Analysis of Hydrogen Supply Chain Readiness in Selected Indo-Pacific Countries

Hussain M. Almajed, Omar José Guerra-Fernández, and Daniella Rough

National Renewable Energy Laboratory

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List of Abbreviations

AEM	Anion Exchange Membrane
AHEAD	Advanced Hydrogen Energy Chain Association for Technology Development
ALARP	As Low as Reasonably Practicable
ASEAN	Association of Southeast Asian Nations
ATR	Autothermal Reforming
AUS	Australia
AZEC	Asia Zero Emission Community
BAU	Business-As-Usual
BECCS	Biomass with Carbon Capture and Storage
BESS	Battery Energy Storage System
BIL	Bipartisan Infrastructure Law
BRN	Brunei Darussalam
CAAS	Civil Aviation Authority of Singapore
CCGTs	Combined Cycle Gas Turbines
CCHP	Combined Cooling, Heat, and Power
CCS	Carbon Capture and Storage
CCUS	Carbon Capture, Utilization, and Storage
CDR	Carbon Dioxide Removal
CH_3OH	Methanol
CH_4	Methane
CIF	Cost, Insurance and Freight
CO_2	Carbon Dioxide
CO_2-eq	CO_2-eqivalent
COP	Conference of the Parties
CWP	Cooperative Work Program
DACS	Direct Air Capture and Storage
DOCS	Direct Ocean Capture and Storage
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
EGAT	Electricity Generating Authority of Thailand
EJ	Exajoules
EPPO	Thailand's Energy Policy and Planning Office
ERIA	Energy Research Institution for ASEAN and East Asia
EVN	Viet Nam Electricity Group
FID	Final Investment Decisions
FIPI	Federation of Indian Petroleum Industry
FJI	Fiji
FMIA	Future Made in Australia
FSPV	Floating Solar Photovoltaics
FY	Fiscal Year
G2G	Government-to-Government
GHG	Greenhouse Gas
GIF	Green Innovation Fund
GO	Guarantee of Origin
GW	Gigawatt

GX	Green Transformation
H_2	Hydrogen
HDF	Hydrogène de France
HFTO	Hydrogen and Fuel Cells Technologies Office
HEIC	Hydrogen Energy Industry Committee
HESC	Hydrogen Energy Supply Chain
HETR	Malaysian Hydrogen Technology & Economy Roadmap
HHI	Hyundai Heavy Industries
HPTI	Hydrogen Production Tax Incentive
HyP SA	Hydrogen Park South Australia
IDN	Indonesia
IEA	International Energy Agency
IHTF	International Hydrogen Trade Forum
IMO	International Maritime Organizations
IND	India
IPHE	International Partnership for Hydrogen and Fuel Cells in the Economy
IPP	Intermountain Power Project
IRA	Inflation Reduction Act
IRENA	International Renewable Energy Agency
IRS	U.S. Treasury and Internal Revenue Service
ISO	International Organization for Standardization
JCEC-2	Second Meeting of the Joint Committee on Economic Cooperation
JDA	Joint Development Agreement
JETP	Just Energy Transition Partnership
JPN	Japan
Kg	Kilogram
KOR	Republic of Korea
Kt	Kilo Metric Tonne
kWh	Kilowatt-Hour
LCA	Life-Cycle Analysis
LCER	Low-Carbon Energy Research
LCFS	Low Carbon Fuel Standard
LNG	Liquified Natural Gas
MCH	Methylcyclohexane
MEA	Ministry of External Affairs
MENA	Middle East and North Africa
MHI	Mitsubishi Heavy Industries
MIDA	Malaysian Investment Development Authority
MNRE	India's Ministry of New and Renewable Energy
MoC	Memorandum of Cooperation
MOTIE	South Korea's Ministry of Trade, Industry, and Energy
MoU	Memorandum of Understanding
MPA	Maritime and Port Authority of Singapore
Mt	Mega (i.e., million) Metric Tonne
MTI	Singapore's Ministry of Trade and Industry
MW	Megawatt

MYS	Malaysia
NDCs	Nationally Determined Contributions
NDP	National Development Plan
NEDO	Japan's New Energy and Industrial Technology Development Organization
NG	Natural Gas
NGHM	India's National Green Hydrogen Mission
NH_3	Ammonia
NZL	New Zealand
O_2	Oxygen
OEMs	Original Equipment Manufacturers
PEM	Proton Exchange Membrane
PEP	Philippines Energy Plan
PETRONAS	Petroliam Nasional Berhad
PHL	Philippines
PNNL	Pacific Northwest National Laboratory
PTC	Production Tax Credit
PTI	Pacific Trade Invest
PTT	PTT Public Company Limited
PV	Photovoltaics
PVN	Viet Nam Oil and Gas Group
PWh	Petawatt-Hour
R&D	Research and Development
RD&D	Research, Development, and Deployment
RDD&D	Research, Development, Demonstration & Deployment
RE	Renewable Energy
REO	Renewable Energy Outlook
ROI	Return on Investment
SAF	Sustainable Aviation Fuel
SEA-DF	Sarawak Electrolyzer Assembly Distribution Facility
SEDC	Sarawak Economic Development Corporation
SGP	Singapore
SIGHT	Strategic Interventions for Green Hydrogen Transition
SMR	Steam Methane Reforming
SOEC	Solid Oxide Electrolysis Cell
TC	Technical Committee
TcF	Trillion Cubic Feet
TGS	The Green Solutions Group Corporation
TRL	Technology Readiness Level
TWGs	Technical Working Groups
TWh	Terawatt-Hour
UN	United Nations
US$	U.S. Dollar
USA	United States of America
USDA	U.S. Department of Agriculture
VNM	Viet Nam

