (Glenk and Reichelstein 2022; Hodges et al. 2022).

Table 5.1: Hydrogen Categories by Generation Method

| | |
|---|---|
| Gray hydrogen | Reflects fossil fuels, natural gas, and water vapor to produce $H_2$ and $CO_2$ through a "steam reforming" process; large amounts of $CO_2$ are emitted into the atmosphere. |
| Blue hydrogen | Reflects fossil fuels, natural gas, and steam to produce $H_2$ and $CO_2$; zero emissions, including capture of produced $CO_2$ and geological storage (CCS). |
| Green hydrogen | Produced through electrolysis of $H_2O$ to $H_2$ and $O_2$ from source electricity generated by renewable energy; zero $CO_2$ emissions. |
| Turquoise hydrogen | Produced a hydrocarbon feedstock, such as methane ($CH_4$) in natural gas, as the source of hydrogen atoms; the high-temperature reactor could use green energy. |
| Yellow hydrogen | Electrolysis of $H_2O$ to produce $H_2$ and $O_2$ using electricity from nuclear power generation; zero $CO_2$ emissions but produces nuclear waste. |
| Brown hydrogen | Produced by gasification, where carbons materials are heated into a gas. Similar to black hydrogen. |
| White hydrogen | $H_2$ produced as a byproduct in the production of other products (e.g., steelmaking); production volume is uncontrollable. |

Source: The authors.

### 5.1.2 Japan’s Roadmap for Hydrogen Society

The Basic Hydrogen Strategy was first announced in 2017 by the Ministry of Economy, Trade and Industry (METI) to set up the hydrogen roadmap with ambitions to establish an integrated hydrogen supply chain domestically and internationally by 2030, including production, transportation, storage, and consumption from upper to down stream (METI 2017). Increasing renewable energy generation capacity is vital to the government’s net-zero plan. However, because renewable energy is intermittent, it cannot balance supply and demand on the power grid. In addition, the increase in renewable energy generation capacity may result in more frequent curtailments (i.e., reductions in renewable energy generation to balance energy supply and demand or due to transmission line constraints) for future renewable energy power plant operators for an optimal energy mix (Huang and Kim 2021). The ambitions were mostly reconfirmed with the long-term strategy under the Paris Agreement and the Green Growth Strategy (METI 2021) towards 2050 Carbon Neutrality to reduce carbon dioxide emissions substantially.

Moreover, the Japanese government has recognized the need for new or modernized regulations on hydrogen and ammonia, and in fact, the Sixth Basic Energy Plan (METI 2021) specifies the importance of Japan playing a leading role in international rulemaking. Despite Japanese companies taking a pioneering role in driving innovation in the field of hydrogen technology with significant government funding, Japan’s regulatory and rulemaking activities have been comparatively limited. However, the success of the next phase of the hydrogen revolution depends on the establishment of a well-coordinated and consistent regulatory framework. Given Japan’s status as an early adopter of hydrogen technology and a major future importer of pure hydrogen, the development of the hydrogen society still requires substantial effort in terms of implementation and popularity.

To interpret the transition to a hydrogen society, simply analyzing the advancement of technology from an engineering perspective is insufficient. There are pilot hydrogen cities equipped with hydrogen energy pipelines, such as in Kitakyushu City (Fuel Cells Bulletin 2011) and in the Harumi area of Tokyo Metropolis (Fuel Cells Works 2019); the broader scope of a sectoral approach will be more beneficial in illustrating the hopeful picture of realizing a hydrogen society. It is expected that the research will bring more insights into hydrogen policy implications from a comprehensive methodology regarding technological improvement, capital investment, the supply chain of hydrogen-related sectors, and the overall economic impact assessment for the transition to a hydrogen society.

### 5.1.3 Rephrasing the Hydrogen Strategy under the Global Trend of Decarbonization

Amid the Ukrainian crisis and the global energy crisis since 2022, Japan rephrased its hydrogen strategy to take the lead in developing pioneering regulations and support systems for a hydrogen society with decarbonization by supporting businesses in developing a low-carbon hydrogen and ammonia supply in Japan by around 2030. According to the Policy Framework (draft) for Realizing a Hydrogen Society (METI 2023), the support consists of an efficient supply infrastructure, such as tanks and pipelines, to promote international competitiveness and efficient supply chains. Moreover, Japan will also promote hydrogen production and utilization in regions through the development of local supply chains and infrastructure networks.

In the power generation sector, the use of hydrogen and ammonia is highly anticipated as a cost-effective source in ensuring energy stability while reducing $CO_2$ emissions from thermal power generation and promoting the expansion of demand and cost reduction through the establishment of a large-scale supply chain towards 2030. Regulations and support will also be implemented to accelerate the use of hydrogen in power generation, such as the Long-term Decarbonization Auctions and the 2030 nonfossil fuel ratio of 44% or more.

In the mobility sector, support for fuel cell vehicles (FCVs) and hydrogen station development has been provided for passenger cars, but there is a need to focus on commercial vehicles, which have greater potential for hydrogen demand and for which the advantages of FCVs are more evident. This includes expanding policy resources, including tax measures, to support the large-scale construction of hydrogen stations. For railways, the development and demonstration of a domestic hydrogen supply chain through the use of fuel cell railway vehicles and low-environmental-impact railway transportation will be promoted.

The amended Energy Conservation Law sets target goals for specific transport operators and shippers, including nonfossil energy conversion targets such as hydrogen. Future goals include the implementation of approximately 800,000 FCVs, equivalent to passenger cars, by 2030 through the accumulation of demand for long-distance transport and the establishment of hydrogen supply chains. For fuel cell railway vehicles and railway transportation, the aim is to achieve social implementation by 2030, and for hydrogen stations, the goal is to make the business self-sufficient by the late 2020s, taking into account cost reductions due to regulatory relaxation, and to establish approximately 1,000 stations by 2030. Overall, Japan is taking steps towards the creation of a hydrogen-based society with a view to achieving carbon neutrality by

2050. In addition, Japan aims to collaborate with local governments and companies to promote the use of hydrogen in various sectors and industries, including ports and factories. The country plans to invest up to 2 trillion yen ($18 billion) in the industry over the next decade.

### 5.1.4 Research Question and Structure

To understand the overall economic assessment of the transition towards a hydrogen society in Japan, the research will apply a quantitative approach to investigate the impact of implementing a hydrogen society through capital investment in the hydrogen-related infrastructure with the foresight technology of 2025–2035. The research proceeds as follows: Section 5.2 will provide a literature review of the hydrogen society trend and its gap in empirical studies; Section 5.3 will introduce the methodology of the calibration for the technological improvement parameters and the structure of the analytical model; Section 5.4 demonstrates the scenario and the setting of policy shocks; Section 5.5 displays the simulation results and their interpretation; and Section 5.6 presents concluding remarks including policy implications, research limitations, and future prospects.

## 5.2 Literature Review

### 5.2.1 R&D Measures for Hydrogen Society Roadmap

Climate change and the interdependency of the global market have highlighted the need for new energy solutions. In 2020, the Japanese government established a target to attain carbon neutrality by 2050 through the attainment of net-zero greenhouse gas emissions. This determination led to the proposed establishment of a “hydrogen society,” with the promotion of fuel cell electric vehicles, hydrogen-based power generation, and synthetic gases in the industry sector. Despite the fact that hydrogen remains an emerging and scarce source of energy, the importance of renewable energy options to meet global energy demands while reducing $CO_2$ emissions should not be underestimated.

A hydrogen society could refer to Japan’s “smart community” concept, which leverages digital and communication technologies to efficiently manage power generation and consumption. The success of this policy is vital for securing Japan’s future economic growth, energy security, and environmental well-being. However, the reliance on imported energy carriers poses a significant challenge for Japan’s energy system and energy security. To accommodate the “hydrogen society" indicated in Japan's basic hydrogen strategy with its carbon neutrality target in 2050, Japan's energy policy has greatly strengthened the green transition by reducing dependence on fossil fuel power plants while promoting renewable energy infrastructure for industry and households.

Over a period of several decades, Japanese energy policy has favored an ambition to advance the development of fuel cells that are cheaper, more efficient, and longer lasting, as well as the advancement of hydrogen production, storage, transportation, and fuel supply systems to facilitate the widespread use of fuel cells. The Japanese government and industry are strongly supportive of this policy, and a political consensus is forming that Japan should shift away from nuclear power and actively pursue an efficient, integrated, and environmentally friendly hydrogen society. To strengthen this strategy, Japan should explicitly focus on expanding research and development efforts in key energy sectors (Behling, Williams, and Managi 2015). The capture of R&D factors would provide measurable indicators, which could substantially help the analysis in making a feasible roadmap for a hydrogen society.

In a recent study, Burandt (2021) utilized a stochastic large-scale open-source energy system model, coupled with full hourly power system dispatch, to analyze the potential impact of hydrogen imports on the power system, electricity prices, import dependency, and other industrial sectors. The findings indicate that the integration of hydrogen imports would have a significant impact on power system development, leading to a substantial shift toward renewable energy sources, such as solar PV, onshore and offshore wind, and hydroelectric power. Notably, solar PV is expected to be the primary source of electricity, accounting for 40%–45% of total generation, while onshore wind power is expected to largely complement it, and hydropower is expected to provide baseload power in all cases. Furthermore, hydrogen imports have the potential to lower the average price of electricity generation in highly urbanized areas, replacing electrification of buildings and the industrial sector with hydrogen-based technologies. It is important to acknowledge the limitations of the modeling approach utilized in the study, and future analyses should consider these limitations in order to provide a more comprehensive outlook.

### 5.2.2 Applicable Sectors for Hydrogen Society

A hydrogen society could help in transitioning from a fossil fuel energy system to a sustainable green economy, taking into account technical, environmental, economic, and social factors. Trattner, Klell, and Radner (2022) highlight the potential of a hydrogen society in facilitating the transition from a fossil-based economy to a sustainable green economy, taking into consideration technological, environmental, economic, and social factors. This transition necessitates a complete shift from fossil fuels to renewable energy sources, such as solar, wind, hydro, environmental heat, and biomass, employing electrochemical machines, including electrolyzers, batteries, and fuel cells, to enhance efficiency and reduce $CO_2$ emissions in all areas of mobility, industry, household, and green energy services. The initial markets for green hydrogen could be intermediate commodities for industrial applications, followed by power generation and mobility (Acar et al. 2019). A range of well-designed multi-generation systems that harness the solar spectrum and generate value-added system products, such as electricity, heat, $Cl_2$, NaOH, clean water, and ammonia, are available. Encouraging sustainable methods of hydrogen production is crucial for promoting international initiatives.

In the realm of sustainability, implementing green power and hydrogen in the mobility sector is crucial, as it can replace traditional fossil fuels and lower carbon emissions in industrial applications. However, the adoption of hydrogen as an energy carrier requires alterations to combustion chambers and burners, and the replacement of fossil fuels in each process must be taken into account. As the utilization of hydrogen for fuel cell electric vehicles grows, a major automotive company in the Republic of Korea has deemed the current hydrogen supply infrastructure and strategies for developing the hydrogen industry feasible (Kim et al. 2023). Various methods for hydrogen production and transportation are being explored, including natural gas reforming, renewable energy, and green hydrogen. In an effort to reduce the price of hydrogen gas, the Korean government is providing subsidies to the private sector to encourage the installation of more hydrogen refueling stations.

To promote a stable supply of, and demand for, hydrogen, countries should capitalize on their strengths to produce hydrogen and develop appropriate fueling strategies through public-private partnerships and international cooperation. In Japan, policymakers face significant challenges in ensuring sustainable energy security in the aftermath of the Fukushima nuclear crisis. Therefore, they need to decarbonize the energy system while ensuring safety and continuity in case of natural disasters. According to Khan, Yamamoto, and Sato (2020), the hydrogen fuel cell vehicles (HFCVs) could barely meet in Japan's green transition even with incentives provided by the government to promote HFCVs as an environmentally friendly technology. Thus, potential demand for HFCVs and government incentives remain critical factors in the adoption of hydrogen as an energy carrier in Japan. The mobility, industry, service, and household sectors are highly correlated with a potential spillover effect generated among different users. Therefore, a comprehensive model platform could serve as a better analytical tool for interpreting an integrated power grid and hydrogen society.

### 5.2.3 Integrated Power System in the Case of Norway

In order to foster the development of low-carbon hydrogen, the Norwegian government has implemented various R&D-related support measures. The "Hydrogen Strategy" was published by the government in June 2020, referring to the entire energy sector and providing a roadmap for hydrogen. According to the IEA (2022), Norway plans to gradually phase out its oil export industry by 2050, and hydrogen will play a central role in the transition towards a low-emission society. This shift towards hydrogen highlights the importance of decarbonization in Norway. Although the oil sector still accounts for approximately 30% of Norway's $CO_2$ emissions, hydrogen is expected to replace fossil fuels in the transportation and industrial sectors.

In light of Norway's ambitious greenhouse gas reduction target of achieving a 90%–95% reduction (excluding sinks) from 1990 levels by 2050, green energy hydrogen fuels are seen as the key to low emission technology (IEA 2022). Despite this, the adoption of hydrogen technology remains limited due to the lack of policy and regulatory support, as well as limited public awareness. In order to promote the widespread use of hydrogen technology, various factors, such as environmental awareness and benefits, the availability of hydrogen infrastructure, the compatibility of household and industrial heat appliances, fuel price levels, media coverage, and support for the hydrogen market, need to be taken into account (Høyland, Kjestveit, and Skotnes 2023).

To investigate the economic impacts of policies aimed at reducing fossil fuel production and promoting the hydrogen demand in integrated power systems, Computable General Equilibrium (CGE) models can serve as a valuable tool. Espegren et al. (2021) employed a dynamic multi-regional CGE model to simulate Norway's energy transition, demonstrating the potential for significant decarbonization by 2050 with the aid of hydrogen. Nonetheless, the study also highlights challenges and trade-offs associated with the transition, including potential impacts on GDP growth. The analysis indicates that GDP growth rates will initially be lower than in the main alternative scenario but will recover after 2030. In order to analyze integrated power systems with various energy sources, the use of CGE models can be beneficial, as they allow for a thorough examination of the economic implications of different policy measures aimed at achieving a sustainable energy system.

Damman et al. (2021) employ a hybrid approach that combines qualitative sociotechnical analysis with quantitative modeling to explore the sociotechnical dynamics that led to the current situation in Norway regarding hydrogen in the energy transition. This method of analysis can be particularly useful in complex situations, with multiple pathways and solutions being considered. They employ two models, namely the bottom-up optimization model of the national energy system (TIMES-Norway) and the top-down general equilibrium model (REMES), to conduct a quantitative analysis of the viability of different routes toward a zero-emission society in Norway by 2050. The study points out that effective transformation necessitates the consideration of numerous pathways and the plausible condition for each pathway to be realized. Norway's abundant resources of hydropower, onshore and offshore wind, and heavy dependence on oil and gas offer various opportunities for hydrogen energy solutions, thereby shedding light on the potential and challenges of deploying and producing hydrogen on a large scale.

### 5.2.4 The Potential of Hydrogen Society for Decarbonization

Hydrogen energy is a critical element in achieving a low-carbon society, but its expansion faces various obstacles, including technical, financial, and institutional challenges. While there have been recommendations from the government and business perspective, studies on hydrogen station users are limited, and respondents often lack sufficient information on the technology. The characteristics of a future hydrogen economy are currently subject to debate. Oliveira, Beswick, and Yan (2021) propose a vision in which hydrogen is primarily used for decarbonization with a three-stage hydrogen deployment plan that includes various sectors, including industry, transportation, building and heating, and electricity, showing that hydrogen could decarbonize around 18% of energy-related sectors. Meanwhile, Hienuki et al. (2021) conducted a survey of users who refuel at hydrogen stations to evaluate the social acceptability of these stations. They compared the acceptance of users of self-refueling hydrogen stations with that of existing gas stations. By assessing users' confidence in the technology, they were able to improve the acceptability of hydrogen stations and build on the existing acceptability model.

Utilizing the power exchange market, in addition to on-site photovoltaics, can improve the unit cost of hydrogen. The power-to-gas (PtG) technology for hydrogen production could serve a mean of stabilizing power systems and reducing $CO_2$ emissions. Yoshida et al. (2022) examine the potential of PtG technology as a means of stabilizing power systems and reducing $CO_2$ emissions through hydrogen production. They propose a mixed-integer linear programming model to optimize the annual hydrogen production schedule, with the unit cost of hydrogen production as the evaluation index. The results indicated that PtG technology could serve as a promising solution for reducing emissions in the industrial sector, particularly as more variable renewable energy sources are introduced in the future, and can contribute to the introduction of hydrogen demand for industrial applications.

In relation to the potential of solar thermal-to-gas (StG) conversion systems in facilitating the transition towards zero-carbon energy in Japan, this technology is considered highly promising due to its ability to convert renewable energy into synthetic gases such as hydrogen and methane, which can effectively store intermittent renewable energy (Wai, Ota, and Nishioka 2022). The production of synthetic chemical gases through StG conversion has significant potential as an alternative to fossil fuels, and the Japanese government is promoting cost-effective renewable energy generation and efficient PtG conversion, specifically for hydrogen production, decarbonization, and storage. Furthermore, Japan is presently engaged in the development of carbon recycling technologies aimed at decreasing $CO_2$ emissions and capturing carbon from the industrial sector.

To achieve a transition towards sustainable sociotechnical systems and establish energy conversion, it is imperative to consider the social dimensions of hydrogen conversion. These dimensions encompass contextual disparities and challenges, including technical feasibility, compliance with national regulations, public acceptance, and economic viability. Incorporating a societal perspective is crucial to ensure stable efficient functioning of sociotechnical systems. However, hydrogen, despite being capable of complementing renewable electricity and contributing to various energy-related sectors, is not the prevailing energy source at present. To meet the future demand for hydrogen, the hydrogen economy must be expanded, and the adoption of green hydrogen in sectors such as chemical synthesis should be prioritized along with conventional energy sources to ensure the hydrogen supply chain for production to achieve economies of scale. Furthermore, hydrogen can aid decarbonization efforts by virtue of its high mass energy density, light weight, ease of electrochemical conversion, and capacity to store energy over extended periods. It would be desirable to develop a quantitative measure to capture the transition of energy sources toward a hydrogen society supported by the technology advancement for assessing the impact on industry and GHG emissions.

## 5.3 Methodology

To make a comprehensive impact assessment for transitioning to a hydrogen society, it is essential to utilize the instrument with the commonly accepted scope of database and a consistent approach. However, under the existing literature on hydrogen mainly focuses on energy efficiency. Moreover, the economic analysis is still limited to cost-benefit analysis, and we find evidence-based technological parameters for implementing hydrogen power with the foresight technology indicators and apply a CGE model to come up with the impact of the hydrogen society.

### 5.3.1 The Capture of Technological Improvement

To quantitatively evaluate the social and economic policies regarding science technology for presenting multiple possible policy options, it is indispensable to capture the technological characteristics of tangible and knowledge capital as intangible fixed assets compilation in the input-output tables (Kuroda et al. 2018). The multisectoral economic general interdependence model explicitly captures the impact on the economy and society through the general interdependence of the economy in terms of both flows and stocks by industry sector based on the activity of three dimensions: main product, intra-ICT, and intra-R&D.

The model uses a reference case of a technological scenario (science and technology and social technology) that is exogenously given to the economy and society without any specific policy measures to compare its impact on the economy and society using various indicators to establish the direction of economic and social change. In addition, the ScREX Policy Intelligence Assistance System – Economic Simulator (SPIAS-e) was created to serve as an analytical tool for understanding the characteristics of science and technology and their economic and social impacts in the scenario of Japan's economy in the projection of 2021–2050 (Huang and Kuroda 2021), the parameters of which could be utilized for economic analysis.

### 5.3.2 GTAP-E-Power Model

For analyzing the energy or power system impact on the economy on a global scale, the Global Trade Analysis Project (GTAP) model developed by Prude University is commonly used (Hertal 1997). The GTAP model is based on a CGE framework with the input-output tables contributed by the research community. In many extensions of the GTAP model, the GTAP-E-Power is an electricity-detailed economy-wide model that has decomposed different power generations from fossil fuels of coal, crude oil, and natural gas, or renewable energy such as hydro, solar, and wind power (Peters 2016a,b). The GTAP-E-Power model implements the GTAP model in presenting economic indicators of output, price, external trades, and carbon dioxide emission from 75 sectors, which makes it a useful policy tool for identifying a domestic or global economic issue (Huang, Iwaki, Liou, 2023). Although hydrogen energy is still not included in the model, we could utilize the parameters sourced from other available databases such as SPIAS-e and other key literature to illustrate the impact of the hydrogen society roadmap.

## 5.4 Scenario

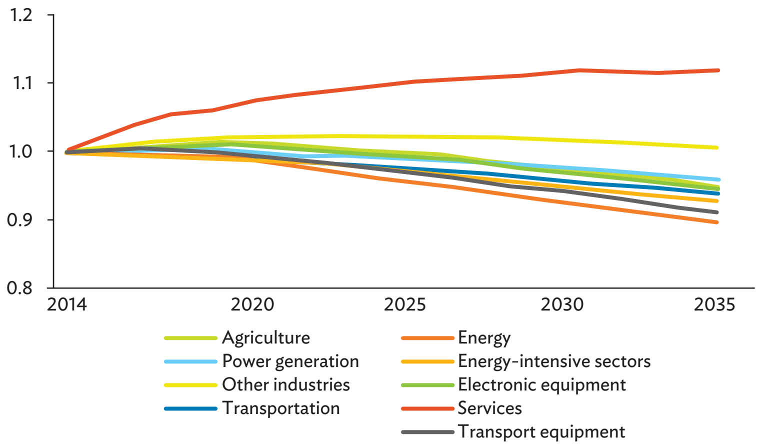
We create a scenario of a roadmap toward a hydrogen society in the GTAP-E-Power model. As indicated, in the absence of the hydrogen energy sector in the model scope, we hereby assume higher productivity thanks to the technological improvement with hydrogen energy generated by different power sources. Therefore, instead of differentiating the hydrogen sources, we demonstrate the implementation of a hydrogen society by using the parameters sourced from SPIAS-e for technological improvement and the assumptions of hydrogen cost (IEA 2021) as the policy shocks.