Key Definitions

Term	Definition
Low-carbon hydrogen	*Defined as the hydrogen produced with a significantly lower carbon intensity compared to conventional routes, which could refer to the use of carbon capture technologies with fossil-based hydrogen production, the use of biomass to produce carbon-negative hydrogen, or the use of renewable power to produce low-carbon-intensity hydrogen.*
Carbon intensity	*Defined as the well-to-gate, unless otherwise noted, life-cycle emissions associated with hydrogen production. We provide a range for the carbon intensity for three hydrogen production methods in* ***Figure ES4****.*
Hydrogen production cost	*Defined as the total production cost associated with the production of hydrogen, which considers the capital and operational costs as well as the capacity of a reference facility (e.g., 50 kilo metric tonnes of hydrogen (kt-H_2) per year).*
Hydrogen procurement price (CIF arrangement)	*For the purposes of this report, the procurement price of hydrogen includes the production cost, insurance cost, and freight cost based on cost, insurance, and freight (CIF) arrangements. This is chosen to be consistent with Japan's reported procurement prices, which are reported to be based on CIF arrangements. Note that the cost here includes production, storage, transportation, and port-related costs up to the delivery of hydrogen to the receiving port.*
Hydrogen production amount	*Defined as the amount of hydrogen produced (or planned to be produced) by a specific country regardless of the end use (i.e., domestically used or exported).*
Hydrogen procurement amount	*Defined as the amount of hydrogen procured (or planned to be procured) by a specific country from overseas.*
Midstream costs	*Defined to include costs in between hydrogen production and commercial end user procurement, which could include storage, transportation, and distribution.*
Port readiness	*Refers to the ports' capabilities to receive hydrogen in different forms, store it safely, and distribute it to end users at the demanded scale.*
Technology readiness level (TRL)	*Defined as a multi-level scale that measures the technical maturity of a technology and its associated progress from fundamental to applied settings. Consistent with the International Energy Agency (IEA), the technology readiness levels are as follows:*[1] ***Concept:*** *TRL 1 (Initial idea), TRL 2 (Application formulated), TRL 3 (Concept needs validation)* ***Small Prototype:*** *TRL 4 (Early prototype)* ***Large Prototype:*** *TRL 5 (Large prototype) and TRL 6 (Full prototype at scale)* ***Demonstration:*** *TRL 7 (Pre-commercial demonstration) and TRL 8 (First-of-a-kind commercial)* ***Early Adoption:*** *TRL 9 (Commercial operation in relevant environment) and TRL 10 (Integration needed at scale)* ***Mature:*** *TRL 11 (Proof of stability reached)*

Executive Summary

The 14 selected Indo-Pacific countries–Australia, Brunei, Fiji, India, Indonesia, Japan, Malaysia, New Zealand, the Philippines, the Republic of Korea, Singapore, Thailand, the United States, and Vietnam–target low-carbon hydrogen production costs of approximately 1.4-4.8 U.S. dollars (US$)/kilogram (kg)-hydrogen (H_2) and procurement prices of approximately US$2.3/kg-$H_2$ by 2030. These targets reduce to US$1.1-2.4/kg-$H_2$ and US$1.6/kg-$H_2$, respectively, by 2050.

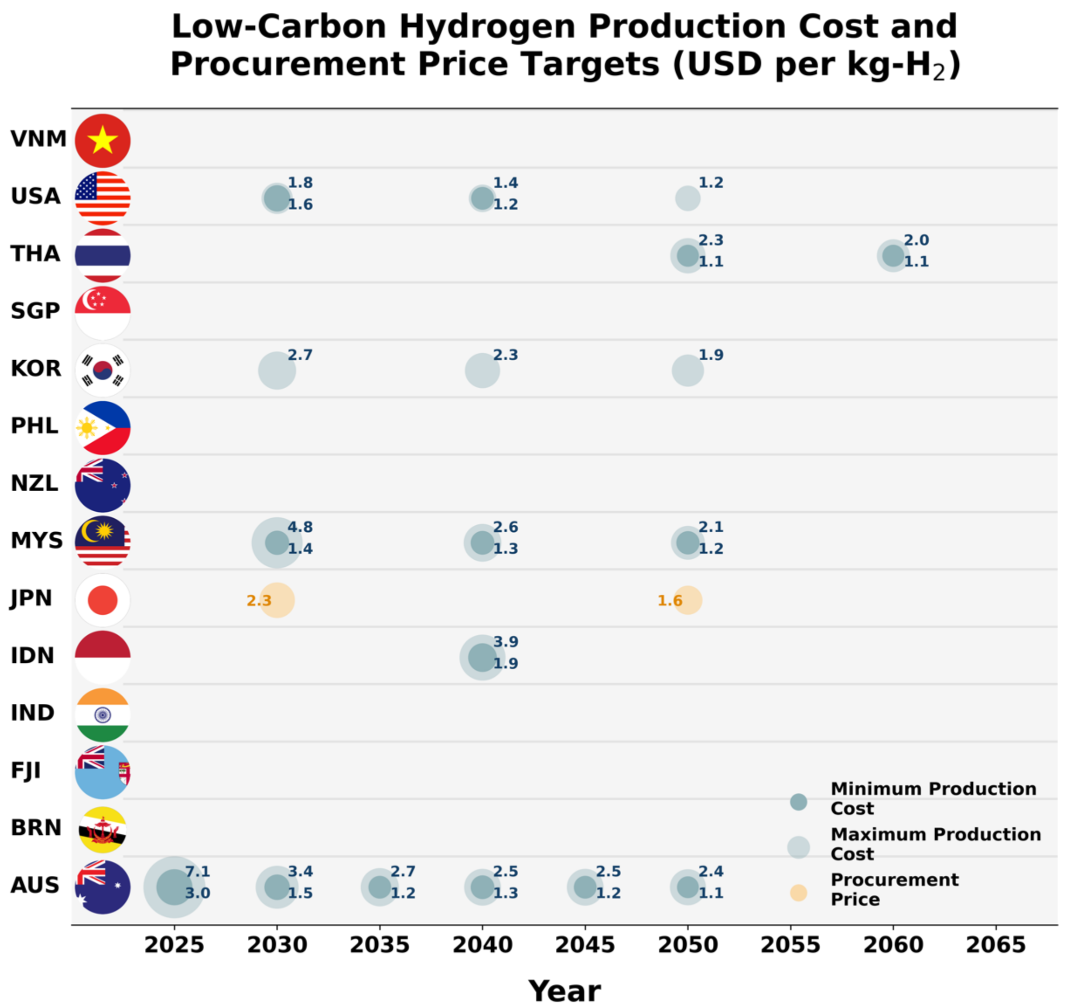

Figure ES1. Target low-carbon hydrogen production costs and procurement prices (USD per kg-H_2) in the selected Indo-Pacific countries.

Note that we consider procurement prices as those paid by the buyer at the port, which are based on CIF arrangements (see **Key Definitions** for details). The light and dark blue circles refer to the maximum and minimum production cost targets, respectively. The yellow circles represent the procurement price targets. Values include hydrogen produced via any low-carbon hydrogen production method (including at least steam methane reforming (SMR) – carbon capture and storage (CCS) and electrolysis), as reported by countries.

Data sources: Countries' roadmaps/strategies and countries' presentations.

Maintaining a stable hydrogen supply chain requires careful planning of production cost and procurement price of low-carbon hydrogen. In the context of this report, hydrogen procurement prices include not only hydrogen production costs but also the storage and transportation costs associated with hydrogen delivery to a receiving port. **Figure ES1** shows the low-carbon hydrogen production costs and procurement prices targeted by the selected Indo-Pacific countries. The wide range of low-carbon hydrogen production costs indicates possible uncertainty in technology choice, readiness level (TRL), and/or assessment. As we approach 2050, the production cost range of low-carbon hydrogen narrows, suggesting an increase in the TRL of low-carbon hydrogen production technologies. By 2050, the cost of producing low-carbon hydrogen is targeted to be in the range of US$1.1-2.4 per kg-$H_2$. It is important to restate that this cost is not the final delivered price of hydrogen, as it excludes midstream costs that could increase the final delivered price of low-carbon hydrogen significantly. Japan, the only subject country that reported procurement prices of low-carbon hydrogen (based on cost, insurance, and freight (CIF) arrangements), targets a low-carbon hydrogen price of US$2.3 per kg-$H_2$ and US$1.6 per kg-$H_2$ by 2030 and 2050, respectively. This price falls within the range of targeted production costs but also includes midstream costs, such as storage and transportation costs. Therefore, estimating both production and non-production cost targets could be important to support future planning of low-carbon hydrogen trades in the region and the globe.

Cost-price matching restricts midstream-related (e.g., storage, distribution, and transportation) costs of low-carbon hydrogen to be less than US$0.9 per kg-$H_2$ by 2030 and less than US$0.5 per kg-$H_2$ by 2050. Developing midstream technologies that meet such targets could be key to enabling the growth of hydrogen trading markets in the Indo-Pacific region.