### 5.4.1 Technological Improvement

We refer to the projection of economic indicators as technology foresight because of its featuring in the accumulated flow of tangible and intangible capital stock. In SPIAS-e, the indicators in the 50-year projection are generated along with the higher efficiency generated by information communication technology (ICT) and demographic change (Huang and Kuroda 2021).

The price index of tangible capital aggregated from 93 sectors represents the cost of capital input (Figure 5.1); a higher index indicates a higher cost. Between 2014 and 2035, the energy sectors show the lowest value, implying that the sector has more significant technological improvement; on the other hand, the services sector shows a high value, indicating that the demographic change in Japan has made the cost of services expensive. The indicators could be referred to as spillover effects contributed by the R&D (Huang, Liou, and Iwaki 2021). We thus calibrated the index from 2025–2035 as our parameters for technological improvement (Table 5.2).

## Figure 5.1: The Price Index of Tangible Capital



Source: Sectors aggregated from SPIAS-e.

## Table 5.2: Technological Improvement Parameters

| Sectors | 2025–2035 |
|---|---|
| Agriculture | 4.96% |
| Energy sectors | 6.10% |
| Power sectors | 2.95% |
| Energy-intensive sectors | 4.64% |
| Manufacturing | 1.64% |
| Electronic equipment | 4.59% |
| Transport equipment | 5.97% |
| Transportation | 3.51% |
| Services | –1.72% |

Source: Sectors aggregated from SPIAS-e.

### 5.4.2 Hydrogen Society Policy Shock

The energy and power generation sectors in the GTAP-E-Power model are more specific than sectors classified in SPIAS-e. Therefore, for simplicity and consistency, we unified the parameters for these two sectors and the capital investment ratio for hydrogen generation (Table 5.3).

## Table 5.3: The Technology and Policy Shocks
(%)

| Sectors | Productivity Growth | Capital Investment* | Energy Efficiency |
|---|---|---|---|
| Coal | 6.10 | n.a. | n.a. |
| Crude oil | 6.10 | n.a. | n.a. |
| Natural gas | 6.10 | n.a. | n.a. |
| Petroleum | 6.10 | n.a. | n.a. |
| Power transmission | 2.95 | n.a. | n.a. |
| Coal-fired power** | 2.95 | 10.0 | 10.0 |
| Oil power** | 2.95 | 10.0 | 20.0 |
| Gas power** | 2.95 | 10.0 | 20.0 |
| Nuclear power** | 2.95 | 10.0 | 10.0 |
| Solar power** | 2.95 | 50.0 | 5.0 |
| Wind power** | 2.95 | 50.0 | 5.0 |
| Hydro power** | 2.95 | 10.0 | 5.0 |
| Other powers | 2.95 | n.a. | n.a. |
| Agriculture | 4.96 | n.a. | n.a. |
| Electronic equipment | 4.59 | 10.0 | n.a. |
| Transport equipment | 5.97 | 10.0 | n.a. |
| Energy-intensive sectors | 4.64 | n.a. | n.a. |
| Manufacturing | –1.64 | 10.0 | n.a. |
| Transportation | 3.51 | 10.0 | n.a. |
| Sea transportation*** | 3.51 | n.a. | n.a. |
| Services | –1.72 | n.a. | n.a. |

Note: *Total investment volume is $924.7 million.
**For energy-intensive sectors, the power supply efficiency is assumed to double.
***Productivity growth is assumed to be at the same level as the transportation sector.

Source: By authors based on SPIAS-e and the assumptions of the IEA (2019) and METI (2021).

## Productivity Growth

In 2025–2035, the R&D activity accumulated in the business-as-usual (BAU) path shows a lower price index for most of the sectors, especially in the energy (6.1%), transport equipment (5.97%), and agriculture (4.96%) sectors, indicating that firms could achieve the same performance with less input. Nevertheless, due to the shrinking population, productivity growth decreased in the services (–1.72%) and manufacturing (–1.64%) sectors.

### Capital Investment

To achieve a hydrogen society, capital investment in hydrogen generation is fundamental. The investment ratio for fossil fuel power generation is assumed to be 10% following the equipment installation with associated sectors. In comparison, the ratio is set at 50% for the renewable energy source of solar and wind power because of the declaration of the net-zero carbon neutrality goal. The total investment volume is $924.7 million.

### Energy Efficiency

According to the cost estimate of hydrogen energy generation by the IEA (2019), as of 2019, the relative cost of $H_2$ per KG by steam methane reforming (oil and gas), coal gasification, and electrolysis (renewable energy) is 1:2:4; we hereby assume that the hydrogen generation efficiency for sectors of services and manufacturing could increase by 20%, 10%, and 5% for each power generation method, respectively. Moreover, given the evidence that a higher usage rate would also increase the efficiency, we thus assume that the peak load power generation for energy-intensive sectors for the simulation analysis.

## 5.5 Simulation Results

Based on the scenario's technological change parameters and policy shocks, we obtained the results of a roadmap toward a hydrogen society. Since the parameters were calibrated for ten years, it implied that the simulation results could be regarded as a ten-year accumulated economic indicator (Figure 5.2). We hereby discuss the simulation

**Figure 5.2: Output and Price Change**

results from four perspectives: (1) output and price change, (2) external trades and supply chain, (3) carbon dioxide emission, and (4) GDP and welfare analysis.

### 5.5.1 Change of Output and Price

Generally speaking, the energy sectors show an increase in output, excluding a slight fall in coal. Given that the volume of Japan's output for energy sectors is minimal, the increase could be disregarded. However, the price decrease could imply the transition of energy sources. The output and price of electricity both showed growth, indicating the rising importance of electricity from all power generation sources.

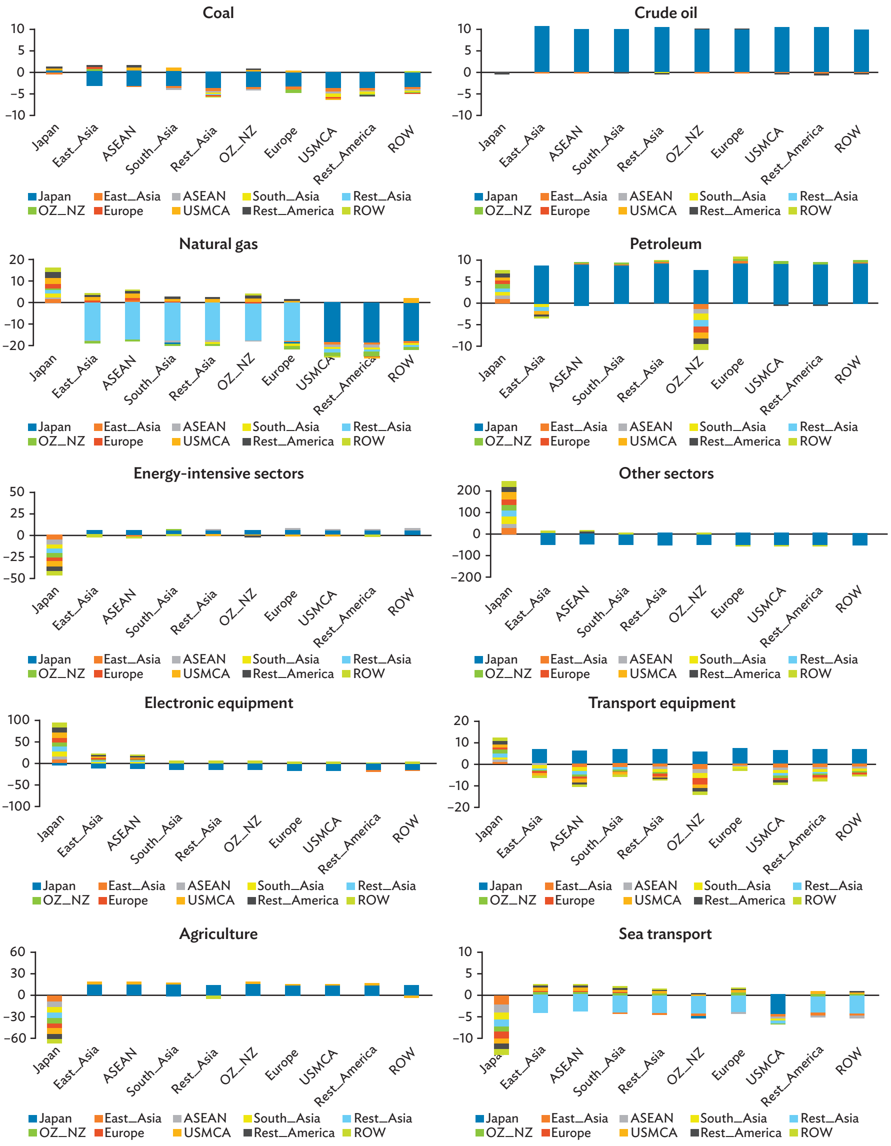
Agriculture output showed a slight 0.5% growth and a 3.1% decrease in price thanks to the higher productivity of smart and autonomous systems. On the other hand, transport equipment showed a vibrant growth of 5.0% with a decreased price, reflecting Japan's competitiveness in the new vehicle production that fits the energy transitions. Meanwhile, it is notable that the output decreased by 3.7% in electronic equipment and 1.0% in the energy-intensive sector despite its increase in productivity. The manufacturing sector's output fell by 6.6%, with the price increasing by 6.1%, indicating the decaying influence.

The demographic change has threatened Japan's service sector, which has the highest economic share. However, the energy transition has helped activate the sector, with slight increases of 0.7% in transportation and 0.4% in services. Even though the price increases reached 5.4% and 15.8%, the positive growth in the services sectors plays a role in maintaining the long-term stability of economic performance.

### 5.5.2 External Trades and Supply Chain

The scenario of policy shocks on power efficiency and investment in hydrogen society-related sectors may also impact the global supply chain regarding the percentage change of trade volume with trading partners (Figure 5.3). Therefore, interpreting the potential consequences may assist firms and facilitate policymaking in preparing for the adjustment of production and fluctuation.

## Figure 5.3: Changes of Import from Trading Partner Country (%)



Coal

Crude oil

Natural gas

Petroleum

Energy-intensive sectors

Other sectors

Electronic equipment

Transport equipment

Agriculture

Sea transport

### Energy Sectors

Since Japan only produces very little energy, we shall disregard the change in Japan's export to other countries. In addition to the stable situation in the coal and crude oil sectors, Japan increases its import of natural gas from Europe and from Asian regions, while exporting refined petroleum to other regions. Meanwhile, Australia and New Zealand reduced the import of petroleum from other regions but substantially increased imports by 7.9% from Japan, which could imply other possible energy partnerships.

### Other Manufacturing Sectors

With a more stable power supply for energy-intensive sectors such as the steel, chemical, and machinery sectors, Japan has become more self-sufficient, with a strong export increase of 5.6% to all regions. Moreover, Japan's core competitiveness in transport equipment also showed in the notable increase in export by 5.7% to 7.2%, especially in Europe and in Asian regions. It is interesting to see the significant increase in export of 15% in Japan's agriculture sector, which mainly contributed to its high value added and smart system. As no policy shock is provided for, Japan could substitute the import with domestic supply for the sea transport sector.

On the other hand, the demand for Japan's manufacturing and electronic equipment sectors showed a significant decrease, implying Japan's diminishing comparative advantages in the global production networks. Nevertheless, the high interdependence between Japan and the world for energy-intensive and transport equipment sectors may highlight the importance of developing the essential process toward a hydrogen society by providing next-generation transport equipment and upgrading the products from energy-intensive sectors.

## 5.5.3 Carbon Dioxide Emission

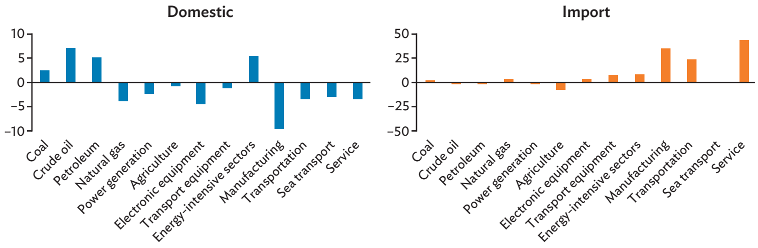
Reducing carbon dioxide emissions through the use of renewable energy is the primary measure to achieve the net-zero carbon neutrality goal (Figure 5.4). The technological improvement parameters we set for policy shocks could project possible pathways of $CO_2$ emission with informative policy implications toward the reduction target. However, as the shocks only apply domestically in Japan, we hereby focus more on the domestic carbon dioxide emission.

A higher emission of fossil fuel may imply a fluctuation in the energy transition, while natural gas showed an emission decrease of 3.7%. By implementing the assumed high-efficiency hydrogen energy generation equipment, the power generation sectors, including coal, crude oil, and natural gas, have contributed to a 2.3% decrease in emissions, or 6.8 million tons. Other significant emission reductions could refer to electronic equipment (–4.4%) and manufacturing (9.5%) sectors, implying the reconstruction of the global supply chain. On the other hand, the energy-intensive sectors showed an increase of 5.2% in emissions due to Japan's sectoral comparative advantage as a trade-off for other manufacturing sectors.

Japan's core competitiveness in transport equipment production has paid off in reducing emissions by 1.0%, which is small but unneglectable because the production of so-called "zero-emission" electronic vehicles is notorious for massive $CO_2$ emissions during its production process. Interestingly, even without energy efficiency policy shocks, the sea transport sector could reach a 2.8% emission reduction, mainly because of the change in external trades and the productivity growth in global logistics.

Meanwhile, the 3.3% emission reduction or a total of 19.8 million tons in the transportation and services sectors is impressive, representing vital indicators for transitioning to a hydrogen society. Lastly, we might begin to worry about the massive emission increase if we look at the indicators from the import firms. This is mainly because no technological improvement parameters were set or policy shocks applied to regions other than Japan.

## Figure 5.4: Change in Carbon Dioxide Emissions
(%)



## 5.5.4 Change in Employment

Along with the demographic change and the technological improvement toward the hydrogen society, sectoral employment also shows the transition (Table 5.4). By implementing the new facilities for hydrogen generation, employment shows a significant growth in solar power (12.9%) and the power transmission system (12.9%), natural gas (12.5%), and thermal power (10.3%), while a decrease is evident in coal (–11.6%) and petroleum (–7.5%). Energy-intensive and other sectors decline by 6.4%–6.9%, whereas a substantial increase is evident in transport equipment (10.5%).

In regard to the number of employees, the higher efficiency and automatic system have decreased transportation by 413,712 people. Nevertheless, the service shows an increase of 614,248 people, indicating a more specific workload allocation to maintenance or the medical care sectors. As a shrinking and aging population is inevitable in Japan, the employment change should not be taken as a shock, but rather a process of transition toward the hydrogen society. The technological

**Table 5.4: Change of Employment**

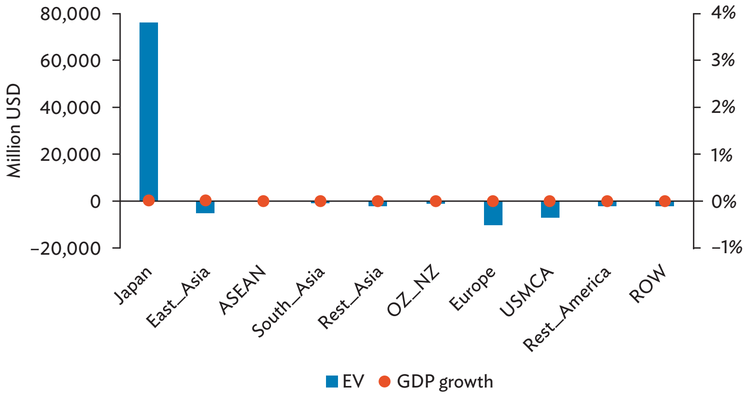
| Sector | People | |
|---|---:|---:|
| Agricultural, forestry, fishery, and animal husbandry | –8,324 | –0.2% |
| Coal | –4,247 | –11.6% |
| Oil mining | 196 | 7.0% |
| Natural gas | 6,969 | 12.5% |
| Petroleum | –1,136 | –7.5% |
| Thermal power | 11,335 | 10.3% |
| Solar power | 2,652 | 12.9% |
| Other power | 3,418 | 7.7% |
| Power transmission | 12,879 | 12.9% |
| Transport equipment | 105,103 | 10.5% |
| Energy-intensive sector | –290,334 | –6.4% |
| Other sectors | –226,982 | –6.9% |
| Electronic equipment | –14,402 | –1.0% |
| Transportation | –413,712 | –11.8% |
| Sea transportation | –57,473 | –23.2% |
| Service | 614,248 | 1.2% |

improvement could still sustain efficient logistics, transportation, and service with a satisfactory quality of life and mitigate climate change with clean and renewable energy sources.

### 5.5.5 Welfare Analysis and GDP

In the GTAP model scope, we use equivalent variations to compare the utility change in the *ex ante* and *ex post* conditions to evaluate the welfare (Figure 5.5). The regional utility is the function of goods, including energy consumed by households in the region. We calibrated the technological growth parameters, capital investment for hydrogen-related sectors, and energy efficiency assumptions, which contributed to a substantial improvement in welfare by $75,696 million. Although the relevant parameters are not applied to other regions, ASEAN showed a $299 million increase in welfare, implying that its economy was also affected positively by our assumed hydrogen society transition in the regional supply chain.

**Figure 5.5: Welfare and GDP Growth**



Consistent results in GDP also reveal that the transition to a hydrogen society could bring a 1.3% economic growth. Upgrading the hydrogen energy system with strategic investment could lead to a higher quality of life with less $CO_2$ emission. The hydrogen society roadmap could positively impact the economy even for a country like Japan with its tremendous pressure on demographic change with a shrinking population.

## 5.6 Conclusions

The composition of a hydrogen society is complex, and it requires an interdisciplinary approach and inclusive analysis to coordinate critical factors to accelerate the development drawn in the roadmap effectively. But, more importantly, a broader approach to socioeconomic analysis could substantially motivate more stakeholders to cooperate for comprehensive implementation for expanding the demand to realize a hydrogen society with clean and sustainable development.

The main contribution of the research is its evidence-based inclusion of the 2025–2035 foresight technology indicator for an assumed hydrogen society transition scenario with GTAP-E-Power economic modeling for plausible policy intuitions. The simulation results provided wide-ranging information that could assist industries in adjusting the fluctuation and opportunity along with the hydrogen society. This method allowed more specialists to join the policymaking process with their expertise to strengthen and accomplish the policy recommendations gradually.

### 5.6.1 Policy Implications

Based on the simulation results of Japan's hydrogen society transition, we found that capital investment in power generation sectors for hydrogen energy generation equipment could improve energy efficiency, thereby contributing to stimulating Japan's economy by increasing GDP by 1.3% with an improvement of welfare by $75,696 million, as well as an estimated reduction in $CO_2$ emissions of 19.8 million tons in the transportation and services sectors.

More specifically, the hydrogen society transition could reduce Japan's dependence on fossil fuels with a more resilient global supply chain for energy-intensive, transport equipment, and even agriculture sectors. Furthermore, the investment in hydrogen-related sectors also reinforced Japan's competitiveness and created the possibility of an energy partnership with Australia and New Zealand and production networks with ASEAN.

Our study indicates that the attainment of economies of scale is imperative to markedly decrease the expenses associated with hydrogen energy. The robustness of the hydrogen supply chain hinges upon the existence of a robust demand for hydrogen energy across all sectors, including transportation, manufacturing, and residential domains. Moreover, to ensure the smooth functioning and upkeep of the hydrogen supply chain, the establishment of production networks in crucial domains such as hydrogen fuel cell vehicles (HFCVs) and other vital constituents of the hydrogen infrastructure is crucial and would yield benefits for regional collaborators in Asia and the Pacific.

The transformation in employment patterns underscores the significance of building capacity and providing training in hydrogen-related industries. While advancements in efficiency could lead to the displacement of some traditional jobs in the fossil fuel sector, the demand for sustainable energy is expected to generate employment opportunities for technicians and service-oriented sectors, thereby enabling greater international mobility of human resources. This transfer of knowledge and skills is likely to have a spillover effect, not only within the region but also among regions, owing to the growing adoption of renewable energy sources such as offshore wind power and associated manufacturing industries. Continuous policy dialogues concerning technology transfer and stakeholder partnerships are vital for effective policy formulation and collaboration within the global supply chain. Finally, we recommend the establishment of a hydrogen society pilot zone to facilitate the adoption of hydrogen energy.

### 5.6.2 Research Limitation

To fill the gap in hydrogen studies between the engineering approach and economic analysis, the research applied a GTAP-E-Power model to simulate Japan's hydrogen society transition with technological improvement parameters calibrated from SPIAS-e. However, even though informative economic indicators were identified through the assumed scenario in the simulation of policy shocks, limitations are inevitable for the current research scope. For instance, the assumption of technological improvement might be oversimplified under the homogeneous energy efficiency parameter setting for all sources of energy goods and power generations. Therefore, more precise indicators of energy parameters should be make to improve the accuracy of the simulation results.

Moreover, the GTAP-E-Power model scope is a static model and thus the recursive impact could not be measured, making it difficult to reflect the fiscal feasibility of massive infrastructure investment. In addition, it is unrealistic that the parameters of technological improvement only occur in Japan, which has dramatically restricted the revelation of the global hydrogen supply chain. It is desirable to overcome these limitations so that the GTAP-E-Power analysis can be a more practical instrument for interpreting the hydrogen society.

### 5.6.3 Future Prospects

Along with recovering from the COVID-19 pandemic, more hydrogen-related systems will be installed to meet the roadmap and the goal for a net-zero carbon society. To cope with the research limitations indicated above, it would be indispensable to apply more accurate parameters for technological improvement indicators for Japan and other regions, specifically to the particular power generation sources, to better illustrate the impact of transitioning to a hydrogen society.

Notwithstanding, it will be essential to revise the GTAP-E-Power model scope from static to dynamic to appropriately capture the recursive impact of investment choices to enable policymakers to designate feasible fiscal plans to support the project under the evidence-based references.

Finally, and fundamentally, similarly to the effort expended in distinguishing renewable energy sectors of solar and wind power generation from fossil fuel, it will be necessary for economists and the statisticians to think about extrapolating hydrogen energy into an independent sector. This task will greatly help in analyzing the interdependence among sectors and making straightforward policy recommendations to accelerate the realization of a hydrogen society.