Midstream, or non-production, costs (e.g., storage and transportation) of low-carbon hydrogen will likely become a determining factor for the capability of hydrogen export in several of the hydrogen-exporting countries within the selected Indo-Pacific countries. The lack of data reporting on the procurement prices of low-carbon hydrogen in the subject countries restricts our cost-price matching analysis. The difference between the target production cost and procurement price of low-carbon hydrogen (**Figure ES1**) represents the midstream cost, which includes storage and transportation of low-carbon hydrogen. For instance, if hydrogen is produced at a cost of $2.0 per kg-$H_2$ in one subject country and another subject country plans to purchase that hydrogen for $1.5 per kg-$H_2$, then the midstream cost would be US$-0.5 per kg-$H_2$, making the trade infeasible. On the other hand, if the production cost was US$1.0 per kg-$H_2$ in this hypothetical scenario, then the midstream cost would be US$0.5 per kg-$H_2$, making the trade feasible under the restriction that the midstream costs are within the US$0.5 per kg-$H_2$ limit. Given the targets in the selected Indo-Pacific countries, the total midstream costs could fall in a wide range of US$-2.5 to 0.9 per kg-$H_2$ by 2030 and US$-0.8 to 0.5 per kg-$H_2$ by 2050, as shown in **Figure ES2**. Note that these ranges include a significant negative region, meaning that worst-case scenarios, where the H_2 production cost is higher than the H_2 procurement price, are likely not going to be feasible for several countries. In addition, the wide cost ranges underscore the critical role that midstream infrastructure (e.g., storage and transportation) could play in low-carbon hydrogen trades. It is worth noting that Australia, India, and the United States have been developing hydrogen production tax credits that would cover a portion of the production costs of low-carbon hydrogen and could relieve some cost burdens related to low-carbon hydrogen storage and transportation in the next 3 to 10 years.

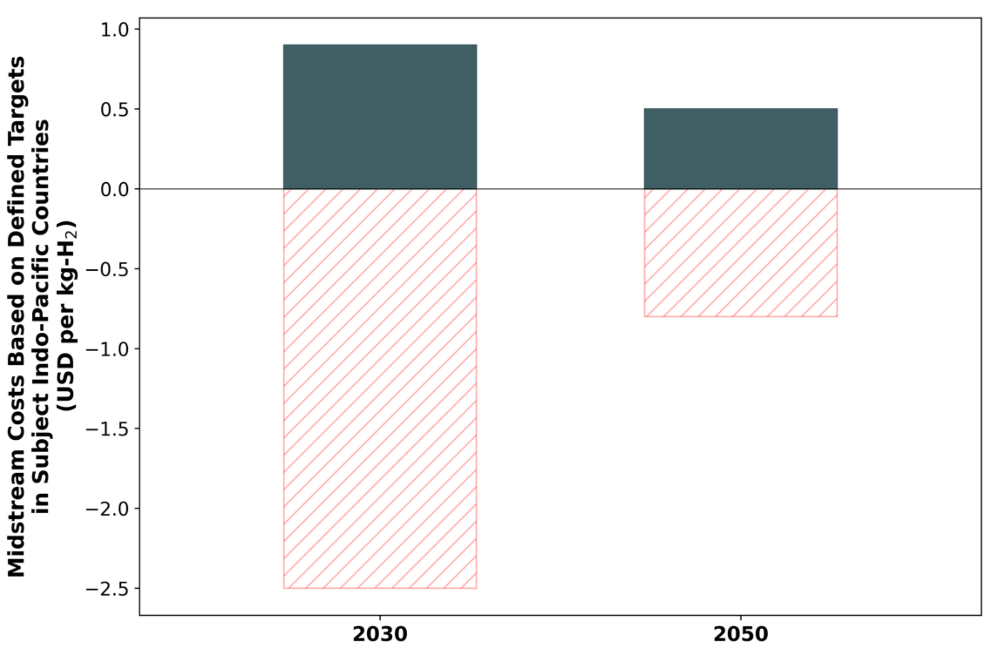

Figure ES2. Estimated midstream costs in 2030 and 2050 based on subject countries' defined targets for low-carbon hydrogen production costs and procurement prices.

Required midstream costs are calculated by taking the difference between the targeted production cost and procurement price of low-carbon hydrogen. Note that the negative region is shown by the red dashed bars.

The production amount of low-carbon hydrogen in the selected Indo-Pacific countries is expected to reach 17-25 million (mega) metric tonnes (Mt)-H_2 per year by 2030, 36-52 Mt-H_2 per year by 2040, and 113-147 Mt-H_2 per year by 2050. Procurement amount of low-carbon hydrogen in the selected Indo-Pacific countries is expected to reach 5 Mt-H_2 per year by 2030, 14 Mt-H_2 per year by 2040, and 44 Mt-H_2 per year by 2050.