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# 6

# How Can Japan Help Create a Sustainable Hydrogen Society in Asia?

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## 6.1 Introduction

Many countries in Asia have demonstrated an interest in relying on hydrogen to achieve net-zero goals. This interest is warranted since Asia's concentration of heavy industries and fast-rising transport emissions require alternative fuels. Japan has been at the forefront of these efforts. However, whether Japan's hydrogen strategy contributes to ambitious climate goals remains an open question. The reason that question remains open is that Japan's policies are unclear about intentions to transition from blue and gray to green hydrogen.

This chapter argues that greater clarity about the transition to green hydrogen will help Japan achieve international cooperation and local socioeconomic benefits. It then outlines recommendations that can clarify its support for transitioning to green hydrogen. Those recommendations include more precise language and tangible milestones for transitions in national policies. They also entail making clearer statements about the intent to support green hydrogen and related actions in international climate and local revitalization strategies that make that commitment credible.

This above argument is not only important for policymakers but for several lines of research on hydrogen. One branch of relevant research underlines that hydrogen is not universally good for the environment. For instance, studies have used analyses to demonstrate that hydrogen strategies need to avoid negative impacts on local ecosystems and freshwater availability (Panchenko et al. 2023). Others have noted that while hydrogen in the energy mix could replace fossil fuels, gaps exist regarding the supply chain and hydrogen production in, for instance, the shipping industry and hydrogen fuel cell vehicles (Atilhan et al. 2021; Khan et al. 2021). Though informative, much of this work has a stronger technical than policy focus

A second line of work is more strongly linked to policy. This includes earlier studies that advocated that Japan introduce long-term plans for increasing the share of hydrogen in its energy mix (Ohta and Abe 1985). A similar, more recent argument can be found in work on opportunities for collaborating with countries in Asia to overcome some of the aforementioned technical hurdles (Aditiya and Aziz 2021). While these studies shed important light on policy, they do not underline the multiple local and international cooperation benefits from committing to transition pathways supporting green hydrogen in Japan (and other countries in Asia).

There is thus a significant gap in the literature. This chapter fills this gap by not only examining Japan's hydrogen policies but also highlighting the benefits of transitioning to green hydrogen. It further examines the role of technology co-innovation in supporting mutually beneficial collaboration on green hydrogen between Japan and other countries in Asia.

## 6.2 Hydrogen's Potential and the Barriers to Transitioning to a Net-Zero Economy

Hydrogen has the potential to play a vital role in the transition to a net-zero economy, as it can be used as a clean energy carrier to store and transport energy from renewable sources such as solar and wind. It can also be used to decarbonize a variety of sectors, including transportation, industry, and heating, that are difficult to electrify using electricity alone. However, there are also significant barriers to the widespread adoption of hydrogen in the transition to net zero. These hurdles include: the high cost of producing "green" hydrogen using electrolysis and renewable energy; the lack of infrastructure for the production, storage, and distribution of hydrogen; and limited public awareness and understanding of hydrogen as a clean energy source. Despite these challenges, the potential benefits of hydrogen make it a potentially important driver in the transition to a net-zero economy.

### 6.2.1 Hydrogen's Potential to Transition to Net Zero

The transition to hydrogen can help reduce emissions and achieve net-zero goals (IPCC 2018), particularly in sectors that are difficult to electrify. These sectors include industries such as steelmaking, high-temperature heating, and long-distance transport. In these areas, hydrogen can be used as a cleaner alternative to fossil fuels, reducing emissions from production processes.

Hydrogen can also play a complementary role in the transition to renewable energy. The intermittent nature of renewable energy sources, such as wind and solar, can be a challenge to grid stability. Hydrogen can provide load balancing to smooth out fluctuations in demand and supply. Electrolysis, the process of splitting water molecules into hydrogen and oxygen, can be used to store excess electricity generated by renewable energy sources. When there is little wind or sun, stored hydrogen can then be burned in gas turbines to generate electricity.

Power-to-gas (P2G) is another way that hydrogen can be used as a form of renewable energy storage. This surplus electricity can be used for green hydrogen production and then consumed when needed (Thorpe 2016). This hydrogen can then be deployed to generate electricity or as a fuel for transport and industrial purposes. Importantly, the use of hydrogen as energy storage does not incur any energy loss over long periods, thus reducing emissions.

Hydrogen is potentially a key contributor to net-zero emission pathways globally (IEA 2019; Hydrogen Council 2021), but its impacts are arguably most promising in Asia. The region is home to many rapidly developing economies that will require alternative fuels in many of the sectors mentioned previously. It is therefore not surprising that governments and private companies in Asia are investing in hydrogen domestically and supply chains regionally (Hydrogen Council 2021a; BBC 2021; Government of UK 2021)..

### 6.2.2 Barriers to the Development of Hydrogen

While there is considerable potential for hydrogen in Asia, its widespread deployment is far from a foregone conclusion. One of the chief barriers to its spread is the issue of economics. The cost of hydrogen needs to be reduced across the hydrogen supply chain, i.e., production, transport, storage, and usage (IEA 2019). To contribute to decarbonization, hydrogen should be produced using green technologies. However, these methods add costs and uncertainty to the use of hydrogen as an energy source.

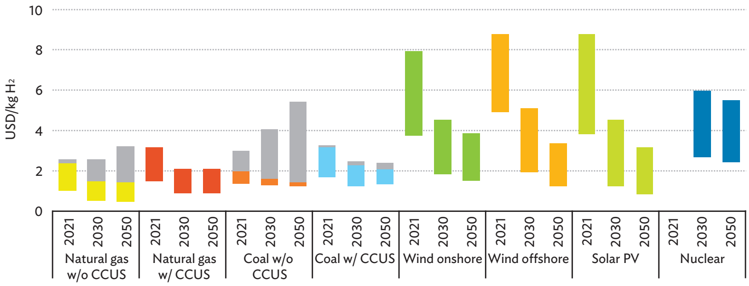
To achieve a hydrogen-based energy system, significant investments in hydrogen production and infrastructure are required. Also, it is crucial to recognize that hydrogen can be produced from a variety of sources that would not reduce emissions, including fossil fuels and biomass. To achieve net-zero emissions, hydrogen has to be produced from clean sources like water and wind energy. There are also issues related to hydrogen transportation and storage—such as the lack of a comprehensive hydrogen infrastructure, the high cost of developing and maintaining hydrogen storage systems, and the lack of suitable materials for storing hydrogen in large quantities—though research and development are identifying ways to make hydrogen increasingly cost-effective and easier to implement in large-scale systems.

Another challenge—and the one most central to this chapter—involves the impacts of hydrogen on climate change. Green hydrogen that is produced from renewables using electrolysis can help mitigate climate change. On the other hand, producing hydrogen from coal, oil, or gas is a carbon-intensive process and does not deliver climate benefits. Meanwhile, according to life cycle assessments, "blue" hydrogen produced from methane reformulation with carbon capture and storage (CCS) and blue ammonia produced from lignite reformulation with CCS are not considered environmentally friendly (Howarth and Jacobson 2021). If there are no clearly defined transition pathways, investing in only "gray" and "blue" hydrogen could stall a shift to cleaner forms of energy.

In addition, some of the cost and sustainability barriers overlap. Figure 6.1 shows that the process of generating green hydrogen is expensive compared to the alternatives. The production cost of green hydrogen is estimated to be between USD2.5/kgH2 and USD6/kgH2 in the short run (KPMG 2020). Improving the cost-efficiency of green hydrogen-producing technologies is a prerequisite for green hydrogen rollout (Otsuki et al. 2019). The good news is that some studies show progress on this front, with the lower range of green hydrogen becoming increasingly cost-competitive with blue hydrogen. As technologies improve and renewable power generation gets cheaper, green hydrogen is expected to become more affordable (IRENA 2022).

Even when cost parity is achieved, the expansion of green hydrogen may still not be a preferred policy choice. For many countries, the priority may be satisfying the electricity demand from renewable resources. In Japan, for instance, the green hydrogen production cost is estimated to come down to USD2.4/kgh2 in 2050, but Japan is expected to use its renewable potential for power generation (IRENA 2022), and import hydrogen from outside the country. Developing a hydrogen economy thus necessitates the development of a hydrogen market and supply chain.

## Figure 6.1: Levelized Cost of Hydrogen Production by Technology in 2021 for Net-Zero Emissions by 2050 Scenario, 2030 and 2050



CCUS = carbon capture, usage, and storage.

Source: (IEA 2022a).

Another barrier is related to the current regulations and policies. While many countries have set ambitious targets for the deployment of green hydrogen, policies and regulations are still not fully supportive of its development. The lack of clear and consistent regulations and policies can make it difficult for companies to invest in green hydrogen projects. Additionally, in some cases, regulations and policies may not be conducive to the development of green hydrogen, making it less attractive for private investment. Similarly, a lack of public awareness and understanding of green hydrogen can also act as a barrier to its development. There is a need to educate and inform the public about the benefits of green hydrogen and its potential to play a crucial role in the transition to a low-carbon energy system. Additionally, addressing any misconceptions or concerns about green hydrogen can help to build support for its adoption.

Overall, while there are challenges to be overcome, hydrogen has the potential to play a significant role in achieving global net-zero emission goals. Its use in various sectors, and its ability to store and transport energy, make it an essential piece of the net-zero puzzle. With ongoing investment and research, the potential for hydrogen to contribute to a low-carbon future is becoming increasingly clear.

## 6.3 Japan's Hydrogen Policies and Strategies

This section explores how Japan's hydrogen strategy has managed the above barriers but also remained unclear on how it will transition to green hydrogen. While the focus is on Japan, it is worth pointing out that other countries in Asia are also promoting hydrogen. This may open opportunities for learning across countries (see Box 6.1).

### Box 6.1: Hydrogen Strategies in Asia

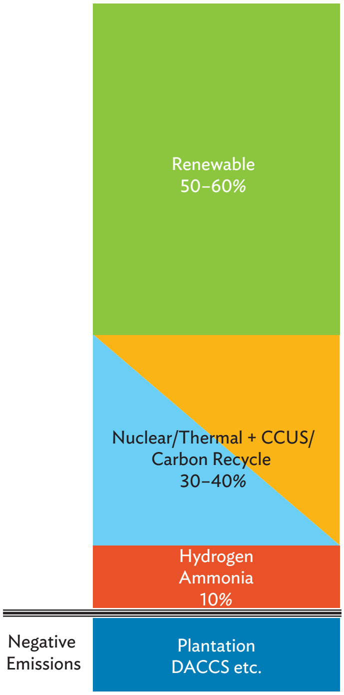
To date, a few countries in the Asia and the Pacific region have developed national hydrogen strategies or roadmaps: These include the Republic of Korea in 2019 and India in 2021, and in 2021, the People's Republic of China (PRC) promulgated hydrogen strategies.

- The Republic of Korea's Hydrogen Strategy highlights several achievements. The country has gained a reputation for mass-producing hydrogen fuel cell electric vehicles since 2013 and has also had success with fuel cells development. In 2018, the release of commercial cars with the longest driving range was seen as a symbol of the Republic of Korea's success in this field.
- In 2021, India announced the National Hydrogen Mission, a strategy aimed at making the country a global leader in green hydrogen production and use. The mission is currently being developed and will have both short-term (4–10 years) and long-term goals. Its objectives include prioritizing and developing green hydrogen, using hydrogen as a storage option for renewable energy, meeting the energy needs of the industry with hydrogen supplies, reducing reliance on fossil fuels, and providing fuel for the transportation sector. The mission also aims to turn India into a global manufacturing hub for hydrogen and fuel cell technologies (MNRE 2021). The mission was approved by the Indian Cabinet in January 2023. The likely outcomes of the mission by 2030 include: the development of a green hydrogen production capacity of at least 5 MMT (million metric tonnes) per annum with an associated renewable energy capacity addition of about 125 GW in the country; over eight lakh crore ($105.9 billion) in total investments; the creation of over 600,000 jobs; a cumulative reduction in fossil fuel imports over one lakh crore INR ($13.7 billion); the abatement of nearly 50 MMT of annual greenhouse gas emissions (PIB 2023).
- In June 2021, the China Hydrogen Alliance released a white paper titled "Hydrogen Energy and Fuel Cell Industry in China 2020," which estimates that the demand for hydrogen in the PRC will increase from 33.42 to 130 Mt by 2060. This increase in demand could assist the PRC in achieving its carbon neutrality goals. While the PRC has made significant progress in the development of renewable and clean technologies, it has not yet matched the progress made by Japan or the Republic of Korea in the hydrogen sector.

The Hydrogen Basic Strategy also aims to establish international supply chains for hydrogen production, storage, transportation, and use to support the production of hydrogen abroad. As part of this strategy, several demonstration projects for the production and importation of carbon-free hydrogen have been launched.

Since the development of the 2017 Hydrogen Basic Strategy, shifts in Japan's broader climate policy have triggered a marked increase in interest in hydrogen. This interest began to rise in October 2020 when former Prime Minister Suga Yoshihide announced that Japan would achieve carbon neutrality by 2050. Since that announcement, renewable energy (RE) and hydrogen, as well as ammonia, have begun to feature more centrally in Japan's energy plans. The growing role of these sources is illustrated in Japan's Strategic Energy Plan, which projects that renewables would comprise 50%–60%, while hydrogen and ammonia would make up 10% by 2050 (Figure 6.2).

**Figure 6.2: Japanese Government's Assumption of Power Generation Mix to Achieve Carbon Neutrality by 2050**



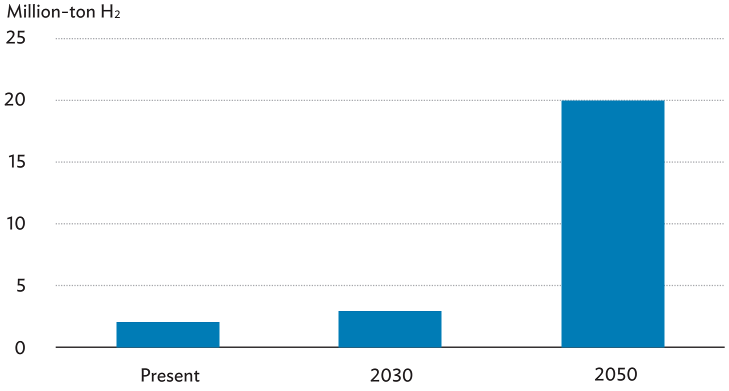
DACCS = direct air capture with carbon storage.

Source: By author, based on information in *Green Growth Strategy Through Achieving Carbon Neutrality in 2050* (METI 2021, p. 5)

It further merits emphasizing that the estimates in the above graph could be adjusted based on other sources of energy. For instance, the future of nuclear/thermal+CCUS/carbon recycling has remained uncertain since the Fukushima nuclear accident in 2011. Moreover, the status of CCUS is uncertain, with a test plant in Hokkaido able to store only 0.3 million tons of $CO_2$ whereas Japan's $CO_2$ emission from the power sector was 450 million tons of $CO_2$ in 2018. Carbon recycling and power generation using hydrogen and ammonia are still under development, suggesting more uncertainty.

Other strategies have suggested the importance of hydrogen—even given this uncertainty. According to Japan's Clean Energy Strategy, the government estimates that the annual domestic hydrogen demand will be 3 million tons in 2030 and reach 20 million tonnes in 2050. Currently, 2 million tonnes of hydrogen are produced as by-products from oil refinery plants. The strategy, therefore, aims to multiply the current amount of hydrogen tenfold by 2050 (see Figure 6.3).

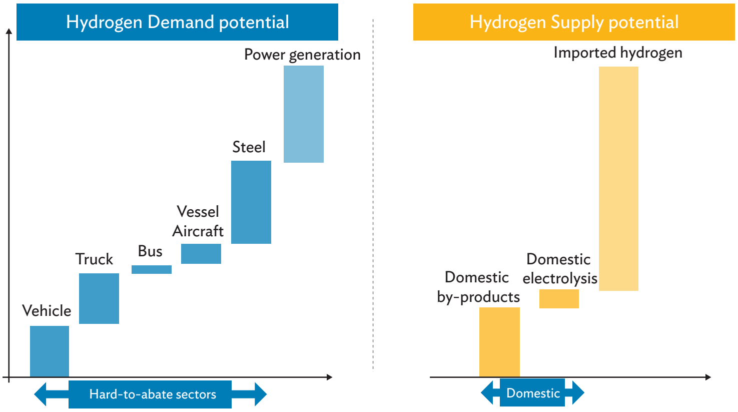
**Figure 6.3: Japan's Estimated Domestic Hydrogen Demand**



Source: Clean Energy Strategy Interim Review (METI 2022, p. 62).

It is also clear from Japan's Clean Energy Strategy that *domestic* hydrogen production will not be at the levels needed to meet demands in 2050 (Figure 6.4). This is partly because the production of hydrogen as a by-product at oil refineries is limited. It is further compounded by the fact that green hydrogen produced from water electrolysis is also insufficient due to the shortage of renewable energy and the high cost of electrolyzers. This shortfall once again underscores the need for Japan to import hydrogen from other countries. Fortunately, some work in this area is already underway. A major hydrogen-related agenda for Japan is to develop a robust hydrogen supply chain (Nakano 2021), with a plan to invest up to 300 billion Japanese yen toward that end (Reuters 2021).

**Figure 6.4: Prospective Hydrogen Demand and Supply Image in 2050**



Source: Discussion toward the realization of 2050 carbon neutral (METI 2020).

Though Japan's relevant policies and strategies increasingly suggest the importance of hydrogen, the support for gray, blue, and green hydrogen is still unclear. For instance, METI's Ideal Energy Policy towards 2030 states: "[I]t is an important approach to expand the hydrogen market by spreading gray hydrogen for the time being, then introduce blue and green hydrogen with technology development and cost reduction" (METI 2021). The report does not state when Japan will switch from gray to blue and green hydrogen or how to procure hydrogen overseas. In other instances, METI appears to back hydrogen and ammonia co-firing by quoting IAEA World Energy Outlook 2019 data showing that in 2040 Asia and the Pacific will still depend on coal in the power sector comprising 40% of 1,820 GW (METI 2022).

Other more general signs of uncertainty include a lack of clarity on how Japan sees the phasing out of coal. On this point, several other countries (CoP UK2021 2021) have committed to the Global Coal to Clean Power Transition Statement at COP 26 in 2021 and to ending coal within the 2040s. Instead, Japan has supported the policy to co-fire coal with ammonia and hydrogen with natural gas for power generation as well as using hydrogen in hard-to-abate industrial sectors.

## 6.4 The Benefits of Transitioning to Green Hydrogen

This section argues that there are significant benefits to be gained from greater clarity about the transition to green hydrogen. Some of these benefits involve stronger alignment with Japan's international decarbonization strategy, while others involve enhanced coherence with local revitalization strategies.

### 6.4.1 Strengthening Energy Security

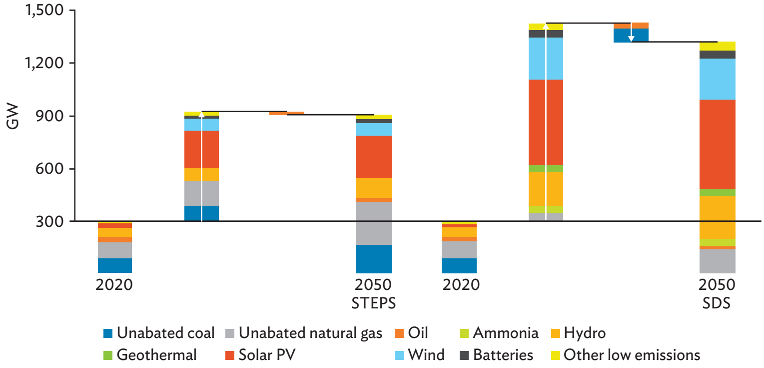
Japan is heavily reliant on imported fossil fuels, such as oil and natural gas, to meet its energy needs. This reliance makes it vulnerable to price fluctuations and supply disruptions, which can have negative impacts on the economy and the welfare of its citizens. By producing its green hydrogen using renewable energy sources, such as solar and wind, Japan can reduce its reliance on imported fossil fuels and increase its energy security. A study by Otsuki and colleagues (Otsuki et al. 2019) found that green hydrogen production using renewable energy sources could provide a stable and reliable source of energy for Japan, particularly in areas with high levels of renewable energy generation. The authors also noted that green hydrogen production could be integrated into Japan's existing energy infrastructure, including the power grid and natural gas network, which could help to increase the flexibility and resilience of the energy system.

### 6.4.2 Alignment with Japan's International Climate Strategy

At COP 26, Prime Minister Kishida pledged up to $10 billion in funds over five years to support Asia's decarbonization (see Figure 5 for an illustration of how technology assistance is being allocated to help achieve net-zero goals in Asia's power sector). For geopolitical reasons, a significant proportion of this assistance will likely flow to Southeast

Asia. Though Southeast Asia relied on renewables for nearly a quarter of its total generation—mostly from hydropower—there is considerable potential to introduce other forms of renewables that would support green hydrogen (IEA 2022b). Figure 5, which showcases of the analysis of IEA compares the electricity capacity between the stated policies scenario (STEPS) and the sustainable development scenario (SDS). In the STEPS, the share of renewables increases until it reaches nearly 40% by 2050. In the SDS (Figure 6.5), renewables would increase to 85%. To achieve a level of 85% by 2050, countries need to add 1,100 GW of renewable capacity in the next 30 years—equivalent to the total renewable capacity of the PRC and India combined (IEA 2022b).

## Figure 6.5: Change in Electricity Capacity in the Stated Policies Scenario and Sustainable Development Scenario, 2020 to 2050

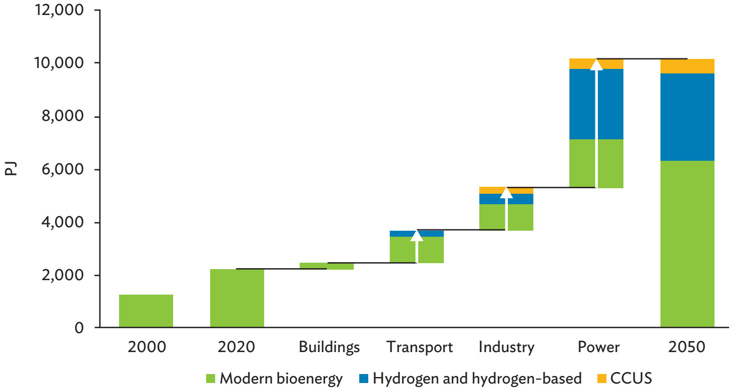


Note: "Other low emissions" includes nuclear, CCUS, and other forms of renewables.

Source: Southeast Asian Energy Outlook 2022 (IEA 2022b).

There is also evidence to suggest that transitions to hydrogen and hydrogen-based fuels such as ammonia could help reorganize the energy structure in Southeast Asia. Figure 6.6 shows the total demand for low-emission fuels in Southeast Asia in the SDS for the period 2000–2050. Brunei has begun exporting small amounts of hydrogen to Japan, while Indonesia, Malaysia, the Philippines, and Thailand are testing the use of green hydrogen. Malaysia and Indonesia are studying the possibility of using ammonia as a fuel in coal power plants with Japan, and both countries are working with Japan to develop hydrogen and ammonia supply chains. Thailand and Singapore are also pursuing similar initiatives. Some major oil and gas companies, including Petronas, Pertamina, and PTT, are planning investments in hydrogen supply chains (IEA 2022b). In the above instances, it would be beneficial for Japan and partner countries to underline the synergies between projected investments in renewables and transitions to green hydrogen.

**Figure 6.6: Total Demand for Low-Emission Fuels in Southeast Asia in the SDS, 2000–2050**



Source: Southeast Asian Energy Outlook 2022 (IEA 2022b).

## 6.4.3 Coherence with Japan's Local Revitalization Strategy

Though hydrogen has been viewed as a potential alternative for the energy demand in heavy industries and freight transport, it also has a role in local revitalization. This is particularly true as green hydrogen development can help achieve many socioeconomic and environmental goals at the local level. For example, the development of new technologies and the creation of new jobs in the hydrogen industry could help to stimulate economic growth and innovation. In addition, Japan has the potential to be a leader in green hydrogen production and can use this position to cooperate with other countries in the region and beyond to accelerate the global transition to clean energy. This could help to create new business and trade opportunities for Japanese companies and boost the country's economy.

The potential to deliver multiple benefits is already on display in some parts of Japan. To illustrate this, a local hydrogen society is gradually being developed in Shikaoi, Hokkaido. Shikaoi is a small town that relies heavily on dairy and upland farming activities. The town produces large amounts of livestock manure, using the excess manure to generate biogas and high-quality organic fertilizer. In 2015, Shikaoi began to develop a biogas-based hydrogen supply chain that produces, stores, transports, supplies, and uses hydrogen. Green hydrogen from this project is used for hydrogen for fueling vehicles. The project is now attempting to reduce emissions in the agriculture sector by powering agriculture vehicles with hydrogen energy. The project is still at the demonstration stage but intends to expand the demand and use of hydrogen in other activities such as dairy farming and vegetable warehousing within the region even after its completion (MoEJ 2019; MoEJ 2021).

Other examples from Japan also suggest the potential for greater coherence with local development plans. For instance, a demonstration project using P2G technology is already underway in Fukushima Prefecture. The project will help address seasonal fluctuations related to grid and adjustment capacity problems (METI 2017).

Beyond the specific case of Shikaoi and Fukushima, there is significant scope to support the promotion of green hydrogen with local revitalization efforts more generally. Japan's most recent Basic Environmental Plan emphasizes the concept of the Circulating and Ecological Sphere (CES). The CES is premised on the notion of integrating climate and biodiversity goals by relying more on local resources and optimizing resource flows between urban and rural areas. The emergence and spread of locally based hydrogen societies could mutually reinforce efforts to give shape and substance to the CES in Japan (OrtizMoya et al. 2021). These efforts could also help to popularize the concepts and their underlying principles in other parts of Asia, strengthening the alignment with Japan's international climate strategy.

## 6.5 Japan's Role in Leading a Hydrogen Economy in Asia

Japan has the potential to lead a pathway towards a hydrogen economy in Asia due to a combination of its advanced technology and competitive manufacturing environment. First, Japan has a strong track record of investing in research and development (R&D) in hydrogen-related technologies, including electrolysis, fuel cell technology, and hydrogen storage. This has enabled the country to develop a range of key technologies that are critical for the production, storage, and use of hydrogen. For example, Japan has developed advanced electrolysis systems that are highly efficient and also developed fuel cell technologies that can convert hydrogen into electricity with high efficiency and low emissions.

Second, Japan has a competitive manufacturing environment that could accelerate the adoption of hydrogen technologies in the region. Japan has a well-developed industrial base and a strong tradition of innovation and technological leadership, which could make it an attractive partner for other countries in the region looking to adopt hydrogen technologies. In addition, Japan's relatively low labor costs and access to a large market could make it an attractive location for the production of hydrogen technologies, which could help to drive down costs and increase the competitiveness of these technologies globally.

Overall, Japan's advanced technology and competitive manufacturing environment position it well to lead the way in the transition to a hydrogen economy in Asia. However, it is important to note that this transition will require the cooperation and collaboration of a wide range of stakeholders, including governments, companies, research institutions, and civil society organizations. By working together, Japan and other countries in the region can accelerate the adoption of hydrogen technologies and contribute to the global effort to combat climate change.

### 6.5.1 Hydrogen Technology and Innovation: Japan's Leading Role in Asia

Innovation in hydrogen energy is driving the development of new technologies and methods for producing, storing, and using hydrogen as a fuel. This includes advancements in electrolysis, fuel cells, and hydrogen storage systems, as well as the development of new hydrogen-powered vehicles. In Asia, Japan has been playing an important role in the research and development aimed at making hydrogen more cost-effective and widely available as a clean energy source.

A recent study conducted by the International Energy Agency (IEA 2023) uses the published International Patent Families (IPFs) as a metric to measure patenting activities in different categories of hydrogen-related technologies. The analysis focuses on the global geography of hydrogen innovation by looking at the locations of applicants and inventors of IPFs for hydrogen-related technologies. Japan has the largest number of IPFs (see Table 6.1) in the hydrogen sector in the world. In the Asian region, though several countries have been shaping ambitious hydrogen development plans, they do not have a notable number of original inventions. Nonetheless, countries like the Republic of Korea and the PRC have been investing strongly in hydrogen technologies.

**Table 6.1: Revealed Technology Advantages in Hydrogen Technologies by Value Chain Segments, 2011–2020**

| | Share of All Hydrogen-Related IPFs | Production | Storage, Distribution, and Transformation | Industrial Applications |
|---|---|---|---|---|
| Japan | 24% | 20% | 22% | 28% |
| US | 20% | 19% | 23% | 19% |
| Germany | 11% | 10% | 14% | 12% |
| Rep. of Korea | 7% | 6% | 5% | 9% |
| France | 6% | 7% | 9% | 4% |
| PRC | 4% | 5% | 3% | 3% |
| Netherlands | 3% | 4% | 2% | 3% |
| UK | 3% | 3% | 2% | 2% |
| Switzerland | 2% | 2% | 1% | 2% |
| Canada | 2% | 2% | 2% | 1% |

Source: (IEA 2023).

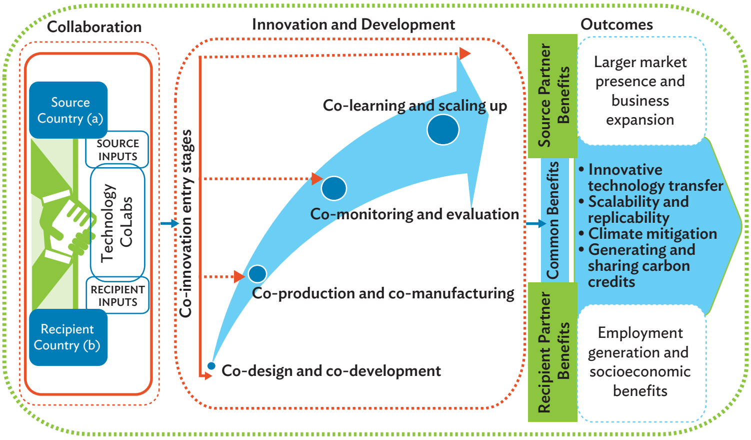
Japanese innovations can help to improve the efficiency and cost-effectiveness of hydrogen production, storage, and distribution, making it more competitive. Collaborating with Asian countries can help accelerate the transformation of Japan's hydrogen innovation into the production, storage, and application of technology in the region in several ways. By working together, Japan and other Asian countries can share their knowledge and expertise in hydrogen technology, leading to faster progress in areas such as hydrogen production and fuel cell development. Such collaborations can allow for more efficient use of resources, such as funding and infrastructure, and help to create economies of scale in the production and distribution of hydrogen. Working with countries like India, which have ambitious hydrogen development plans, can help to standardize and harmonize standards and regulations, which would increase the accessibility for countries to trade hydrogen and hydrogen-related products and services, boost the cooperation and interconnection of hydrogen infrastructure, and accelerate the deployment of hydrogen across Asia.

### 6.5.2 Can Co-Innovation Help Boost Japan's Collaboration with Asian Economies in Developing Hydrogen?

Co-innovation is a collaborative process in which different organizations, such as companies, research institutions, and government agencies, work together to jointly innovate technology, and develop and produce new products and services. This approach can be particularly effective in the field of hydrogen production, as it allows different stakeholders to share knowledge, resources, and expertise in order to accelerate the development and commercialization of hydrogen technologies (Figure 6.7).

There are several ways in which co-innovation can help Japan and other Asian countries to jointly innovate technology, and develop and produce hydrogen. First, co-innovation can facilitate the sharing of knowledge and expertise among different organizations, which can lead to more efficient and effective innovation. For example, companies can collaborate with research institutions to access specialized knowledge and expertise in areas such as electrolysis, fuel cell technology, and hydrogen storage. This can help to speed up the development and commercialization of hydrogen technologies, as well as reducing the costs and risks associated with innovation. Second, co-innovation can allow different organizations to share resources and infrastructure. Third, co-innovation can enable Japanese and other Asian companies to work together to share risks and rewards. Overall, co-innovation can be a powerful tool for Japan and other Asian countries to jointly innovate technology, and develop and produce hydrogen. By fostering collaboration and aligning incentives among different stakeholders, co-innovation can help to accelerate the transition to a hydrogen economy and contribute to the global effort to combat climate change.

**Figure 6.7: Co-innovation Framework**



Source: (Janardhanan et al. 2020; Janardhanan et al. 2021).

## 6.6 Recommendations

The previous sections suggested that there are both considerable barriers and benefits to promoting a transition to green hydrogen for Japan. These include a stronger alignment with international climate strategies and local revitalization plans. At the same time, relevant national hydrogen policies and strategies have remained ambiguous on Japan's commitment to transitioning to green hydrogen. This could result in a lost opportunity for Japan. Several recommendations follow that can help Japan capitalize on this opportunity. The first recommendation is to provide greater clarity in national policies on the intention to support the transition to green hydrogen. This clarity can be demonstrated through the use of more precise language in relevant policy statements, as well as the inclusion of visible milestones that are consistent with timetables for nationally determined contributions (NDCs). In addition, policy statements should place a greater emphasis on transition pathways, rather than just one-off demonstration projects, in order to provide a clearer roadmap for the shift to green hydrogen. It is also important to highlight the climate benefits of green hydrogen in these policy statements and contrast them with the delays that can occur when transitioning to green hydrogen. There is evidence to support the effectiveness of such approaches: For instance, a study by the International Renewable Energy Agency (IRENA) found that clear, long-term policy frameworks and targets are key to increasing the deployment of renewable energy technologies, including hydrogen.

A second recommendation is to strengthen the connections between hydrogen policies and strategies and local revitalization plans. For example, supporting and showcasing successful demonstrations of hydrogen use, like those in Shikaoi town in Japan, can be helpful. Additionally, providing funding to support more demonstrations in areas that are focused on addressing climate change or climate-energy systems (CESs) can be useful. Another suggestion is to offer localities stronger incentives to develop and implement their plans for locally relevant hydrogen societies, to scale up local experiments. Lastly, the national government should strengthen the necessary infrastructure to support the transportation of hydrogen fuels from rural to urban areas.

A third recommendation is to bring the same level of clarity and commitment to green hydrogen in international climate strategies. By expressing the intention to build a sustainable hydrogen supply chain, rather than just any hydrogen supply chain, countries can better align with regional decarbonization plans and encourage partner countries to see the value of strengthening connections between their renewable energy and green hydrogen plans. This can also be achieved by placing a greater emphasis on a mutually beneficial process of co-innovation, rather than one-way technology transfer. Establishing a hydrogen economy in Asia will require a functioning hydrogen market that enables cooperation and trade within the region and beyond. To capture the benefits of leadership in this market, it is essential to adopt a co-innovation process that facilitates and shares the benefits of the transition to green hydrogen.

A fourth recommendation is to allocate a significant portion of the funds pledged by the Japanese Prime Minister, Kishida, during CoP21 (Okutsu 2021), towards supporting the development and deployment of green hydrogen technologies in Asia. This can be achieved through collaboration with local governments and private sectors in the region, including joint research and development projects, technology transfer, and demonstration projects. To maximize the impact of these funds, it is important to prioritize projects that have the potential to scale up and achieve significant emissions reductions in the region. This funding can also be used to support capacity building in the region, such as training programs for policymakers, local engineers, and technicians in green hydrogen technologies, and to support the development of necessary infrastructure for green hydrogen production and transportation.

A fifth recommendation pertains to countries outside Japan. Several countries in developing Asia have been shaping strategies to include hydrogen in their energy mix. Developing countries in Asia would be well advised to reinforce these domestic efforts by establishing agreements for joint research and development, technology transfer, and investment in the hydrogen sector. These agreements could include the exchange of technical knowledge, funding support, and sharing best practices. Additionally, developing countries in Asia can work together with Japan to promote regional cooperation in the hydrogen sector. This could include establishing a regional hydrogen market, sharing infrastructure for hydrogen production and distribution, and coordinating policy approaches to support the deployment of hydrogen technologies. Moreover, developing countries in Asia can collaborate with Japan to develop a joint roadmap for the development of the hydrogen sector in the region. This roadmap could include specific targets, timelines, and actions to promote the deployment of hydrogen technologies and infrastructure.

These efforts can help developing countries in Asia to not only benefit from Japan's advanced technology and expertise in green hydrogen but also to build stronger collaboration in the region for the deployment of hydrogen technologies. The policy takeaway for these countries is the importance of having a clear roadmap for the deployment of hydrogen technologies and infrastructure, establishing strong policy frameworks, and promoting regional cooperation to build a sustainable hydrogen economy. Further, collaborating with advanced countries like Japan can help them leapfrog in the development of green hydrogen technologies and provide access to funding and technical expertise.

## 6.7 Conclusion

The idea of a hydrogen society in Asia is gaining traction in international policy circles and particularly in Japan. The growing interest makes sense for Japan: It is an industrially advanced economy with a strong track record of investing in hydrogen-related research and development, and it has the potential to lead the way in the large-scale commercialization of, and collaboration on, hydrogen in the region. As an industrially advanced economy, it has already invested in hydrogen-related R&D and developed key hydrogen-related technologies (Otsuki et al. 2019; Janardhanan et al. 2021). Japan's advanced technology, combined with the competitive manufacturing environment in developing countries in Asia, could accelerate the transition to a hydrogen society in the region.

However, a lack of clarity about the transition to green hydrogen could hinder efforts to use hydrogen to meet ambitious climate targets. This chapter recommends a set of policies for Japan to consider in its national and regional efforts to promote the use of hydrogen in Asia. While the focus of this chapter is on Japan, many of these recommendations apply to other countries in and outside of Asia. By embracing greater clarity about the transition to green hydrogen, countries have the opportunity to benefit both the planet and its inhabitants.

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# 7

# Toward a Hydrogen Economy in Kazakhstan

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## 7.1 Introduction

Kazakhstan is a major fossil energy exporter. The export of fossil fuels is strategically important–the country's foreign economy. In 2018, the country was the world's ninth-largest coal exporter, ninth-largest crude oil exporter, and 12th-largest natural gas exporter (IEA 2020). The local economy of Kazakhstan also relies heavily on fossil fuel-dominated energy generation and energy-intensive extracting and processing of natural resources (KazEnergy 2015). Nevertheless, Kazakhstan is committed to reducing the climate impacts on its economy.

The transition from fossil fuels to clean energy solutions is on the agenda of the national strategy today. In 2012, the government launched the "Kazakhstan 2050" strategy, which sets the course for long-term economic development. According to the strategy, alternative and "green" energy technologies should generate up to 50% of all energy consumed by 2050. The President of Kazakhstan, Kassym-Jomart Tokayev, sees the decarbonization of the economy as one of the main directions of the national economic course. In December 2020, at the Climate Ambition Summit, President Tokayev announced that Kazakhstan is committed to achieving carbon neutrality by 2060. Earlier, in 2016, Kazakhstan also ratified the Paris Agreement.

Many developed countries of the world are prioritizing the conservation of the environment and exploring options for the transition to a green economy. A promising direction in this joint effort is hydrogen energy. More than 40 countries around the world have developed a hydrogen strategy or roadmap. The United States, Canada, Great Britain, Germany, France, Spain, the Republic of Korea, Chile, the People's Republic of China (PRC), and India developed roadmaps as part of these initiatives (Bruce et al. 2022). Under the "Fit for 55" agreement, the EU countries are aiming for a 55% reduction in net greenhouse gas emissions by 2030. Also, under the agreement terms, the EU expects to produce up to 5.6 million tons of green hydrogen by 2030 (IRENA 2022).

The current decarbonization strategy of Kazakhstan is mainly focused on the widespread development of renewable energy sources (RES) (Strategy 'Kazakhstan 2050'). In the transition to a green economy, hydrogen energy acts as a unique bridge that can facilitate the large-scale usage of RES. Hydrogen will play an important role in balancing intermittent electricity production from RES, electricity demand, and grid stability. Also, hydrogen has the capacity to decarbonize various emissions sectors (industry, transport, energy) in Kazakhstan. For this reason, President Tokayev tasked the government to identify hydrogen energy as one of the priorities and to create a Hydrogen Energy Competence Center at KazMunayGas National Company (national oil company). Since April 2022 the center has been functioning as a research hub that investigates hydrogen energy technologies. The Competence Center conducts research on hydrogen technologies along with domestic universities and research institutes to implement projects on the production, storage, transportation and use of hydrogen, as well as CCUS solutions (KMGE 2022). This work presents the Competence Center's preliminary findings in exploring opportunities for the future hydrogen economy in Kazakhstan.

The topic of hydrogen energy is new not only for Kazakhstan but also for Central Asia. The National Energy Report 2021 from KazEnergy contains a short review of the possibilities of hydrogen energy in Kazakhstan (KazEnergy 2021). Nevertheless, there has been no systematic study covering the potential for a full chain of hydrogen technologies in the Central Asia region. Our work aims to provide the first country-level assessment of hydrogen technologies in Kazakhstan covering various policy, technology, and economy aspects:

(1) Section 7.2 identifies the main drivers, which can affect the adoption of the hydrogen economy in Kazakhstan.
(2) Section 7.3 analyzes opportunities for the hydrogen value chain in Kazakhstan (production, storage, transportation, and utilization) covering various technical and economic aspects.
(3) The final section provides our preliminary conclusions, recommendations, and limitations for the development of a hydrogen economy in Kazakhstan.

## 7.2 Why Does Kazakhstan Need Hydrogen?

A recent review of various national hydrogen strategies reveals different stances adopted by countries on the future hydrogen economy (IEA 2021). Three main reasons are driving different nations to pursue the development of a hydrogen economy: (1) decarbonization, (2) export potential, and (3) energy security. Below we discuss which of these drivers could work in Kazakhstan while establishing a hydrogen economy.

### 7.2.1 Decarbonization in Kazakhstan

Kazakhstan first expressed its interest in regulating GHG emissions in 1999 by signing the Kyoto Agreement. The terms of the Kyoto Agreement laid the foundation for the development of the Kazakhstan Emissions Trading System (ETS), which regulates GHG emissions with market mechanisms such as "cap and trade." The approval of the "Green Economy Concept" in 2013, commitment to achieving the Sustainable Development Goals in 2015, and ratification of the Paris Agreement in 2016 only bolstered the commitment of Kazakhstan to GHG emission reduction by introducing more ambitious goals in this regard (Table 7.1). Both conditional and unconditional targets (328 and 290 Mt $CO_2$ eq.) set by the Paris Agreement have already been exceeded in 2014 and 2016, respectively (Abuov, Seisenbayev, and Lee 2020). The President's recent announcement about the carbon-neutrality goal of Kazakhstan by 2060 requires substantial work to be done on the regulation of each GHG emission sector (UN PAGE 2021).

**Table 7.1: GHG Emission Targets of Kazakhstan**

| Year | GHG Emissions, Mt $CO_2$ eq. | Regulating Document |
|---|---|---|
| 1990 (base year) | 386 | Not regulated |
| 2030 | 328 (unconditional target)<br>290 (conditional target) | Paris Agreement |
| 2060 | 0 | Doctrine of carbon neutrality (not approved yet) |

General approaches to emission reduction were outlined in the Green Economy Concept of 2013, which revealed low efficiency and high GHG emissions in the energy system of Kazakhstan compared to developed countries (Kazakhstan Government 2013). The Concept proposed approaches such as an increase in energy efficiency, modernization of existing power plants, deployment of RES, a decrease in $CO_2$ emissions, and increased use of natural gas (gasification) to establish a green economy. Compared to the last decade, Kazakhstan's energy system has seen some progress by mainly relying on RES deployment and an increased share of gasification. The share of RES reached around 3% in 2020. Gasification of regions reached 53% of the population. The share of gas-fired thermal plants reached 20%, as stated in the Concept of 2013 (KazEnergy 2021).

In the coming decade, Kazakhstan will have to challenge itself to achieve even more ambitious decarbonization goals. Approaches suggested by the Concept of 2013 are not sufficient to reach carbon neutrality given the further increase in energy demand of the country. The decarbonization capacity of RES technologies is limited for so-called "hard-to-abate" sectors (heavy industry and transport) (IEA 2020). The GHG emissions from "hard-to-abate" sectors can be reduced by low-carbon technologies, such as hydrogen and carbon capture utilization and sequestration (CCUS), which are not featured in the Green Economy Concept of 2013. Although the current energy and climate policy of the country does not recognize the importance of hydrogen, the new decarbonization policy of Kazakhstan – the Doctrine of Carbon Neutrality – does. The Doctrine is in the development stage and has not been approved yet. The first draft for public consultation appeared in 2021, covering hydrogen-related decarbonization solutions (UN PAGE 2021). Nevertheless, the country needs a dedicated hydrogen strategy or roadmap to accelerate the transition from a hydrocarbon economy to a hydrogen economy. The hydrogen roadmap should provide confidence to the interested stakeholders along the hydrogen value chain.