Six of the fourteen subject countries have indicated their plans to become net exporters of low-carbon hydrogen, whereas four of the fourteen countries have indicated their intention to become net importers of low-carbon hydrogen (**Table ES1**). With current reported production and procurement amounts (**Figure ES3**), 30-39% of the planned low-carbon hydrogen production in 2050 is expected to be traded to reach demand-supply stability within the selected Indo-Pacific countries, assuming no hydrogen trades with non-subject countries. Such a high percentage requires significant effort in deploying hydrogen storage and transportation solutions, including using intermediary carriers (e.g., ammonia, methanol, etc.), which are considered by some of the selected Indo-Pacific countries (e.g., Australia, Japan, New Zealand, and Singapore). In addition, although the production amount is ≥3 times larger than the procurement amount, it is critical to consider domestic demand, which have been neglected in the present analysis due to the lack of available data. Thus, accounting for domestic demand could suggest potential expansion of low-carbon hydrogen production in hydrogen-producing countries to meet the non-domestic demand of low-carbon hydrogen in the region. Similarly, international collaborations with non-subject countries are expected to rise as we near 2050 to help meet the extra demand of low-carbon hydrogen by hydrogen-importing selected Indo-Pacific countries.

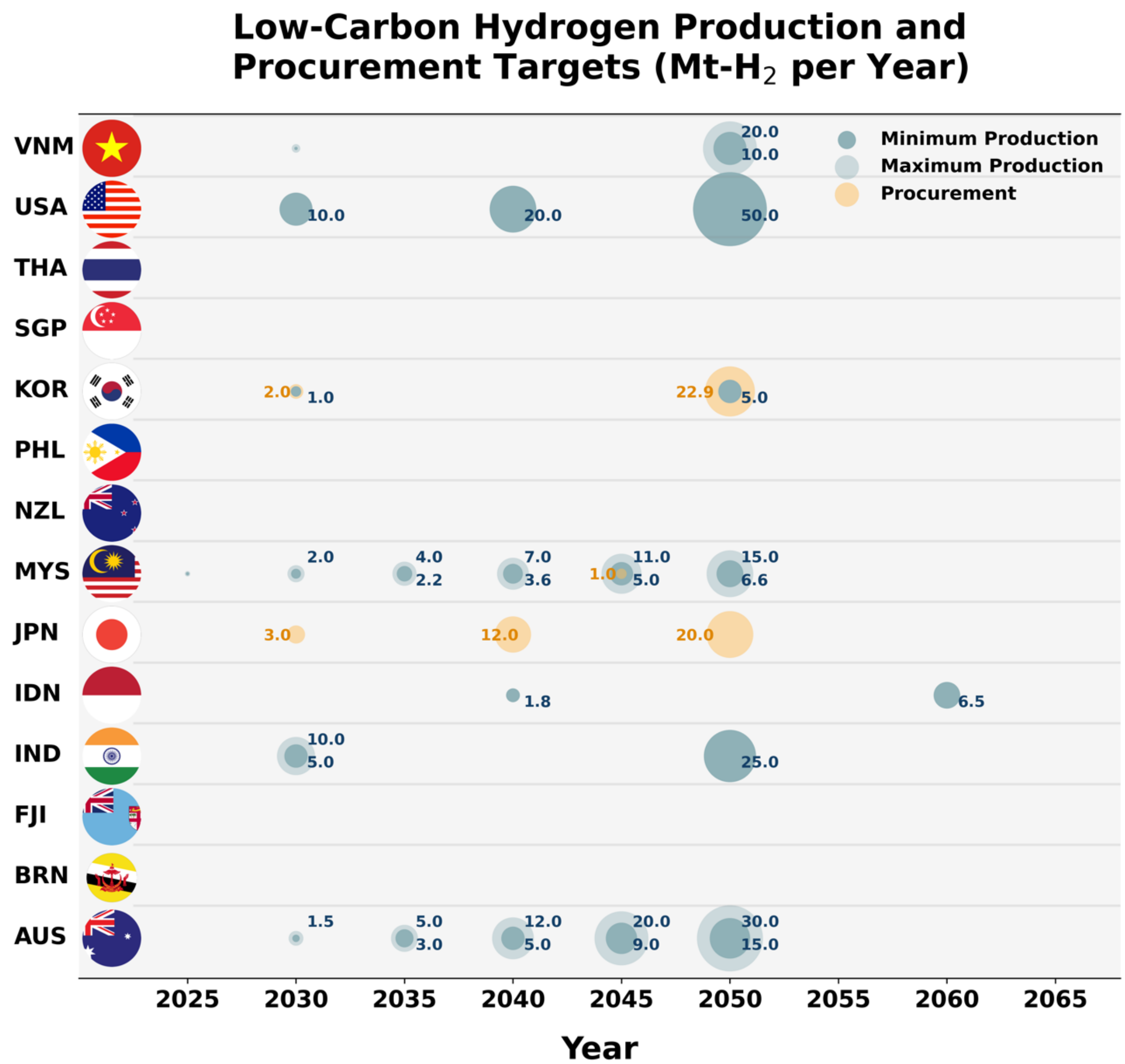

Figure ES3. Target low-carbon hydrogen production and procurement amounts in selected Indo-Pacific countries.