### 7.2.2 Carbon Regulation and Hydrogen

Carbon regulation is the policy instrument of decarbonization and it presents a significant driver for the hydrogen economy. Carbon regulation exists in many jurisdictions of the world, and Kazakhstan is not an exception. The hydrogen industry in Kazakhstan can be affected by both internal and foreign carbon regulations.

Internally, carbon emissions in the country are regulated by the Emissions Trading System (ETS), which is Kazakhstan's analog of the EU ETS. The ETS in Kazakhstan was pre-launched in 2013 in the testing mode (Jasyl Damu JSC 2021). The time period between 2013 and 2018 was used to identify and fix regulatory and technical issues, namely a trading mechanism was defined and the Environmental

Code was improved. The ETS was fully launched on 1 January 2018. Sectors involved in the ETS include the power sector, metallurgy, oil and gas, mining, the chemical industry, and production of construction materials (lime, cement, brick, and gypsum production). The National Allocation Plan for 2018–2020 was set with a total quota for GHG emissions of 485,909,138 t $CO_2$ (Ministry of Justice 2017). As for 2018–2020, the ETS covers operators with 225 units with each having more than 20,000 t $CO_2$/year (ICAP 2021). Table 7.2 demonstrates that power generation is the key $CO_2$ emitter, while metallurgy and oil and gas industries are the second and third major emitters, respectively. All three sectors can be decarbonized to some extent by applying hydrogen technologies. A more detailed analysis of hydrogen utilization in each ETS-regulated sector can be found in Section 7.3.3. Currently, $CO_2$ prices in Kazakhstan are low (1.1 USD/t $CO_2$) to drive the implementation of decarbonization technologies including hydrogen (ICAP 2021).

Unlike the internal carbon regulation of Kazakhstan, foreign carbon regulation is strong enough to provide incentives for industries to adopt various decarbonization technologies. For instance, carbon prices in EU ETS reached 80 USD/t $CO_2$ in 2021 (Reuters 2022). Recently, EU members also agreed to launch the Carbon Border Adjustment Mechanism (CBAM) in 2023. The Mechanism is a key aspect of the EU's broader "Fit for 55" package, which aims to reduce 55% of the EU's net greenhouse gas (GHG) emissions by 2030 (EY 2021). The CBAM is directly related to the EU ETS and is its future replacement. After the Mechanism starts working in 2023, a transitional period will last until the end of 2025, during which no carbon tax will be charged. The transitional period will oblige importers to report the carbon footprint of imported products. After 2026, the payment of the carbon footprint will be made by purchasing emission certificates at a price set during a weekly auction. The CBAM industry coverage is limited during the initial stages. Now it covers products from ferrous metallurgy, aluminum, cement, nitrogen fertilizers, and power, which together represent about 5% of EU imports. The CBAM tax will get stronger by adding new products to the list and by increasing carbon prices. The CBAM presents financial risks for Kazakhstan's exporters trading the above-mentioned goods in the EU territory. Metallurgy in Kazakhstan is one of the goods exported to the EU that may start losing part of its revenue due to the CBAM tax from 2026 (LSM.KZ 2021). The utilization of low-carbon hydrogen in Kazakhstan's industries might tackle the negative consequences of the CBAM.

**Table 7.2: Distribution of the CO2 Cap from the National Allocation Plan for 2018–2020**

| Regulated Industry | Number of Units | Quotas for 2018–2020, Tons of $CO_2$ |
|---|---|---|
| Power generation | 94 | 269,954,543 |
| Oil and gas | 67 | 68,564,839 |
| Mining | 24 | 30,642,622 |
| Metallurgy | 20 | 91,153,819 |
| Chemical | 6 | 4,686,201 |
| Production of construction materials | 14 | 20,907,114 |
| Total | 225 | 485,909,138 |

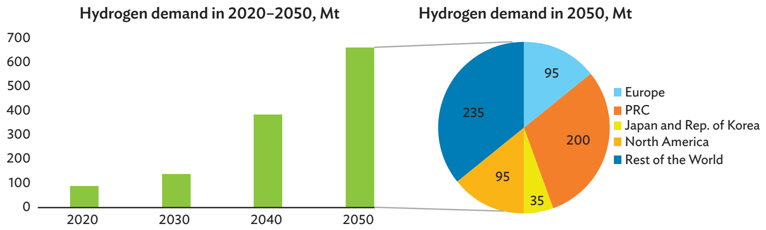
Source: Ministry of Justice 2017.

## 7.2.3 Hydrogen as an Export Commodity

A review of the current hydrogen market and projection of future demand was published in a recent study by the Hydrogen Council and McKinsey (2021a). In 2020, 90 Mt of hydrogen was produced mainly from natural gas followed by coal and by-products. The hydrogen market will reach 660 Mt in 2050. Some 45% of the market is represented by the PRC and Europe, which are expected to consume 200 Mt and 95 Mt of hydrogen, respectively (Figure 7.1). More and more giga-scale hydrogen projects have been announced in the world recently, but their capacity is unable to fulfill the demand for hydrogen that is essential for reaching the net-zero goal. In this regard, Kazakhstan's unique location between the two largest hydrogen markets of the PRC and the EU can be a key factor for the further development of the hydrogen industry with a priority for low-carbon hydrogen (green/blue) to succeed even in markets with strong carbon regulation.

Another driver for hydrogen industry development is energy security. The instability of the gas and oil market caused by the geopolitical situation has prioritized energy security over the energy transition. For instance, Germany has recently adopted an emergency law that allows the launching of coal-fired plants to fulfill the electricity demand until March 2024 (Robertson 2022). For energy-importing countries, hydrogen can be a new energy source with diversified local production and import options. In the case of Kazakhstan, its vast amount of renewable and fossil fuel resources indicates that the country can meet local energy consumption for a long period. Currently, hydrogen does not have a big role in the energy security strategy of the country. Kazakhstan can help other countries to address their energy security concerns by exporting both traditional and alternative energy sources like blue/green hydrogen.

**Figure 7.1: Hydrogen Demand in 2020–2050**



Source: Hydrogen Council and McKinsey 2021b.

# 7.3 Establishing A Hydrogen Value Chain In Kazakhstan

## 7.3.1 Low-Carbon Hydrogen Production

The following subsections discuss the availability of fossil fuel resources and renewable power supply for blue hydrogen and green hydrogen production, respectively. We also explore carbon intensity, water footprint, and cost aspects of low-carbon hydrogen production technologies in Kazakhstan. A summary of our analysis is provided in Table 7.3.

### Blue Hydrogen

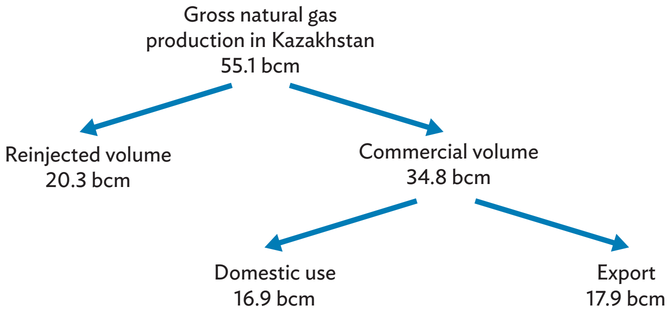
***Blue hydrogen from natural gas or associated petroleum gas (APG)***

The main feedstock resources for blue hydrogen are natural gas, associated petroleum gas (APG), and coal. Syngas obtained from steam methane reforming (SMR)/ autothermal reforming (ATR) of natural gas or coal gasification can produce syngas, which contains hydrogen and CO. Further processing in water-gas shift reactions results in $CO_2$ emissions. The $CO_2$ from syngas processing should be captured and stored for hydrogen to be considered blue.

Kazakhstan positions itself as an energy exporter with huge natural gas, oil, and coal reserves. According to BP 2021, Kazakhstan holds the 16th-largest hydrocarbon gas reserves in the world, which represents 1.2% of global reserves with the vast majority being located in the western part of the country and few gas fields located in the southern part (KazEnergy 2021). Nevertheless, the country might have difficulties in having available feedstock natural gas for large-scale blue hydrogen production.

Gross gas production in the country reached 55.1 bcm in 2020, with 34.8 bcm and 20.3 bcm being commercial and reinjected volume, respectively (Figure 7.2). Commercial volume was used domestically and exported to other countries. The country sees natural gas as an opportunity to decrease the carbon intensity of its economy, thus Kazakhstan has been gradually increasing domestic gas consumption since 1999 and has already started to face shortages. Recently the government announced its plan to divert 2 bcm of the export volume into the domestic gas market (Reuters 2022). Exported volume also cannot be considered for blue hydrogen production with current gas prices, since returns from selling gas are probably higher than from converting it into hydrogen and selling it (Isidore 2022).

**Figure 7.2: Natural Gas Production in Kazakhstan (2020)**



Source: KazEnergy 2021.

Reinjected volume (20.3 bcm) is tightly used mainly for the reinjection needs of the three largest hydrogen reservoirs, namely Karachaganak, Tengiz, and Kashagan, which produced 79% of Kazakhstan’s commercial natural gas in 2020 (KazEnergy 2021). Each of the three fields has production plans for the next several decades to increase or maintain oil production, thus reinjected gas volume cannot be used if they cannot be replaced with some other gas. One option would be to add new SMR units to the existing gas processing facilities of three large oil fields to obtain syngas from natural gas and APG. Syngas should be later processed into hydrogen and $CO_2$ streams. $CO_2$ used in enhanced oil recovery (EOR) could effectively replace the currently reinjected gas if captured in sufficient volume. The blue hydrogen project with a similar concept is operated by Air Products in Port Arthur, Texas. Smaller oil and gas fields can also consider blue hydrogen production if they use the cluster approach by sharing gas processing facilities and gas pipelines. In general, the following blue hydrogen production options for Kazakhstan should be studied in detail:

- Blue hydrogen production potential from the three largest reservoirs (replacing reinjected gas with $CO_2$ emitted from $H_2$ production)
- Cluster option for smaller oil fields to process their APG in shared infrastructure (sharing gas processing facility)
- Integrate utilization of emitted $CO_2$ with enhanced oil production (EOR) and chemical complexes (urea, methanol production, beverage industry, etc).

### *Blue hydrogen from coal*

The gasification of coal with subsequent $CO_2$ capture can result in blue hydrogen. Kazakhstan is considered the tenth-largest coal resource holder in the world with 29.4 billion tons across 49 deposits, with major reserves being located in the north and central parts of Kazakhstan (Karagandy, Ekibastuz, and Turgay coal basins). Energy consumed in Kazakhstan was primarily generated by coal and accounted for 56% in 2020 (KazEnergy 2021). IHS Markit estimates that domestic coal demand will decrease by 2030 and 2040 to 51% and 42%, respectively (KazEnergy 2021). The dropping share of coal stems from the development of gasification infrastructure across the country, as the country plans to decrease the carbon intensity of its economy by using natural gas. Nevertheless, coal will remain an affordable and indispensable fuel in Kazakhstan for the next several decades.

GHG emissions from traditional combustion technologies are responsible for 171.63 million tons of $CO_2$ eq., which represents ~59% of GHG emissions in energy and industry (Andrew 2021). The gasification of coal to obtain hydrogen gas from syngas with subsequent capture of $CO_2$ can provide a clean energy solution for both energy and industry uses. Commercial coal gasification facilities operate in the US, the PRC, and Australia (CoalAge 2021). Coal gasification technology in Kazakhstan has not reached the commercial stage and remains in the R&D stage with several projects related to fixed-bed, plasma, and underground coal gasification (Tokmurzin et al. 2019; Messerle, Ustimenko, Lavrichshev 2021; Martemyanov et al. 2021).

Unlike natural gas, coal in Kazakhstan has no resource shortage problem. Blue hydrogen production will not compete with current coal use, and thus coal could provide feedstock for the longer term. A problem may arise with subsequent utilization and storage of $CO_2$ during blue hydrogen production. Identified $CO_2$ storage and potential utilization areas are located in the western part of Kazakhstan, while the geography of coal reserves is mainly central and northern parts of the country (Abuov, Seisenbayev, and Lee 2020). Without nearby $CO_2$ storage and utilization, the cost of $CO_2$ transportation can provide a serious hurdle for coal gasification in Kazakhstan. Thus, $CO_2$ storage and utilization options need to be explored in nearby geological formations and industries (North and Central Kazakhstan).

## Green Hydrogen

Hydrogen production from electrolyzers can be classified as green only if the electricity comes from renewable energy sources (RES). According to the new Environmental Code (2021) of Kazakhstan, solar, wind, hydro, biomass, and waste energy are classified as RES (Table 7.2). Kazakhstan has been gradually increasing the share of RES in the country's energy mix. The share of wind and solar power has reached 1.47 GW (6.2%) out of 23.6 GW of the total installed capacity in the country (KazEnergy 2021). The government plans to increase RES capacity to 4.5 GW by 2028 (Ministry of Energy 2022). According to the Green Economy Concept of 2013, power generation by RES is planned to reach 50% of the total power output by 2050. Nevertheless, we expect that existing and near-future RES capacity will be in tight use due to the power shortage in the country (south region), thus existing and near-future RES capacity is insufficient for large-scale green hydrogen production. But with the planned 50% power generation from RES in 2050, the risk of mismatch between generated and consumed electricity grows. Due to the volatile nature of RES power generation, some part of generated power will be surplus or "lost." In the longer term, green hydrogen production developers can benefit from excess RES power during power surplus seasons of the year, although surplus power will not be stable enough throughout the year to sustain the continuous operation of electrolyzers (IEA 2017). In the near term, it makes more sense to focus on the unrealized RES potential of Kazakhstan by building an off-grid renewable energy supply for electrolyzers.

Generally, the southern part of the country has an advantage over the northern for both solar and wind project potential for future RES projects. Currently, the majority of RES projects are based in southern Kazakhstan. Recently, German-Swedish company Svevind signed an MoU with Kazakhstan's government to build a green hydrogen production facility in the Mangystau region, which will be powered by wind and solar energy with a combined output of 45 GW (Energy Connects 2021). The project is in the Pre-FEED stage today. If approved, the construction of wind and solar farms with a capacity of 45 GW will be commissioned between 2030 and 2032. Ultimately, 2 million ton/year of green hydrogen will be produced. However, as the electrolysis relies on the water to extract hydrogen, local challenges (especially in the Caspian Sea) with water supply should be strictly considered (Box 7.1). More details on the water footprint of hydrogen production are covered in Section 3.1.3. Another issue would be the proper management of brine resulting from large-scale desalination of water. Disposing effluent brine back to the water body might have negative consequences for the marine environment.

### Table 7.3: RES Plants in Kazakhstan

| # | Type of Renewable Energy Source | Number of Plants |
|---|---|---|
| 1 | Hydro | 47 |
| 2 | Solar | 45 |
| 3 | Wind | 29 |
| 4 | Biogas | 1 |

Source: Ministry of Energy RoK 2022.

### Box 7.1: Unlocking Green Hydrogen Potential in Central Asia

**Investing in Green Hydrogen Projects in Central Asia**

Financing renewable energy and green hydrogen production are vital for accelerating green hydrogen development in Central Asia. In 2022–2023, we have witnessed agreements on two joint mega projects for the development of renewables, especially wind and solar, and green hydrogen production using this renewable energy in Kazakhstan and Uzbekistan.

1. In 2022, Svevind, a Swedish-German renewable energy firm, signed a $50 billion deal with the Government of Kazakhstan for 20 gigawatt (GW) green hydrogen production in West Kazakhstan by 2030 (Dezem 2022; Astana Times 2022, 2023) named "Hyrasia One". Kazakhstan could become one of the world's largest suppliers of green hydrogen (Official Information Source of the Prime Minister of the Republic of Kazakhstan, 2022; Astana Times, 2022)

*continued on next page*

**Box 7.1** *continued*

2. In 2022, ACWA Power, a Saudi Arabian company, signed a $10 billion 5-year investment agreement with the Ministry of Energy of Uzbekistan for the development of large-scale green hydrogen production (ACWA Power 2023).

### Table: Green Hydrogen Signed Agreements in Central Asia

| | Kazakhstan "Hyrasia One" | Uzbekistan |
|---|---|---|
| Deal amount | $50 billion | $10 billion |
| Capacity (GW) | 20 GW | 1.5 GW |
| Capacity (MT) | 2 MT | 0.12 MT |
| Renewable energy capacity | 40 GW solar and wind | 100 MW wind |
| Company name and country | Svevind (European Union) | ACWA Power (Saudi Arabia) |
| Signed year | 2022 | 2023 |
| Agreement with | Government of Kazakhstan | Ministry of Energy and Ministry of Investment, Industry and Trade |

Source: Authors using ACWA Power (2023) and Astana Times (2022, 2023).

**What Can Be Done to Further Accelerate Green Hydrogen Development?**

In the production phase, the high production cost is the major hindering factor for the application of green hydrogen. Cost reduction could be achieved by reducing the cost of renewable energy and improving electrolyzer technologies. The latter could be achieved through innovation, performance improvements, and upscaling to large (multi-gigawatt) scale projects (IRENA 2020). The cost of green hydrogen is expected to significantly decrease by 2030–2050 due to the cost reduction of renewables. Only then it is expected that green hydrogen will become cost-competitive with fossil fuel-based hydrogen (blue or gray). For more detailed recommendations for cost reduction see IRENA (2020).

Cross-border, especially long-distance, transport of green hydrogen is a major obstacle for land-locked countries. As transportation by sea is cheaper than by land, the region can leverage existing gas pipelines for pure hydrogen or hydrogen mixed with natural gas. The region should strategically explore transportation methods and cost-effectively expand infrastructure to unlock its potential as global green hydrogen suppliers. Active involvement with international dialogue and agreements on taxonomy and the certification of green hydrogen are also vital to secure external demand for green hydrogen within the robust global value chains (Kodama et al., forthcoming).

*continued on next page*

**Box 7.1** *continued*

As hydrogen transportation is challenged by its low volumetric energy density, it is also important for governments to facilitate the export of energy-intensive "green products," such as steel produced using green hydrogen. This entails decarbonizing hard-to-abate sectors in the region and beyond.

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Source: This box was authored by Dina Azhgaliyeva (senior research fellow, Asian Development Bank Institute) and Sumika Hori (master's student at the Graduate School of Public Policy, The University of Tokyo).

From a renewable power supply perspective, future developers of green hydrogen production projects should consider the following:

- Near-term green hydrogen production projects should rely on a dedicated power supply, as current RES capacity is tightly used to cover local electricity demand.
- In the longer term, when the RES share reaches 50%, power surplus might be available for green hydrogen production during seasonal peak power generation by RES.

## Carbon Intensity, Water Footprint, and Cost of Low-Carbon Hydrogen Production

Carbon intensity is the main trading feature of hydrogen in the energy transition era. The carbon intensity of natural gas-based and coal-based blue hydrogen is around 9 kg $CO_2$ eq/kg $H_2$ and 20 kg $CO_2$ eq/kg $H_2$, respectively (Table 7.4). Applying CCUS technology with a 90% capture rate can bring down numbers to 1 kg $CO_2$ eq./kg $H_2$ and 2 kg $CO_2$ eq./kg $H_2$ for natural gas-based and coal-based blue hydrogen, respectively (IEA 2020). However, data provided by IEA represent the global average and these numbers cannot exactly describe the carbon intensity of blue hydrogen in Kazakhstan. Two factors drive GHG emissions of natural gas-based blue hydrogen: (1) the carbon intensity of natural gas (especially methane emissions), and (2) the $CO_2$ capture rate (Bauer et al. 2022). Kazakhstan has one of the lowest flaring rates from APG (1.2%) in the world, thus it can have an even lower low-carbon intensity of blue hydrogen than the global estimate of IEA (KazEnergy 2021). The carbon intensity of green hydrogen depends on the source of electricity feeding electrolyzers. As long as the power source is renewable (wind, solar, etc.), green hydrogen has no GHG emissions.

Water is another important resource in hydrogen production. A recent study shows that green hydrogen production requires about 9 liters of water to produce 1 kg of hydrogen. In the case of the PEM electrolyzer, this number goes up to 18 kg per kg of hydrogen (Table 7.4). The water footprint of the natural gas-based hydrogen process varies between 13 kg and 18 kg of water per kg of hydrogen. The highest water footprint with 40–85 kg water/kg hydrogen belongs to low-carbon hydrogen obtained from coal gasification (Hydrogen Council 2021). Kazakhstan has eight water basins, seven of which lie in transboundary territories. Some 45% of annually renewable resources of surface water come from the territory of neighboring countries (Senate 2019). Given the impending challenge of water scarcity in the country, careful analysis of water balance must be carried out by clearly outlining how much water would be consumed by each sector. Developing hydrogen energy in the country should not prioritize energy transition at the cost of water security.

Currently, the cheapest hydrogen production pathway is gray with USD1–1.9/kg $H_2$ (IEA 2020). Adding CCUS unit to SMR and coal gasification results in blue hydrogen cost ranges of USD1.4–2.4 and 2.0–2.2/kg $H_2$, respectively (Table 7.4). The cost driver of natural gas-based blue hydrogen is the cost of natural gas feedstock. Having one of the lowest prices of natural gas globally, Kazakhstan could have one of the lowest costs for blue hydrogen production. The coal-based blue hydrogen cost is mostly driven by Capex and Opex. The $CO_2$ capture rate has a substantial impact on both types of blue hydrogen, with high capture rates resulting in high production costs. The cost of green hydrogen production is the highest, ranging between USD2.5 and 6.6/t $H_2$. The main cost drivers for green hydrogen are electricity cost, load factor, electrolyzer efficiency, and Capex with the latter being the main driver. Decreasing the Capex of green hydrogen in the longer term requires establishing local manufacturing of low-carbon technology involved in the supply chain of green hydrogen production (electrolyzers, wind turbines, solar panels, etc.). Lastly, high carbon prices in the future can increase the competitiveness of both blue and green hydrogen types significantly.