Note that the light and dark blue circles refer to the minimum and maximum production amounts, respectively. The yellow circles represent the procurement amounts of potential H_2-importing selected Indo-Pacific countries. Values include hydrogen produced via any low-carbon hydrogen production method (including at least SMR-CCS and electrolysis).

Data sources: Countries' roadmaps/strategies and countries' presentations.

Policy, regulation, and commercial readiness of low-carbon hydrogen trade is still not fully mature yet in all of the selected Indo-Pacific countries. At least seven of the selected Indo-Pacific countries have invested in hydrogen research, development, and deployment (RD&D) and in cost sharing of low-carbon hydrogen facilities, both in upfront and operational costs.

The selected Indo-Pacific countries acknowledge the critical role of regulations in low-carbon hydrogen deployment. These regulations can come in the form of certifications, standards, codes, labeling, and safety measures. So far, four selected Indo-Pacific countries (India, Japan, Republic of Korea, and United States) reported that they implemented low-carbon hydrogen certification/standard schemes, and seven (Australia, Indonesia, Malaysia, New Zealand, Philippines, Singapore, and Viet Nam) reported that they have plans to implement similar schemes or are in the process of implementing one. These efforts support the development of hydrogen-related regulations that could ensure transparency regarding the low carbon intensity of the produced hydrogen as the market grows both regionally and globally.

Moreover, hydrogen-related RD&D investments have been announced by most of the selected Indo-Pacific countries. In addition, three countries (Australia, India, and United States) implemented hydrogen production tax incentives to cover a portion of the production costs of low-carbon hydrogen. Australia plans to provide approximately US$1.40 per kg-$H_2$ (i.e., AU$2.00 per kg-$H_2$) for ten years to qualifying hydrogen producers that maintain a carbon intensity of less than or equal to 0.6 kg-CO_2 per kg-H_2 and reach final investment decisions (FID) by 2030. This effort is supported under Australia's hydrogen production tax incentive (HTPI) program. India plans to provide a hydrogen production tax incentive over the first three years to hydrogen-producing facilities that could reach up to US$0.60 (i.e., ₹50), up to US$0.48 (i.e., ₹40), and up to US$0.36 (i.e., ₹30) per kg-$H_2$ in years 1, 2, and 3, respectively. This incentive is planned to fall under the Incentive Scheme for Green Hydrogen Production, which is a component of India's Strategic Interventions for Green Hydrogen Transition (SIGHT) program. The U.S. proposed and finalized the 45V hydrogen production tax credit (H_2 PTC) that would provide up to US$3.00, US$1.00, US$0.75, and US$0.60 per kg-H_2 for produced hydrogen with CO_2 emission intensities of up to 0.45, 1.50, 2.50, and 4.00 kg-CO_2 per kg-H_2, respectively. The 45-V tax credit is planned to be paid to facilities over a 10-year period but will require a starting operation date before the end of 2032.

Table ES1. Summary of quantitative hydrogen-related metrics in the 10 selected Indo-Pacific countries that announced hydrogen roadmaps.

Country	Certification / Standard Scheme	Hydrogen Incentives	Port Readiness	Storage and Transportation	Net Importer / Net Exporter
Australia	In Progress	RD&D Per kg	Export Import	Exists Plan Repurp.	Net Exporter
Brunei Darussalam	Not Reported	Not Reported	Not Reported	Not Reported	Not Reported
Fiji	Non-existent	Non-existent	Export Import	Plan	Net Importer
India	Implemented	RD&D Per kg	Export Import	Exists Plan	Net Exporter
Indonesia	In Progress	RD&D	Export Import	Plan	Net Exporter
Japan	Implemented	RD&D	Export Import	Exists Plan	Net Importer
Malaysia	In Progress	RD&D	Export Import	Plan	Net Exporter
New Zealand	In Progress	RD&D	Export Import	Exists Plan	Net Exporter
Philippines	In Progress	RD&D	Not Reported	Not Reported	Undecided
Republic of Korea	Implemented	RD&D	Export Import	Exists Plan Repurp.	Net Importer
Singapore	In Progress	RD&D	Export Import	Plan Repurposed	Net Importer
Thailand	Not Reported	Not Reported	Not Reported	Not Reported	Not Reported
United States	Implemented	RD&D Per kg	Export Import	Exists Plan	Net Exporter
Viet Nam	In Progress	RD&D	Export Import	Plan Repurposed	Undecided