**Table 7.4: Gray, Blue, and Green Hydrogen Production**

| Hydrogen Color | Gray Hydrogen | | Blue Hydrogen | | Green Hydrogen |
|---|---|---|---|---|---|
| Production technology | SMR | Coal gasification | SMR | Coal gasification | Water electrolysis |
| Resources estimate for Kazakhstan | Tight natural gas supply, but resource base can be expanded | Abundant coal resources | Tight natural gas supply, but resource base can be expanded | Abundant coal resources | Abundant renewable energy resources, but installed RES capacity is limited |
| Carbon intensity (kg CO2 eq/kg H2)** | 9 | 20 | 1 | 2 | 0 |
| Water footprint (kg water/kg H2)*** | 14–17 | 41–86 | 13–17 | 41–86 | 9–18 |
| Production cost (USD/kg H2)* | 1.0–1.9 | 1.6–1.8 | 1.4–2.4 | 2.0–2.2 | 2.5–6.6 |

Notes: * Global estimate from IEA 2020.
** Hydrogen Council 2020.

## 7.3.2 Hydrogen Storage and Transportation

Since hydrogen is considered one of the main instruments for hitting the goals of decarbonization, it will be massively used in the different sectors of the economy. Hydrogen can be transported in different phases (gas, liquid, and solid). Operating conditions such as temperature, pressure, gravimetric capacity, etc. form the cost of hydrogen storage and transportation. It was suggested that the most cost-effective option for hydrogen distribution will be a pipeline system for distances below 1,500 km. For longer distances, shipping is the most efficient alternative way (IEA 2019). However, shipping hydrogen is not applicable in Kazakhstan today as the country is in a different position with limited access to the sea/ocean but with sufficient facilities to connect Europe and Asia via continental territory.

Technical and related economic parameters of hydrogen storage and transportation were discussed for different phases such as liquid, gaseous, and solid (Table 7.5 and Table 7.6). The study first looks at using existing pipelines to blend hydrogen with natural gas. This is followed by a discussion on hydrogen storage and delivery in liquid form. Finally, it examines the application of metal hydrides to store and distribute hydrogen.

### Hydrogen Storage and Transportation in Gaseous Form

Currently, hydrogen is stored in liquefied and compressed forms, which are mostly used on sites. Hydrogen storage in gaseous form is suitable for small-scale storage where gaseous hydrogen is achieved by compressing it up to 350–700 bar (Table 7.5). Hydrogen distribution via pipelines is a well-known practice. The length of existing hydrogen pipelines is around 5,000 km where hydrogen is mostly utilized as a chemical feedstock (IEA 2019, 2021). Repurposing existing natural gas pipelines into a pure hydrogen network needs proper engineering solutions (Cerniauskas 2020). Existing pipelines can accommodate around 1% of hydrogen and natural gas mix without engineering modifications. Many countries have limited amounts of hydrogen injection in natural gas networks for safety reasons. Currently, there are several pilot projects and studies developing pipeline systems for blending (Wu et al. 2022).

The annual report of the NC “QazaqGaz” (previous name NC “KazTransGaz”) for 2020 states that the total length of the natural gas pipelines is more than 20,000 kilometers, with a piping capacity of 227.9 bln.m$^3$ per annum (Annual report 2020). In the last decade, due to intensive gasification, around 53% of the population has been able to use natural gas in their home. However, the country is facing low investment in the oil and gas industry today, which could lead to a decrease in the volume of natural gas in the future. To increase a resource base, hydrogen could be blended with natural gas and delivered by the existing pipeline system. Pipelines are likely to be a cost-effective option not only for local hydrogen distribution but also for exports for distances of less than 5,000 km as there is an increase in the cost of engineering services (Table 7.6). Overall, the blending of hydrogen with natural gas could be considered a transitional step toward the deployment of hydrogen energy and broadening a resource base for the country. The pipelined distribution of hydrogen could also boost the demand in the hydrogen market.

## Hydrogen Storage and Transportation in Liquid Form

Hydrogen in the liquid phase can be achieved at temperatures below −253°C by reducing its volume by 800 times compared with gaseous hydrogen (Table 7.5). Liquid hydrogen is transported in super-insulated, cryogenic tankers or trucks for longer distances (Ren et al. 2017). Currently available technologies for liquid hydrogen storage and transportation have several drawbacks, including the need to maintain cryogenic conditions resulting in high energy consumption of more than 30% of the energy content of the hydrogen (Dagdougui et al. 2018). Another issue with liquid hydrogen is boil-off (Aziz, Oda, and Kashiwagi 2018). Issues of liquid hydrogen transportation can be handled by incorporating hydrogen into large molecules such as liquid organic hydrogen carriers (LOHCs) and ammonia. LOHCs include methylcyclohexane (MCH) and toluene (Chiyoda corporation). It is suggested that over long distances, hydrogen transportation such as LOHCs and ammonia presents cost-effective solutions, especially overseas (IEA 2019).

As Kazakhstan is a landlocked country, sea and river shipping are not a widespread type of transportation. The marine transport industry is represented on the Caspian Sea by the ports of Aktau, Kuryk, and Bautino. Transit shipping in the Caspian Sea includes routes from Aktau to Baku (475 km), Turkmenbashi (550 km) and Bandar Anzeli (700 km) (Table 7.6) (Overview CAREC Program 2021). Currently, shipping on the Trans-Caspian International Transport Route (TITR), known as the Middle Corridor, has increased by 41% (MIID 2022). Nevertheless, the transport capacity of Kazakhstan ports is limited currently. Also, hydrogen transport via the Caspian Sea does not reach target export destinations directly but only transit countries such as Azerbaijan, the Russian Federation, and Iran. Further, it needs to be transported via terrestrial transportation modes such as pipeline, railway, or truck.

## Table 7.5: Hydrogen Storage Methods

| Phase | Gas | Liquid | | | Solid | | |
|---|---|---|---|---|---|---|---|
| Storage type | Gaseous hydrogen | Liquid hydrogen | Ammonia | LOHC (MCH) | Intermetallic hydrides | Complex hydrides | Porous materials |
| Method | Compressed | Cryogenic | Chemical | Chemical | Chemical | Chemical | Chemical |
| Gravimetric capacity*, wt % | 13 | 100 | 17.8 | 6.16 | 0.91–3.3 | 2.96–18.5 | < 20 |
| Volumetric capacity*, (kg-H2/m³) | < 40 | 70.8 | 121 | 47 | 150 | 147 | < 20 |
| Temperature, °C | r.t. | –253 | 25 | 240 | r.t. | > 100 | varies |
| Pressure, bar | 350–700 | 1 | 10 | 10 | 1 | 1 | 100 |
| Advantages | • Good fit for small-scale applications | • High volumetric and gravimetric capacity | • Cheap<br>• Existing technology | • No cooling<br>• Existing technology | • High volumetric capacity<br>• Safe<br>• Reversible | • High volumetric capacity | • Reversible<br>• Fast cycle life |
| Disadvantages | • Low volumetric capacity<br>• High pressures | • Energy-intensive<br>• Boil-off risk | • Toxic<br>• Requires conversion | • Desorption at high temperature<br>• Requires conversion | • Low gravimetric capacity | • Low gravimetric capacity<br>• Low reversibility | • Clustering problem<br>• Weak interaction with hydrogen |

Note: * Zuttel (2003), Ley et al. 2014; Niaz, Manzoor, and Pandith (2015); Bellosta von Colbe et al. (2019); Aziz, Oda, and Kashiwagi (2018).

### Hydrogen Storage and Transportation in Solid Form

Hydrogen can also be incorporated into solid-phase materials such as metal hydrides, complex hydrides, and porous materials. Hydrogen adsorbed in metal alloys can offer a safe and high volumetric storage capacity under standard conditions. Nowadays, this method of storage and transportation is in its demonstration stage and is used by several companies (Bellosta von Colbe et al. 2019). The practical application of metal hydrides requires a good kinetic rate of hydrogen adsorption/desorption and higher gravimetric capacity. Despite having relatively low gravimetric capacity, hydrides can achieve a high volumetric capacity of hydrogen storage with up to 150 kg $H_2/m^3$ (Table 7.5). Carrying high-mass and low-volume cargo is particularly suitable for railway transportation.

There has been a study suggesting hydrogen storage and transportation by Ti-based alloys in Kazakhstan via railway (Zholdayakova et al. 2020). This study shows that Kazakhstan has reserves of titanium, chrome, manganese, and iron ores that could be used to develop new hydrogen storage alloys at a much more affordable price. Unlike shipping, railway transportation is prevalent and much more affordable for landlocked countries (Table 7.6). Kazakhstan has become the most important partner in the “One Belt, One Road” program to connect Europe and Asia, which promises an expansion in the railway transportation capacity of the country. Developing optimum metal hydride technology can enable large-scale transportation of hydrogen from Kazakhstan to the largest hydrogen markets such as the EU and the PRC.

**Table 7.6: Hydrogen Transportation in Kazakhstan**

| Transportation Type | Distance, km | Cost*, USD/kg$H_2$ | Phase |
|---|---|---|---|
| Pipelines | 1000–5000 | 0.6–3.3 | Gas |
| Railways | 500–5000 | Not evaluated | Gas, liquid, and solid |
| Trucking | < 1000 | 0.2–3.3** | Gas, liquid, and solid |
| Shipping | 500–1000 | < 2.2 | Liquid |

Notes: * Costs include conversion and moving costs (based on Figures 28 and 29 in IEA 2019).
** The cost of tracking does not include hydrogen distribution in the solid phase.

## 7.3.3 Hydrogen Utilization

Hydrogen can decarbonize many emission sectors, however current hydrogen utilization costs cannot compete with the costs of conventional carbon-intensive technologies. The role of carbon regulation is vital in making hydrogen technologies attractive to investors. Thus, we have categorized hydrogen utilization in the context of ETS in Kazakhstan. The average of regulated emissions in 2018–2020 constitutes around 43% of the total GHG emissions in the country in 2019 (KazEnergy 2021). In the subsections below, we have categorized each emission sector as existing, near-term, or long-term hydrogen utilization sectors. Target hydrogen utilization areas and decarbonization effects were identified in each sector (Table 7.7). The decarbonization effect implies the extent of the expected carbon emissions reduction in a particular hydrogen utilization area.

## Existing Hydrogen Utilization Areas

Currently, gray hydrogen is utilized in regulated oil and gas and chemical sectors, which are responsible for 5.2% and 0.5% of the total GHG emissions in the country. Two refineries and one ammonia plant in Kazakhstan produce gray hydrogen from natural gas via the SMR process and utilize it in their own technological processes (hydrocracking in the refineries, feedstock for the "Haber-Bosch" process in the ammonia plant). From a decarbonization perspective, an obvious step would be adding $CO_2$ capture units to obtain blue hydrogen in the SMR units of the refineries and the ammonia plant. The decarbonization effects of blue hydrogen use in refineries and ammonia will be different due to the different shares of SMR emissions in the total GHG emissions of the two facility types. Some 30–40 % of cradle-to-plant-gate GHG emissions in the ammonia plant come from the carbon intensity of the feedstock, which is mainly natural gas used for hydrogen production (Hydrogen Council and McKinsey 2021a). Thus, opting for low-carbon hydrogen can result in a significant reduction of GHG emissions in the ammonia plant. In a typical refinery, the SMR unit is responsible for around 11% of GHG emissions; thus, using blue or green hydrogen in refineries will not significantly reduce the carbon footprint of refinery products (Sunny et al. 2022). Nevertheless, refineries and ammonia plants are the first targets for low-carbon hydrogen utilization in Kazakhstan, as they are already utilizing hydrogen. While switching to low-carbon hydrogen utilization in refineries and ammonia plants, it is necessary to dispose of or utilize emitted $CO_2$. $CO_2$ could be directed to nearby oil fields experiencing a decline in pressure ($CO_2$-EOR). Another option is integration with future petrochemical and chemical complexes (methanol production, urea production, beverage industry, etc.).

## Near-Term Hydrogen Utilization Areas

Regulated GHG emissions from metallurgy are responsible for 8% of the total GHG emissions in Kazakhstan. The decarbonization of the iron and steel sector can be achieved by switching away from coal to electricity or natural gas, especially by using an electric arc furnace (EAF) to purify metal scraps or direct reduced iron (DRI) into steel (IEA 2021). EAF steel has 14 times less carbon intensity than steel obtained from an integrated blast furnace (BF) and basic oxygen furnace (BOF), which mainly rely on coal combustion (Hydrogen Council and McKinsey 2021b). Feedstock for an EAF can be metal scraps or direct reduced iron (DRI). The reduction of iron oxides into metallic iron for DRI can be achieved by using hydrogen as a reductant gas. A 100% hydrogen-based steel production for full decarbonization would be difficult for the industry, but injecting 25% hydrogen can partially decarbonize the steel sector without major modifications in steel plants (IEA 2018). Kazakhstan produces steel from both BOF and EAF processes. Metallurgy products will be first subjected to the CBAM from 2026 if exported to Europe (EY 2022). Utilizing hydrogen for the manufacturing of DRI-EAF steel may help to avoid high carbon taxes incurred by the CBAM.

## Long-term Utilization Areas

Around 25.7% of GHG emissions in Kazakhstan belong to the ETS-regulated power and heat sectors. GHG emissions in the power and heat sector are dominated by coal, which produced 56% of the energy consumed in Kazakhstan as of 2020 (KazEnergy 2021). Currently, the government plans to reduce GHG emissions in this sector by increasing the share of natural gas in the energy mix of the country. Replacing coal with natural gas can result in twice fewer GHG emissions. The carbon intensity of heat and power would be further reduced by blending hydrogen with natural gas in the longer term. Hydrogen blend does not require significant infrastructure upgrades and can be operated under safe blending limits. Current natural gas pipeline networks could cope with a 10% hydrogen blend, but the capacity of end users to consume hydrogen blend is rather limited. Current gas turbines would handle a 1% blend, which could be increased to 5–15 % after some modifications (IEA 2017). The IEA (2018) estimated that a 20% hydrogen blend in the European natural gas network would reduce GHG emissions by 7% (Table 7.7). The hydrogen blend would also alleviate the impending issues of the natural gas deficit in Kazakhstan.

Using electricity power to obtain hydrogen and converting hydrogen back to power would result in low efficiency. However, hydrogen is interesting in storing excess energy that may result during peak power generation of RES. Unlike fossil fuels, RES power fluctuates according to the season, weather conditions, and rotation of the Earth. As the share of RES in the energy mix increases, the risk of mismatch between generated and consumed power will increase as well. According to the Green Economy Concept of Kazakhstan, the RES electricity generation will reach 50% in 2050 (Kazakhstan Government 2013). A 50% share of

RES can worsen the existing problem of the Kazakhstan power system's balancing and stability. The country has a shortage of flexible capacity (KazEnergy 2021). Hydrogen can provide flexibility to Kazakhstan's electricity grid by storing excess RES energy for a seasonal period. This would provide a long-term balance between energy production and consumption.

GHG emissions from the transport sector are not regulated by the ETS and they represent 7% of emissions in Kazakhstan (Forbes 2021). Around 80% of transport emissions belong to vehicles, which are mostly represented by cars over ten years old running on diesel. Diesel engines are also responsible for the low air quality in many of Kazakhstan's cities (OECD 2017). Existing decarbonization solutions for the transport sector include fuel cell electric vehicles (FCEVs) and battery electric

## Table 7.7: Hydrogen Utilization Perspectives in GHG Emission-Regulated Sectors

| Regulated Sectors | Emissions Share*, % | Target Hydrogen Utilization Area | Decarbonization Effect from Hydrogen Utilization | Perspectives in Kazakhstan |
|---|---|---|---|---|
| Metallurgy | 8 | • Direct reduction in iron production | Major | Near-term |
| Construction materials | 1.9 | • Heating in cement kilns | – | Unknown |
| Chemicals | 0.5 | • Ammonia production<br>• Heating and drying | Major | Existing (gray hydrogen) |
| Mining | 2 | • Tracks on fuel cells | – | Unknown |
| Power and heat | 25.7 | • Seasonal power storage<br>• Residential and industrial heating | Minor | Long-term |
| Oil and gas | 5.2 | • Oil refining (Hydrotreating) | Minor | Existing (gray hydrogen) |
| Nonregulated GHG emissions | 56.7 | • Transport (FCEVs, hydrogen stations) | Major | Long-term |

Note: * The share of regulated sectors in 2019 was calculated using the average of emission values from 2018 to 2020.

vehicles (BEVs). FCEVs run on hydrogen. The competitiveness of FCEVs increases over long-range distances. Thus, demand for hydrogen will be mainly from medium-range vehicles, transit buses, medium-duty trucks, heavy-duty trucks, cargo vans, and shuttle buses (Global Commercial Drive to Zero Program 2022). Hydrogen utilization in the transport sector of Kazakhstan is possible only after establishing hydrogen infrastructure (hydrogen station), which might be a reality in longer-term perspectives.

## 7.4 Conclusion

Decarbonizing the part of Kazakhstan's emission sectors with hydrogen is the priority for the longer term. Hydrogen should not bring another "Dutch disease" to the country's economy by becoming the only export material after the decades of hydrocarbon economy. But it should bring a competitive advantage to goods produced from various economic sectors of Kazakhstan by decreasing their carbon footprint. Achieving decarbonization in Kazakhstan with hydrogen requires more financial and time resources, as it involves the development of all elements in the chain of the hydrogen industry: production, storage and transportation, and utilization. The financial burdens of establishing a local hydrogen economy could be alleviated by firstly focusing on the export of low-carbon hydrogen in the near future. The focus should be later diverted towards the development of a local hydrogen utilization economy once the country starts to accumulate revenues and knowledge from hydrogen export.

While looking at policy aspects and the full technology chain of the hydrogen economy, we came to the following preliminary conclusions for Kazakhstan:

- Hydrogen is essential for achieving the carbon-neutrality goal of Kazakhstan. The role of hydrogen should be clearly defined in the long-term energy and decarbonization strategy of the country. The hydrogen strategy should provide confidence that there will be a marketplace for low-carbon hydrogen and relevant technologies (Section 7.2.1).
- Foreign carbon regulation (especially the CBAM) may force Kazakhstan's exporters to adopt various decarbonization technologies, including hydrogen, to increase the competitiveness of products by lowering carbon intensity. The same effect can be expected from the ETS in Kazakhstan when it will get stronger in the future (Section 7.2.2).
- Kazakhstan's unique location between the two largest hydrogen markets – the EU and the PRC – presents an opportunity

to develop hydrogen export with a priority for low-carbon hydrogen (green/blue) to succeed even under strong carbon regulation (Section 7.2.3).

- Our preliminary analysis indicated that blue hydrogen in Kazakhstan may have lower carbon intensity and lower cost than the global average, especially in the three largest hydrocarbon reservoirs of the country. Potential exists for green hydrogen production as well, but a high Capex is still expected. In both cases, the effects of hydrogen export on the water security of the country need to be considered (Section 7.3.1).
- Hydrogen transport and storage infrastructure for exports should be developed in the near future. For a landlocked country like Kazakhstan, nearby hydrogen markets are available via pipeline and railways. Trucks could be considered for the transport of hydrogen within the country. The financial burdens of infrastructure development for hydrogen export could be shared between interested stakeholders (green and blue hydrogen developers, transit countries, and hydrogen importers) (Section 7.3.2).
- Demand for hydrogen should be stimulated at a local scale to launch the hydrogen economy in Kazakhstan. Near-term utilization areas for low-carbon hydrogen in Kazakhstan should focus on existing industrial clusters (ammonia plants, refineries, and iron/steel factories). Long-term utilization areas are energy storage in the power sector, residential heating, and transportation (Section 7.3.3).

There are three limitations to the deployment of hydrogen energy in Kazakhstan:

- R&D investment is needed to decrease technology costs and to build local capacity. Potential hydrogen research areas for Kazakhstan include hydrogen production from H2S, water electrolysis technologies, storage and transportation of hydrogen in metal hydrides, fuel cells, and hydrogen-based fuel blends.
- Appropriate regulations should be approved at country level to establish clear rules for stakeholders. Regulations should cover both technical standards and investment policy. For first movers, mitigation measures for investment risks should be provided and unnecessary regulatory barriers should be eliminated.
- Further studies on the economic, environmental, and social impacts of the hydrogen value chain in Kazakhstan should be carried out.

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# 8

# Green Hydrogen International Market: Barriers and Prospects for South and Southeast Asia

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## 8.1 Introduction

Reducing carbon emissions through decarbonization strategies is critical for mitigating the impending climate crisis. Decarbonization encompasses a broad range of methods, but for the purpose of this discussion, we focus on two primary strategies. The first strategy aims to reduce greenhouse gas emissions, primarily those resulting from fossil fuel combustion. This can be achieved using renewable energy sources like wind, solar, and hydroelectricity. However, it is important to note that carbon emissions originate from a variety of processes, not just fossil fuel combustion. Industrial processes, such as cement production also emit carbon dioxide ($CO_2$), and agriculture and livestock farming contribute significantly to methane emissions. The second strategy involves mitigating the impact of emissions already present in the atmosphere, typically through carbon capture and sequestration. In the context of these strategies, green hydrogen—hydrogen produced using renewable energy—can contribute significantly to the first goal of reducing emissions. This is because its production and combustion do not directly result in greenhouse gas emissions. However, it is essential to consider the complete lifecycle emissions of green hydrogen production, including the emissions associated with manufacturing and decommissioning the necessary infrastructure, to fully understand its potential for decarbonization.

Furthermore, green hydrogen's transportability and storability make it a viable alternative fuel source in specific sectors of transport and heavy industry where electrification is challenging. This includes sectors like long-haul shipping, aviation, and steel production, where other green energy sources—such as solar and wind—may not be as effective due to their intermittent nature and the energy intensity of these industries. Countries aspiring to achieve net-zero $CO_2$ emissions have begun developing national hydrogen strategies. These strategies primarily focus on methods to produce green hydrogen, aiming to reduce production costs and identify effective ways to utilize it. Despite advancements in green hydrogen policies, the inability to meet forecasted demand has broadened the policy discussion to include international production and trading of green hydrogen. IRENA estimates that by 2050, over 30% of hydrogen will be traded across borders, a percentage higher than the current trade of natural gas (Tsafos 2018; IRENA 2022). The emerging global networks for hydrogen trading—with international sales of hydrogen expected to generate $600 billion by 2050—will change the current geopolitical status of the international energy market (IRENA 2022). Consequently, the economic-political leverage dynamics of hydrogen-exporting countries will be transformed (Anouti et al. 2020). For these reasons, this chapter discusses barriers and prospects for entering the green hydrogen international market for countries in South and Southeast Asia, specifically India, Malaysia, Thailand, the Philippines, Viet Nam, Brunei Darussalam, and Indonesia. The focus on this region is justified by its substantial availability of renewable resources, among other factors, such as water resources and market potential, which can facilitate and lower the cost of green hydrogen production if harnessed effectively.