- In progress: indicates subject country reported ongoing development of a low-carbon hydrogen certification/standard scheme.
- Implemented: indicates subject country implemented a low-carbon hydrogen certification/standard scheme.
- Non-existent: indicates subject country reported the metric is not currently considered.
- Not reported: indicates subject country did not report whether the metric is considered.
- RD&D: indicates that the subject country is investing in low-carbon hydrogen RD&D.
- Per kg: indicates that the subject country has an investment mechanism that pays facilities for producing low-carbon hydrogen per kg-H_2.
- Export/Import: indicates that the subject country reported readiness for exporting/importing hydrogen and/or its derivatives today.
- Export/Import: indicates that the subject country reported lack of readiness for exporting/importing hydrogen and/or its derivatives today.
- Exists: Indicates subject country reported that storage and/or transportation of hydrogen exist today.
- Plan: Indicates subject country reported that storage and/or transportation of hydrogen are in the planning stage.
- Repurposed: Indicates subject country reported that storage and/or transportation of hydrogen are planned to be repurposed from other commodities (e.g., natural gas).
- Net Exporter: Indicates subject country reported plans to become a net hydrogen exporter.
- Net Importer: Indicates subject country reported plans to become a net hydrogen importer.
- ? Undecided: Indicates subject country reported undecided for importing/exporting hydrogen.

Advancements in port readiness as well as storage, transportation, and distribution capabilities of low-carbon hydrogen could enable faster growth in hydrogen trades between selected Indo-Pacific countries. Reaching high TRLs in midstream infrastructure in the short term could bridge the gap between production and utilization capabilities of low-carbon hydrogen in the region.

In the presented context, port readiness refers to the ports' capabilities to receive hydrogen in different forms, store it safely, and distribute it to end users at the demanded scale. The readiness of ports for hydrogen varies from one country to another in the selected Indo-Pacific countries. This is a major challenge for hydrogen trades since the expected scale of hydrogen trades within the selected Indo-Pacific countries is targeted to reach 5 Mt-H_2 per year by 2030, 14 Mt-H_2 per year by 2040, and 44 Mt-H_2 per year by 2050. So far, only four countries (Australia, India, Indonesia, and New Zealand) reported their readiness for exporting hydrogen and/or its derivatives today, whereas five countries reported they are still developing their capabilities to export hydrogen and/or its derivatives (**Table ES1**). For instance, the U.S. and Malaysia reported potential readiness for export of hydrogen by 2026 and 2027, respectively. Moreover, Fiji and Japan are the only countries that reported readiness for importing hydrogen and/or its derivatives today. The Republic of Korea reported its potential readiness by 2028. This data suggests potential expected growth for hydrogen-fit port infrastructure; however, it also suggests lack of port readiness in most of the selected Indo-Pacific countries today.

Furthermore, trading low-carbon hydrogen requires advanced capabilities of storage, transportation, and distribution. Six subjects (Australia, India, Japan, New Zealand, Republic of Korea, and the United States) reported the existence of hydrogen transportation capabilities in their countries to facilitate initial efforts for distributing hydrogen domestically. However, most of the subject countries, including those with existing hydrogen transportation capabilities, reported they are still planning to build and establish storage and transportation infrastructure. This data indicates the nascency of low-carbon hydrogen storage and deployment in the selected Indo-Pacific countries today. Therefore, future efforts could benefit from special focus on these barriers to ensure smoother deployment of low-carbon hydrogen in the Indo-Pacific region.

Existing infrastructure of hydrogen derivatives in the selected Indo-Pacific countries could be leveraged to advance low-carbon hydrogen trades in the region.

Some of the selected Indo-Pacific countries have reported the existence of ammonia and methanol infrastructure as well as their port readiness to utilize them as hydrogen carriers. For instance, New Zealand reported their ability to export more than 2 Mt of methanol (CH_3OH) per year, potentially enabling the country to produce local low-carbon methanol and export it regionally and globally. Similarly, Indonesia and Malaysia could leverage existing ammonia infrastructure to produce low-carbon ammonia for use or for hydrogen-related storage and transportation. In addition, Singapore could leverage its port, being one of the busiest ports in the world, as a hub to refuel ships with low-carbon methanol and/or ammonia as they are introduced as potential low-carbon fuels for ships. It is worth noting that planned infrastructure in the selected Indo-Pacific countries may be developed for methylcyclohexane (MCH), liquified hydrogen, and gas hydrogen, given their strong potential to be used in storing and transporting renewable electrons across countries.

Lack of data availability regarding the carbon intensity of targeted hydrogen production methods, certification schemes, relevant regulations, and project tracking presents a gap within the selected Indo-Pacific countries. Future hydrogen development efforts could benefit from consistent data reporting methodologies in hydrogen planning reports.