Despite prospects granted by geography, climate, and other factors in this region, the lack of policy for green hydrogen production in the countries reviewed in this paper presents a barrier to entering the international market when it becomes viable. Global market viability is predicted by IRENA (2022) to occur in 2027–2030, but bilateral, country-to-country green hydrogen trade may occur sooner, depending on the goals and timelines set by importing countries in their national green hydrogen roadmaps. For instance, as Wang, Yan, and Shang point out in Chapter 3 of this book, Japan's policy plans to establish international supply chains of green hydrogen starting in 2025. The market's viability and consideration of trading plans held by countries with a comprehensive green hydrogen strategy allow this study to ascertain obstacles to be overcome and the time constraints upon doing so. Additionally, comparison countries enable the identification of key policy features that must be included in green hydrogen strategies for them to be beneficial in the international green hydrogen market.

**Table 8.1: Countries Reviewed**

| Country | Presence of Green Hydrogen Policy (as of August 2023) |
|---|---|
| India | Yes |
| Malaysia | No |
| Thailand | No |
| Philippines | No |
| Viet Nam | No |
| Brunei Darussalam | No |
| Indonesia | No |

Source: Authors.

**Table 8.2: Countries of Comparison**

| Country | Presence of Green Hydrogen Policy |
|---|---|
| United States | Yes (EPACT, 2005) |
| People's Republic of China | Yes (14th Five Year Plan, 2022) |
| Japan | Yes (Vision 2050, 2020) |
| Republic of Korea | Yes (Hydrogen Economy Roadmap, 2022) |
| European Union | Yes (Hydrogen Strategy, 2020) |
| Singapore | Yes (National Hydrogen Strategy, 2022) |

Sources: Authors; US Department of Energy (2022); Nakano (2022); Clifford Chance (2022); IEA (2020); European Commission (2022); Seah (2022).

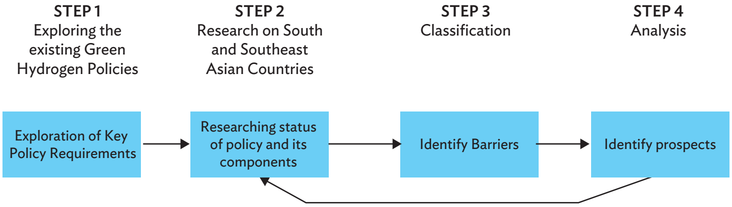
## 8.2 Methodology

This chapter explores the current green hydrogen scenario for countries in South and Southeast Asia (Table 8.1) through a step-by-step procedure that develops a policy framework to evaluate barriers and prospects to entering the green hydrogen market. The framework requires a policy to include demand projections, production plans (including harnessing green energy and R&D investments), infrastructure plans, and utilization. This policy framework understanding is also shared by Janardhanan et al. in Chapter 6 of this book. Figure 8.1 graphically represents the framework and methodology used in this chapter. Based on the framework, the paper then performs a Qualitative Comparative Analysis (QCA) between variables present in national green hydrogen policy in reference countries (Table 8.2) and policies in the countries reviewed (Table 8.1). This is used in Section 8.2 to understand the status quo of countries in South and Southeast Asia. Further, this chapter uses a color-coding framework to understand and compare the scenarios between the countries reviewed (Tables 8.4, 8.6, and 8.7) regarding the respective barriers and prospects.

The research then seeks to expand policy discussion to the international realm by bridging gaps in the literature regarding the global green hydrogen value chain, taking a look at the complementary sectors required to produce green hydrogen (Figure 8.2). Figure 8.2 shows the complementary sectors of electronics manufacturing and harnessing of natural resources necessary to assemble the stack and the Balance of Plant (BoP) of electrolyzers, which are crucial for the production of green hydrogen. In addition, Figure 8.2 highlights the end-use complementary sectors of transport, heavy industry, and fertilizers, as the efficient use of them aids production of green hydrogen by reducing its cost through increased demand.

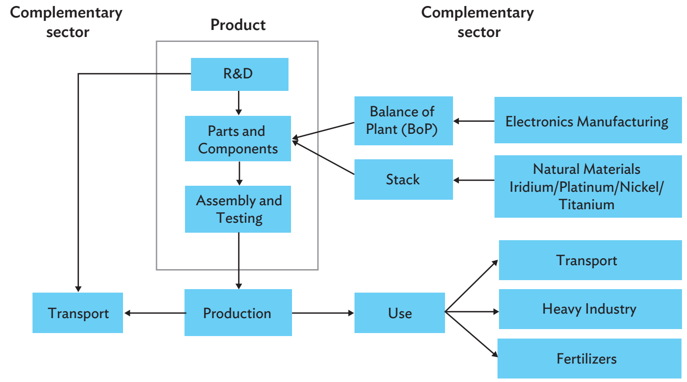
On the basis of the complementary sectors identified in Figure 8.2 and additional sector-specific literature, Figure 8.3 shows the connections between national policy requirements for effective green hydrogen policy and international profit. Figure 8.3 highlights in bright green the three methods for benefiting from these connections: trading of green hydrogen, trading of manufacturing components required to produce green hydrogen, and trading of intellectual property in the form of patents regarding green hydrogen technology. Considering the causal relationship between aspects shown by the arrows in Figure 8.3, it is possible to notice the dependence of the latter two methods on national policy for green hydrogen, while the export of manufacturing components is independent from it. Applying the model to the countries reviewed, three barriers are identified: policy, infrastructural, and legal. These barriers will be discussed in turn, respectively, in Sections 8.3, 8.4, and 8.5 of the chapter. In contrast, the export of manufacturing components is revealed to be a prospect for the countries reviewed to profit from the international green hydrogen market.

**Figure 8.1: Methodology**



Source: Authors.

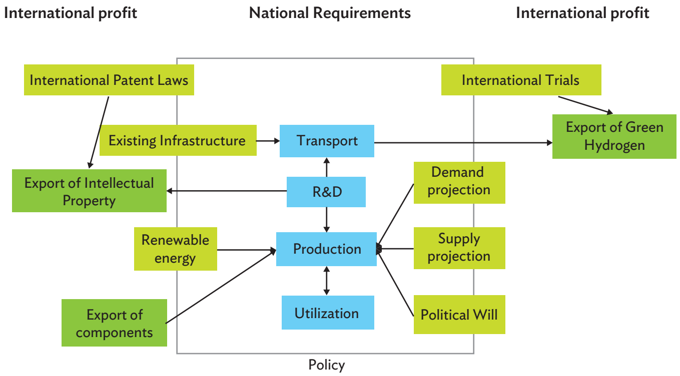
## Figure 8.2: International Global Value Chain of Green Hydrogen



Source: Authors.

The pathways and elements of the model that allow for benefitting from the international green hydrogen market are closely interlinked with each other. Barriers in the form of a lack of complete policy limit the country's capacity to develop patents and build infrastructure. Given the high cost, political will, and time required to develop feasible green hydrogen strategies, the chapter also looks at alternative paths to mitigate the limitations imposed by such barriers.

## Figure 8.3: Cause-Consequence Flow Chart



Source: Authors.

## 8.3 Barriers to Green Hydrogen Production and Trade in South and Southeast Asia

Green hydrogen production and trade is an intricate process, given technical and economic complexities. For these reasons, countries need policy plans or roadmaps outlining goals and means of production to produce green hydrogen. As of 2022, 18 countries and the European Union (EU) have national hydrogen strategies (IRENA 2022). The countries in Asia and the Pacific are the People's Republic of China (PRC), Japan, the Republic of Korea, Singapore, Australia, and New Zealand. Of these countries, the PRC, Japan, and the Republic of Korea have a long-standing history of hydrogen policy in the form of blue hydrogen (IRENA 2022). The lack of a complete green hydrogen policy—understood per the framework described in Section 8.2—is a barrier to production and, by proxy, to the export of the green hydrogen chain in the countries reviewed in this chapter. However, except for India and the PRC, the countries reviewed in this chapter still lack a national green hydrogen policy. Only India has published an explicit strategy for green hydrogen, albeit incomplete. (Based on the publicly available policy information in the English language as of October 2022).

Research and development are the most crucial steps for relatively new technology to become feasible and thus pace up to become efficient and cost-effective. Regarding the use of green hydrogen, R&D along with existing renewable energy infrastructure are posed to become ground factors. The choice of these factors is also given their relative independence to hydrogen policy, meaning they can exist in national plans despite lacking a green hydrogen policy. Sections 8.3.1 and 8.3.2 observe the extent of research and development and renewable energy infrastructure for policy development to determine obstacles to overcome in the short term at the policy level. Section 8.3.3 delves deeper into the green hydrogen policy of India as a novel case in South and Southeast Asia.

### 8.3.1 Insufficient Research and Development

Evaluating the current investment in R&D in the countries reviewed reveals a diverse landscape for green hydrogen policy. Singapore, for example, has committed $170 million to research related to green hydrogen production in the region. While this is the highest absolute investment among the countries discussed, it only equates to 0.05% of the country's total GDP. This comparison illustrates that investment is not only about the total amount but also about the proportion of national resources committed. In comparison, the Republic of Korea has pledged to invest 0.6% of its national GDP, amounting to around $13 billion, in green hydrogen research. This commitment, as a proportion of GDP, is significantly higher than Singapore's, reflecting the Republic of Korea's strategic decision to prioritize green hydrogen in its national energy strategy. However, it is important to recognize that each country has unique resources, capabilities, and strategic interests. Therefore, a "one-size-fits-all" approach to investment may not be appropriate. For instance, Singapore has less land and fewer natural resources compared to other countries, which may justify a lower level of investment in green hydrogen. Determining a "reasonable" or "sufficient" level of investment is complex and varies by country. It depends on a range of factors, including the country's renewable energy potential, water availability, technological capabilities, market demand, and strategic objectives. Therefore, while comparison can be informative, each country needs to evaluate its own circumstances and set investment levels that will best achieve its specific green hydrogen goals.

Regarding the other countries in the region, Brunei Darussalam and the Philippines invest respectively 0.1% and 0.138% of their total GDP into R&D. However, it is unclear what fraction of that is reserved for green hydrogen production given the lack of national policy on the matter (Aditiya and Aziz 2021). More hopeful is Thailand's 1.33% in R&D investment (World Bank Data 2022).

It must be noted that national R&D investment in the upcoming years may not be as essential for becoming a player in the international green hydrogen market as it has been. Opportunities for bilateral research and production offer the capacity to produce in countries in South and Southeast Asia despite the lack of inclusion of R&D in policy plans. An example of this is Brunei Darussalam's previous export partnership with Japan's Advanced Hydrogen Energy Chain Association for Technology Development (AHEAD), funded by New Energy and Industrial Technology Development (NEDO) (Aditiya and Aziz 2021). The PRC provides additional examples to this point. Examples of collaboration include PEM electrolysis technology developed by Sinopec in partnership with Cummins in a 50/50 joint venture, which will see factories built in the Chinese regions of Foshan and Guangdong. Similarly, Norway's HydrogenPro is collaborating with Tianjin HQY Hydrogen Machinery to develop electrolyzer production of 300 MW in Tianjin to export hydrogen internationally (Brown and Grünberg 2022). This demonstrates a path for South and Southeast Asian countries interested in achieving technological capacity without significant R&D investment, relying instead on technological transfers. The number of foreign firms working in the PRC is so high that IRENA (2022) warns countries not to overly focus on the PRC's low manufacturing cost and lose a competitive edge in the long run for hydrogen products. However, it must be noted that the other requirements of a hydrogen policy and renewable energy availability remain necessary foundations for production, as a lack of them might negatively affect foreign firms' decision to collaborate with certain countries. For instance, the PRC likely sees many foreign hydrogen companies deciding to work in the country thanks to the low cost of renewable energy and manufacturing, given the PRC's long-lasting and complete hydrogen policy.

For these reasons, joint ventures provide an alternative to high R&D investment but do not preclude the need to develop roadmaps for green hydrogen production, particularly regarding renewable energy. A sustainable and alluring strategy to harness renewable energy in these countries can become a prospect for participation in the green hydrogen international market through trading and a method to overcome the barrier of low R&D investment.

## 8.3.2 Lack of Renewable Energy Infrastructure

Renewable energy is required to power the electrolysis process for hydrogen to be green. Countries in South and Southeast Asia have high renewable energy potential. Indonesia has a renewable energy potential of 332 GW, Viet Nam has a 311 GW potential, Malaysia has over 280 GW, and Brunei Darussalam has 3.6 GW of solar energy potential alone (Sustainable Energy Development Authority Malaysia (SEDA) 2022; Rasjid and Siregar 2022).

However, the potential for renewable energy and green hydrogen in each country is not uniformly reflected in policy goals. Table 8.3 displays the current energy capacity and respective targets for upcoming years in countries across South and Southeast Asia. When compared with the Republic of Korea and Japan, which aim to have around 40% of all energy produced by renewable sources (REN21 2019), most countries analyzed in this chapter, with the exceptions of India and the Philippines, have set relatively modest goals in terms of renewable energy share. For example, Brunei Darussalam, despite its potential as an exporter of green hydrogen (given its current hydrogen exports to Japan), has not set a robust renewable energy policy. It aims to have only 10% of its energy share coming from renewable sources by 2035 (United Nations Climate Change 2022). Thailand, Viet Nam, Malaysia, and Indonesia's targets exceed those of Brunei Darussalam's, yet they are still below the 40% renewable energy share planned by Japan and the Republic of Korea for 2035, and currently lack specific green hydrogen plans (REN21 2019). It is important to note, however, that a universal renewable energy target may not be feasible or desirable due to the varying renewable energy resources and economic conditions of each country. For instance, Thailand's lower renewable energy target may be due to cost considerations, effects on externalities, and investment constraints. Nevertheless, a low share of renewable energy in the energy mix may challenge these countries' ability to meet both internal energy demands and the demands of green hydrogen production. Additionally, lower shares could lead to higher renewable energy production costs, potentially decreasing these countries' appeal as green hydrogen production hubs. Yet, it is essential to remember that the market of green hydrogen will likely be dominated by the players who have the best renewable energy resources and conditions, rather than simply those with the most ambitious targets.

On the other hand, given India′s current 24% renewable energy share, if the annual growth rate of the renewable energy sector has been consistently high and is projected to continue, this could support the assertion that the target of a 40% renewable energy share is realistic. (Table 8.3) (REN21 2019). Similarly, the Philippines's Renewable Energy roadmap, aiming to have a 50% renewable-based capacity by 2030, is promising, as such a large share can ensure a low cost of renewable electricity (REN21 2019). India and the Philippines can sustain internal green hydrogen production if adequate policy is provided and may open prospects for bilateral collaboration on green hydrogen. However, in the short term, these goals do not suffice to compete with countries that aim to be green hydrogen exporters. According to Lee and Yep (2023), countries that will lead in hydrogen export—namely Australia, the US, and Spain—have goals of 80% of the energy mix being composed of renewable energy by 2030.

Moving further, Table 8.4 represents the extent to which countries in South and Southeast Asia have overcome or tackled the barriers identified in this section. The countries coded in red are still far from overcoming these barriers, while yellow countries are on the way or show promise to overcoming them. On the other hand, countries coded in green have already significantly overcome the mentioned barriers.

## Table 8.3: Renewable Energy Outlook

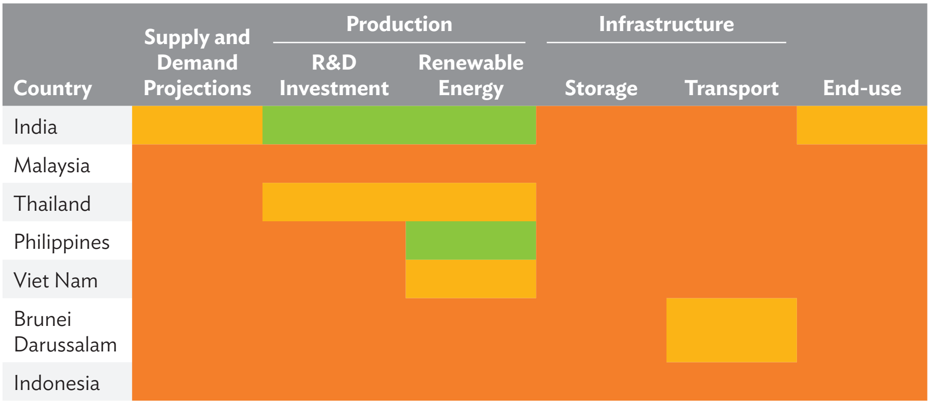
| Country | 2022 Energy Capacity | | | Energy Projection and Targets for 2030–2035 | | |
|---|---|---|---|---|---|---|
| | Total, GW | Renewable, GW | Renewable, % | Total, GW | Renewable, GW | Renewable, % |
| India | 420 GW | 100 GW | 24% | 1,175 GW | 450 GW | 40% by 2030 |
| Malaysia | 117.6 GW | 7.6 GW | 7.2% | 108.4 GW | 18.4 GW | 17% by 2030 |
| Thailand | 60.6 GW | 9 GW | 14.9% | 62.2 GW | 18.6 GW | 30% by 2037 |
| Philippines | 29.9 GW | 5.4GW | 22% | 30.6 GW | 15.3 GW | 50% by 2030 |
| Viet Nam | 76 GW | 20 GW | 26% | 146 GW | 46 GW | 31.5% by 2030 |
| Brunei Darussalam | 889 MW | 0.45 MW | 0.05% | n/a | n/a | 10% by 2035 |
| Indonesia | 64.4 GW | 9.6 GW | 13% | 83.7 GW | 25 GW | 23% by 2025 |

Notes: Figures in the table reflect the most commonly found figures across different sources, although some inconsistencies were found. It must also be noted that for specific countries, the total energy capacity is less in the projected column than in the current column. This can be explained by plans to increase energy efficiency as part of net-zero goals. Furthermore, it is essential to note that some of the figures are extrapolated based on known values provided by the readings. In addition, the current data column contains values from different years for different countries. Check the list below to see which year.

While this might diminish the reliability of specific numbers, this table provides a general understanding of energy goals in the countries reviewed in this paper, providing helpful comparative information for policymakers, given the unavailability of official resources with a table containing all values.

Sources: Authors; Enerdata (2019); Yeap (2022); International Trade Administration (2022); Tractus (2022); Shani (2019), Tachev (2022); Esser et al. (2021).

## Table 8.4: Extent of Overcoming Barriers



| Country | Supply and Demand Projections | Production | | Infrastructure | | End-use |
|---|---|---|---|---|---|---|
| | | R&D Investment | Renewable Energy | Storage | Transport | |
| India | 🟨 | 🟩 | 🟩 | 🟧 | 🟧 | 🟨 |
| Malaysia | 🟧 | 🟧 | 🟧 | 🟧 | 🟧 | 🟧 |
| Thailand | 🟧 | 🟨 | 🟨 | 🟧 | 🟧 | 🟧 |
| Philippines | 🟧 | 🟧 | 🟩 | 🟧 | 🟧 | 🟧 |
| Viet Nam | 🟧 | 🟧 | 🟨 | 🟧 | 🟧 | 🟧 |
| Brunei Darussalam | 🟧 | 🟧 | 🟧 | 🟧 | 🟨 | 🟧 |
| Indonesia | 🟧 | 🟧 | 🟧 | 🟧 | 🟧 | 🟧 |

🟧 Barrier not overcome 🟨 Barrier partially overcome 🟩 Barrier significantly overcome

Source: Authors.

### 8.3.3 Case Study on Barriers: Green Hydrogen Policy in India

India offers the possibility to evaluate green hydrogen policy among the selected countries. This exercise is helpful for the scope of the chapter as it applies the model for a complete green hydrogen policy to a country demonstrating the political will to produce green hydrogen. In other words, the review of India's green hydrogen policy allows us to observe barriers in a vacuum without consideration of political and economic barriers. The Indian Ministry of Power announced in February 2022 India's intention to produce green hydrogen, considered essential to meet the country's goal of achieving net zero emissions by 2070. India aims to produce 5 million tons of green hydrogen annually by 2030 and has a 20 GW electrolyzer demand (Cummins 2021). Depending on at what point the production target is achieved in the following 8 years, it might suffice to meet the national demand of 11 million tons and have a surplus for exports (Sachan et al. 2022). Despite this, the country lacks official accounts for the figures used above, rendering an estimation of how much exports and profit the country will be able to make difficult.[1] The absence of official demand and production forecasting, a critical factor for an efficient green hydrogen policy, is one of several areas where India's policy could improve.

India's plan includes incentives in the form of long-term (25 year) waiver of inter-state transmission charges and open access for sourcing renewable energy. In addition, it facilitates transport through shipping ports and access to websites for permits. It also discusses the production of green ammonia, which, according to a June 2022 report by NITI Aayog (a think tank of the Government of India), can be a further avenue for exports in the future. However, the policy is not complete as it lacks consideration of all possible routes for production incentives, such as reductions of goods and services taxes (GSTs) and transmission and distribution (T&D) charges, which can reduce the cost of hydrogen from the current \$7/kg to \$3.2/kg, making green hydrogen competitive with gray hydrogen (Raj et al. 2022). In a best-case scenario where these additional considerations are taken, the cost of hydrogen can fall to \$1.60/kg by 2030 and \$0.70/kg by 2050, making the country's price competitive (Raj et al. 2022).

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[1] It must be noted that in January 2023 the Government of India published additional information regarding their green hydrogen strategy in a paper named "National Green Hydrogen Mission", available at: https://mnre.gov.in/img/documents/uploads/file_f-1673581748609.pdf. The conclusions and criticisms discussed in this section refer to the information available as of October 2022, given the most recent document was not available at the time of writing.

Regarding infrastructure, natural storage rock caverns need to be further explored, and the use of pipelines for transportation must be studied. Pipelines become a cost-effective trade method only when daily exports exceed 10,000 tons (Raj et al. 2022). In addition, India's existing pipeline system needs to be improved to supply the country or export to neighboring nations. Like in the case of Spain and other EU countries, LNG import terminals can be repurposed for exports, but a study of safety and feasibility is warranted in addition to addressing safety concerns regarding hydrogen embrittlement of steel, both lacking from current hydrogen policy roadmaps (Raj et al. 2022).

Regarding end use or utilization, the language is absent from official Indian government documents on green hydrogen policy. The report by NITI Aayog proposes the end use to be refineries and fertilizers, which would be suitable and require less research than the Republic of Korea's transport sector application. To obtain small-scale application and utilization, the Indian government should encourage states to launch pilot projects, replicating how the PRC's provinces lead innovation in the hydrogen sector, resulting in bottom-up policymaking and implementation (Raj et al. 2022). Thus, this process can reduce the administrative burden on the central government, which can instead be redirected toward export avenues.

India should also increase investment to $1 billion in R&D development by 2030 to research different aspects of the R&D value chain. To meet electrolyzer targets and the associated renewable energy needed to provide it with electricity, more than $250 billion will be required (Raj et al. 2022). In India's 2022 GDP, the investment of electrolyzers needed equals 7% of the national GDP. This is a very ambitious investment. For comparison, the Republic of Korea's New Green Deal is expected to invest 0.6% of the national GDP (around $13 billion) into green hydrogen R&D (United Kingdom Department for International Trade 2021). However, the Republic of Korea has a long-standing history of hydrogen investment and production (although in the context of blue hydrogen). Thus, it requires less investment for value chain aspects, such as transportation and utilization.

Table 8.5 summarizes the key policy features of India's green hydrogen policy. Although the publicly available information lacks some crucial policy components, it can be attributed to the fact that the policy is very recent. Given high renewable energy potential, R&D investment capacity, and the political will of India, it must consider a comprehensive hydrogen policy to prepare for entry into the international green hydrogen market, which is expected to take off in 2035 (IRENA 2022). In addition to including all framework elements of green hydrogen policy, the discussion of timelines and the incremental use of green hydrogen in different industries allows for better ascertaining feasibility. India must first surpass these policy shortcomings to become a hydrogen exporter. Still, its case offers inspiration for other countries in the region as it elucidates the required steps to take to produce hydrogen.

Table 8.5: India Green Hydrogen Evaluation—Summary of Findings

| Key Policy Feature | India's Green Hydrogen Policy |
|---|---|
| Demand and supply projections | Excluded from the policy |
| Production | Green energy policy—present<br>R&D—included<br>Political will—present |
| Infrastructure | Storage—excluded<br>Transportation—excluded |
| End-use | Absent from the policy |

Note: This table is based on the information available as of October 2022, given the most recent document was not available at the time of writing.

Source: Authors.

## 8.4 Infrastructural Barriers

The current infrastructure in South and Southeast Asia, both intra-regionally and with potential green hydrogen importers, is currently not robust enough to support the envisioned trade in green hydrogen. This issue is not just about infrastructural challenges related to the storage and production of green hydrogen, which are closely tied to the lack of comprehensive policy on this subject, but also about the specific transport infrastructure needed for green hydrogen. When discussing infrastructure for green hydrogen, we are primarily referring to pipelines capable of transporting hydrogen gas. This is distinct from oil or natural gas pipelines, as hydrogen gas has unique properties that can cause issues like embrittlement in pipelines that are not designed for it. Pipelines are a common method of oil and natural gas transport in regions like central Asia and Europe, but such infrastructure is less developed in the South and Southeast Asia region. For instance, only 16% of the world's hydrogen pipelines traverse the Asia and the Pacific region (Hussein 2021). Currently, India has natural gas pipeline network connections to Pakistan and Bangladesh, and there are plans for Thailand, Myanmar, Malaysia, and Singapore to be interconnected. Indonesia has established oil and gas connections with Singapore and Brunei Darussalam (Mohammed Hussein 2021). In contrast, countries in the EU have already developed extensive networks of oil and natural gas pipelines, and the PRC has also launched several ambitious projects to build hydrogen infrastructure. Both regions have recognized the potential of hydrogen as a green energy source and have incorporated it into their long-term energy strategies. Considering the existing natural gas and pipeline infrastructure and policy landscape, the Indonesia-Singapore-Brunei Darussalam connection appears promising for Indonesian exports, assuming the government develops a comprehensive green hydrogen strategy. Given the lack of extensive gas pipeline connections and the need to consider potential import partners in the region, such as Japan and the Republic of Korea, exploring alternative transportation methods, like shipping, is necessary.

Hydrogen can be transported through sea routes in three forms: liquid organic hydrogen carrier (LOHC), cryogenic LH, and NH3 (Roos 2021). Conversion, storage, and transportation costs must be considered when choosing which method to use to transport hydrogen. Cryogenic liquid hydrogen (LH2) has a high energy density. However, it is more expensive to generate given its low boiling point of -253°C and requires large amounts of energy for compression and cooling, making its CAPEX value—total expenses invested—higher than the other two methods (Roos 2021). It is also more expensive to transport. LOHC is cheap to store and transport given it is stable at ambient temperature and atmospheric pressure. This means that it is even more affordable than NH3, but its shipping costs are higher than NH3 since 0.1% of the LOHC degrades every time it is converted. Due to its high weight, more fuel is needed to ship it (Roos 2021). NH3 is attractive both for the low cost of transportation and because re-transformation upon arrival is unnecessary. Solid NH3 can be used for fuel cells, which countries planning to import hydrogen invest highly in as a utilization method (Roos 2021). These alternatives allow countries lacking pipeline connections or safety assessments of pipelines to transport hydrogen across borders. To do so, however, pilot projects should be performed to assess feasibility, such as the Japan-Australia Hydrogen Energy Supply Chain (HESC) Project, the first instance of hydrogen being transported over the ocean. Other cross-continental hydrogen exports (blue hydrogen) include US exports to Japan, the Republic of Korea, Germany, and the PRC (OEC World 2023). In summary, considering potential green hydrogen importers and the lack of pipeline infrastructure in the region, sea transportation of green hydrogen is the most viable option for green hydrogen exports for countries in South and Southeast Asia. For sea transportation to be viable, pilot projects must be performed to assess feasibility and additional barriers.

In conjunction with a lack of infrastructure and export routes, barriers reveal the difficulty for countries in the region to become green hydrogen exporters in the short term. These barriers are economically and politically costly to overcome, except for increased renewable energy targets. The need to improve energy efficiency to support the latter partially increases the complexity of policy change, but despite this, increasing the renewable energy share and reducing its costs of production and use is the best avenue for countries in the region to benefit from option 1—trading of green hydrogen—in the international market.

## 8.5 Legal Barriers

The second pathway to benefit from the international green hydrogen market is trading intellectual property through patents. For this to be a viable pathway, national patent law and international mechanisms of patent sharing must be convenient. The strength of patent protection laws and patent trading agreements dictates convenience. Countries with convenient intellectual property arrangements will benefit more from their innovations and attract foreign investors. For instance, the PRC's protection of over 90% of innovators under property rights increases its attractiveness as a manufacturing hub (IRENA 2022).

National laws regarding patent protection have been partially standardized by the country's signatory to the TRIPS agreement, but this is not the case for all countries. Hence, federal rules on patent protection can be placed on a spectrum from strong to weak. Strong patent countries attract foreign investment for R&D and better protect national inventions, transforming inventions into higher profits than countries with more fragile patent protection. The Index of Patent System Strengths, developed by the University of Liverpool in 2014, measures the strength and effectiveness of patent systems in 51 economies annually (Papageorgiadis et al. 2014). This composite index focuses on the impact of transaction cost and patent protection. High transaction costs, for instance, characterize weak patent protection: servicing costs (cost arising from dealing with an economy's patent system), protection costs (costs arising from whether ownership rights are upheld by the patent system and effectiveness of judiciary), and monitoring costs (costs arising from the efforts undertaken to monitor the activities of parties which breach intellectual property). This correlation is helpful in the context of this chapter as high transaction costs further discourage foreign investment. According to the index, India, Thailand, Indonesia, and the Philippines score low, indicating weak patent protection laws. Malaysia and Taipei,China have moderately strong patent protection laws, while Singapore scores within the strong patent protection economies (Papageorgiadis et al. 2014). An example of the increasing strength of patent protection is the PRC's January 2021 law, which allowed a partial design and extended protection period, which shifted the economy's score from weak to strong (US Chamber of Commerce 2022).

Strong patent laws allow for higher profit from national inventions and encourage firms to export technology to economies with strong patent protection. This reduces initial investment costs and reliance on national R&D investments toward the production of green hydrogen thanks to technology transfer. In contrast, economies with weak patent laws face legal barriers that increase dependence on national R&D and reduce chances to benefit from innovation.

However, increasing the strength of patent laws can negatively impact national economic development (Iwaisako and Futagami 2013) as stronger patent law reduces demand for capital, which leads to less capital accumulation, slowing economic growth (Iwaisako and Futagami 2013). In economies where R&D productivity is low, a reduction in demand for capital arising from strengthening patent laws is higher than the rate of innovation (Iwaisako and Futagami 2013). This results in a reduced rate of output (Iwaisako and Futagami 2013). In summary, strengthening patent protection to reduce reliance on R&D will paralyze R&D output and increase reliance on foreign actors. Instead, increased investment in R&D allows economies to produce green hydrogen in the long term but fails to provide them with legal economic benefits associated with possible innovative discoveries in the field.

Alternatively, to strengthen patent protection, economies can invest in infrastructure and control of utility models, a different type of intellectual property protection catered toward more minor innovations. Utility models benefit economies hosting firms with low technological capacities and limited resources (Kim et al. 2012). Utility models are cheaper to obtain, reducing the burden on firms in developing countries to acquire property rights. Despite this, utility models have some limitations. First, not all countries have utility model laws, i.e., they need to balance the cost of strengthening patent law and its negative impacts on the demand for capital with the cost of implementing and the practical constraints, such as having to train lawyers on the matter.

Furthermore, while utility models can allow for some profit from intellectual property protection within a nation, it is unclear whether it would attract foreign investment to the same extent strong patent law does. Therefore, strengthening patent law while considering the negative macroeconomic impacts of such legal changes is a path to increasing foreign firm collaboration and generating higher profits from hydrogen innovation abroad. This reliance, which can present itself as joint ventures, as discussed in the barriers section, reduces profits compared to independently developed patents. The exception in the case of the PRC is the construction of the world's first 1,300 cubic meters/h alkaline electrolyzers in partnership with the Belgian company Cockerill Jingli Hydrogen, a partnership resulting from previous collaboration in the field of solar energy and electrolyzer (Brown and Grünberg 2022). Even if this project allowed the PRC to obtain intellectual property, the profit from the patent would be shared with the Belgian company, reducing profit overall. Despite all this, R&D international collaboration allows developing countries that lack the technological development or expertise to implement infrastructure for hydrogen to start production.

Beyond the degree of strength of national protection laws, international legal barriers are faced by countries looking to export intellectual property. For instance, Japan scores among the strongest for patent protection, but most Japanese innovations lack protection from abroad. As a result, while Japan holds 41% of all hydrogen-related patents, its earnings from patents are lower than EU member states (IRENA, 2022). This is caused by the cost Japan faces by exporting patents, which is not likewise faced by EU countries that export within EU borders. Most of the countries observed in the chapter are signatories to the primary patent export treaties (Paris, PCT, Budapest, and Trips) except for the Patent Law Treaty (PLT), but this does not necessarily reduce costs for patent exports, although it reduces bureaucratic complexity. For example, the Patent Cooperation Treaty (PCT) allows signatory countries to submit a particular application for search and opinion on patentability (UK Government, 2022). Following application, countries must apply to specific national offices for patent approval and protection in their country. The cost would be around $1 million to $2 million to have an internationally protected patent (UK Government, 2022). Comparatively, the EU patent office centrally handled the patents from EU member states, simplifying the process and reducing costs. This explains the higher profits by the EU compared to Japan despite lower ownership of inventions and exemplifies the upfront costs of benefitting from international intellectual property trading.

Table 8.6 summarizes the key point of the above discussion by identifying the level of patent protection law and treaties to export patents in the economies reviewed in this chapter. The strength of patent laws may become a legal barrier since the weaker laws make the countries less likely to join joint ventures or profit from intellectual property trade. Therefore, countries coded in red have weaker laws, while those with stronger patent laws are coded in green. On the other hand, being a signatory to an export of the patent treaty can ease the situation. If not part of a treaty, a country faces this additional barrier to trade in addition to patent laws. The green color code represents that countries have significantly overcome the barrier, while the yellow one shows that the barrier has been only partially overcome.

**Table 8.6: Legal Barriers**

| Country | Level of Patent Protection Law | Export of Patent Treaties |
|---|---|---|
| India | 🟧 | 🟩 |
| Malaysia | 🟩 | 🟩 |
| Thailand | 🟧 | 🟨 |
| Philippines | 🟧 | 🟩 |
| Viet Nam | 🟧 | 🟩 |
| Brunei Darussalam | 🟧 | 🟩 |
| Indonesia | 🟧 | 🟨 |

🟧 Barrier not overcome 🟨 Barrier partially overcome 🟩 Barrier significantly overcome

Source: Authors.

## 8.6 Manufacturing Prospects for Trade

The low cost of manufacturing, the widespread electronics manufacturing industry, and the availability of natural resources related to electrolysis present a prospect for trade in the international market of green hydrogen.

### 8.6.1 Natural Resources

Countries can benefit in the international green hydrogen market by exporting natural resources needed to build stacks or harnessing said natural resources and exporting stacks themselves. For instance, the availability of iridium in Malaysia (contributing to 0.13% of global exports of iridium) and Singapore (contributing to 0.11% of global exports of iridium) qualifies them as possible exporters of Proton Exchange Membrane (PEM) electrolyzer stacks (OEC World 2023). PEM electrolyzer stacks are a key component of PEM electrolyzers, which are devices used to split water into hydrogen and oxygen using electricity. The "stack" refers to the assembly of cell units in the electrolyzer that carry out this process. Iridium is often used as a catalyst in the electrolysis process in PEM electrolyzers. Iridium, being a rare and expensive metal, is one of the factors that contributes to the high cost of producing hydrogen through electrolysis. However, the low efficiency of PEM electrolyzers reduces their demand in the short term, making the export of iridium itself a more profitable pathway in the upcoming years. Given the PRC's large share of electrolyzer production and hydrogen policy, iridium demand from the country might rise, encouraging exporters to remain iridium exporters rather than manufacturers of PEM electrolyzers.

The availability of titanium needed for PEM electrolyzer balancing plates provides some avenues for profit for India and Viet Nam. However, despite India and Viet Nam producing titanium in the region, these countries are far behind countries leading in the field, such as the PRC and the US, meaning the export of titanium provides only a limited prospect for profit (OEC World 2023). Regarding alkaline electrolyzers, Indonesia can profit from their export or the increasing demand for nickel, given that Indonesia is the leading nickel exporter in the world, exporting 1 million MT in 2021 and having 21 MT in reserves (Pistilli 2022). The Philippines is also a prominent nickel exporter in the region, exporting 370,000 MT in 2021 (Pistilli 2022). While the export of nickel is a prospect, the lack of policy regarding producing electrolyzers reduces the competitiveness of these countries compared to others. For instance, the EU has set a 40 GW electrolyzer capacity target by 2030, ensuring future electrolyzer demand and encouraging the private sector to begin production (Raj et al. 2022). It could be beneficial for countries like Indonesia and the Philippines to consider setting similar goals to harness their potential as alkaline electrolyzer exporters while benefitting fron nickel exports in the short term.

### 8.6.2 Manufacturing Capacity

The capacity to enter the market as BoP exporters is dependent upon the countries' electronics manufacturing sector. Further, around 20% to 50% of Asian countries' exports come from electronics, with Viet Nam exporting 5%, Malaysia 4.7%, Thailand 1.9%, Philippines 1.3%, and Indonesia 0.3% of total global exports in electronics (Brodzicki 2021). Although these shares may seem low, Taipei,China is the second-largest exporter in the region after the PRC, and its global export share is 7%, just 2% higher than Viet Nam. In particular, Malaysia and the Philippines, together with Taipei,China, specialize in the export and production of electronic valves, tubes, and semiconductors, mainly needed for BoP assembly (Brodzicki 2021). India's $70 billion electronics manufacturing market—especially if we consider its capacity for quick future expansion, given its past $41 billion growth in 5 years between 2014 and 2019—of which $8 billion are exported, also places it in an advantageous position to become a BoP exporter or exporter of BoP components (Raj et al. 2022). Hence, countries in South and Southeast Asia have avenues to reap profit from exports of BoPs.

The effectiveness of BoP is also crucial for making PEM electrolyzers more cost-effective in the long run, as it can increase their output capacity in terms of energy. This means that increased investment and research in BoP production and lowering costs can benefit the countries exporting iridium as it can increase the demand for PEM electrolyzers globally. The export of components is also facilitated by ASEAN, which bridges export gaps between Southeast Asian countries and larger economies in Asia, such as the PRC and Japan, which has primarily helped the manufacturing industry in the past and can now serve as a bridge between manufacturers of BoP and countries with hydrogen policies in the region (ASEAN 2023).

Table 8.7 summarizes the manufacturing prospects for green hydrogen in countries under review regarding the availability of natural resources (iridium and nickel) and an established electronics manufacturing market. Countries in the region, therefore, possess some comparative advantages for producing electrolyzer stacks due to the availability of natural resources (in particular nickel in Indonesia and the Philippines) and BoPs, thanks to the presence of the electronics manufacturing sector (Table 8.7). In the short term, resource-rich countries will likely remain resource exporters rather than component exporters due to external factors, such as lack of specified global demand for electrolyzers, and internal factors, such as lack of policy incentives and R&D.

**Table 8.7: Manufacturing Prospects**

| Country | Presence of Electronics Manufacturing Sector | Availability of Natural Resources | |
|---|---|---|---|
| | | Iridium | Nickel |
| India | 🟩 | 🟧 | 🟧 |
| Malaysia | 🟩 | 🟩 | 🟧 |
| Thailand | 🟨 | 🟧 | 🟧 |
| Philippines | 🟨 | 🟧 | 🟩 |
| Viet Nam | 🟩 | 🟧 | 🟧 |
| Brunei Darussalam | 🟧 | 🟧 | 🟧 |
| Indonesia | 🟧 | 🟧 | 🟩 |

🟧 Prospects not present 🟨 Prospects partially present 🟩 Prospects present

Source: Authors.

## 8.7 Conclusion and Policy Recommendations

Countries in South and Southeast Asia face a series of policy, infrastructural, and legal barriers, limiting their capacity to profit from the international green hydrogen market. The lack of R&D investment and policy harnessing renewable energy resources leads to a lack of policymaking on green hydrogen, precluding production prospects. Lack of production leads to an inability to export green hydrogen. The situation is worsened by a lack of research into transportation avenues from the region to prospect green hydrogen importers. Lack of R&D also prevents countries in the region from profiting by exporting intellectual property in the form of patents. Weak national patent protection laws and the negative impacts of stronger protection laws on economic growth, coupled with the high costs needed to achieve patent protection from abroad, further complicate the capacity of countries in the region to benefit from this avenue. These issues are not easily tackled in the short term. The inability to produce policy or strengthen patent protection law is caused by GDP status, requiring aspects secondary to green hydrogen policy to be set in motion. Further, a lack of global forecasts for hydrogen demand can discourage countries from investing in the field, as the investment might not be paid back soon.

Despite this, certain avenues exist for countries in the region to benefit from the international green hydrogen market. Exporting components for electrolyzers is a feasible goal for countries in the region, given the current size of electronics manufacturing and export markets and the availability of required metals such as iridium and nickel. To facilitate this and to make explicit wishes to profit from this trade, countries in the region are to set manufacturing production targets. Increased certainty on forecasts of needed electrolyzer capacity will serve as an incentive for production and increase clarity on profits in the field. Low manufacturing cost and policies harnessing it create avenues for countries in South and Southeast Asia to host foreign firms' projects for increasing efficiency of the balance of plant (BoP) components, allowing to a certain extent to benefit from the international trade of patents.

This chapter recognizes limitations with the methodology because numerical data are extrapolated from text rather than datasets. In particular, the unavailability of complete reports on targets for renewable energy capacity and share of renewable energy in the future energy mix undermine the evaluation of the capacity to produce green hydrogen. Furthermore, even when data is available, additional research is necessary to evaluate the accuracy of energy goals and forecasts regarding energy demand. Despite this, the skeleton of the national policy requirements and limitations to profits in the international market remains truthful as it is less dependent on quantitative data and relies on qualitative policy analysis.

In summary, countries in South and Southeast Asia can benefit from the international green hydrogen market in the short term by exporting manufacturing components. However, countries should develop targeted policies to strengthen this profit in the long term. Such policies will not only focus production efforts but also signal to other green hydrogen-producing/importing countries the interests of South and Southeast Asian countries to enter the market.

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# Hydrogen in Decarbonization Strategies in Asia and the Pacific

Green hydrogen produced by renewable energy could be a "game-changing" solution for both energy security and ambitious climate targets. The most promising applications of green hydrogen are those where renewable energy cannot be used, including decarbonizing hard-to-abate sectors, such as steel and cement; long-term and seasonal energy storage; and cross-border trade.

Global investment in green hydrogen is still small compared to investments in renewable energy, mainly due to the high costs. However, these costs are expected to significantly decline during 2030–2050. Asia and the Pacific is playing an important role in the move toward a society in which hydrogen will be vital for daily life and economic activities. National hydrogen strategies have already been developed in a growing number of countries in Asia and the Pacific, including Australia, India, Japan, New Zealand, the People's Republic of China, the Republic of Korea, and Singapore, and are under preparation in many others.

*Hydrogen in Decarbonization Strategies in Asia and the Pacific* focuses on both importing and exporting countries of hydrogen and features innovative and insightful research examining hydrogen society development. The discussions aim to inform and be accessible to a broad audience, including policy makers and non-energy experts looking to stay abreast of the latest decarbonization trends in the region.

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The Asian Development Bank Institute (ADBI) is the Tokyo-based think tank of the Asian Development Bank. ADBI provides demand-driven policy research, capacity building and training, and outreach to help developing countries in Asia and the Pacific practically address sustainability challenges, accelerate socioeconomic change, and realize more robust, inclusive, and sustainable growth.

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