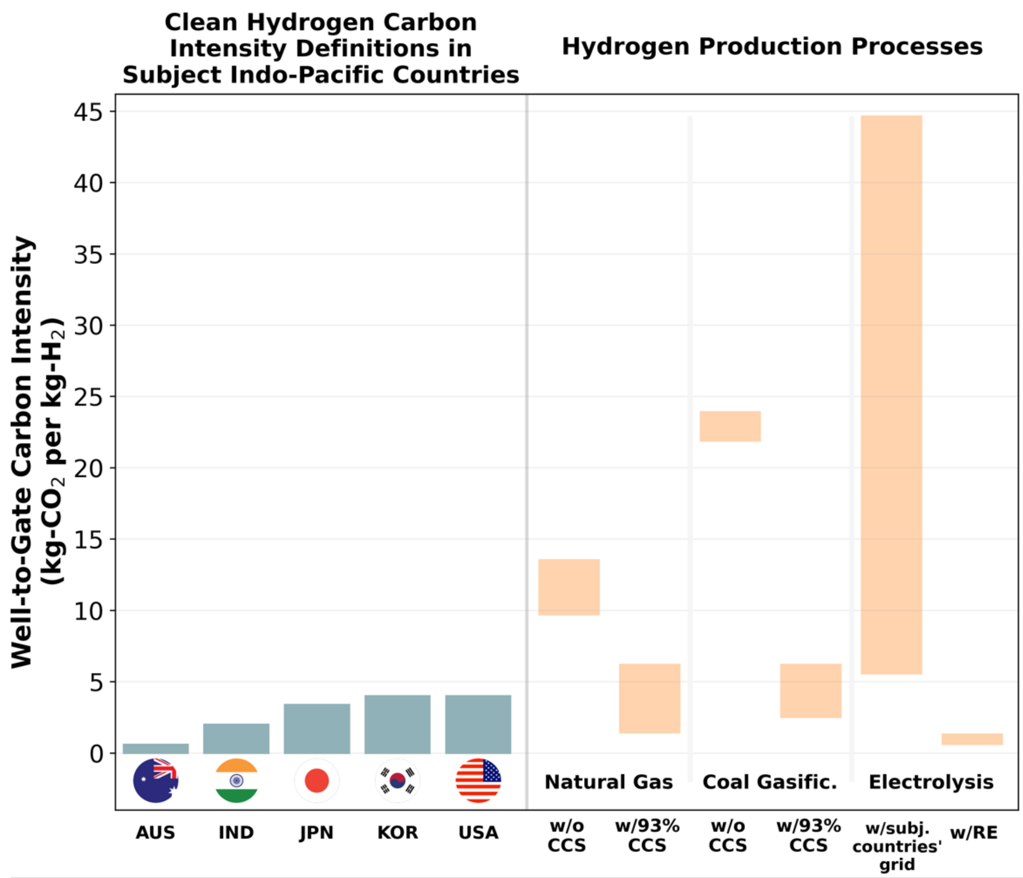

Figure ES4. Well-to-gate carbon intensity as defined by some selected Indo-Pacific countries for low-carbon hydrogen and as calculated and reported for different hydrogen production processes.

See the caption of **Figure 17** for details about the data on this figure.

The analysis of this report identifies a lack of available hydrogen-related data that could facilitate the progress of low-carbon hydrogen market in the region. For instance, only five countries have reported their definition of low-carbon hydrogen using a well-to-gate carbon intensity (**Figure ES4**). This gap could present a challenge for regional low-carbon hydrogen trades that may require certification of the carbon intensity of traded hydrogen. Similarly, there is a lack of available data on the amounts of low-carbon hydrogen to be exported by specific countries. Although production and procurement targets may have been defined by some subject countries, the specific amounts to be exported from the produced hydrogen are still unclear. Understanding and sharing these, and similarly relevant, details could inform future supply chain and techno-economic analyses. Therefore, future efforts could benefit the most from unifying a definition for low-carbon hydrogen and from establishing agreements on reporting methodologies that could facilitate international and regional collaborations in low-carbon hydrogen, ensuring transparency and data-informed decision-making that could strengthen the decarbonization efforts in the region.

Country Profile Summaries

Australia (AUS). Being the world's second-largest exporter of liquified natural gas (LNG) and fourth-largest energy exporter, Australia's maintenance of its energy exporting position is critical as the country transitions away from fossil-based to low-carbon hydrogen. The Australian hydrogen roadmap highlights several key elements for achieving a low-carbon hydrogen economy in the country smoothly. First, Australia plans to build hydrogen hubs to lower investment risks in low-carbon hydrogen technologies. The Government has announced funding for **seven hydrogen hubs** so far in Western Australia, New South Wales, Tasmania, Queensland, and South Australia. Second, Australia recognizes the large value of certification and regulations around clean hydrogen. The current methodology for calculating hydrogen-related carbon emissions under the Guarantee of Origin (GO) scheme is expected to include **upstream emissions**, **direct emissions**, **and post-production emissions**. Implementing the GO certification scheme could reduce uncertainty of hydrogen-importing countries regarding the emissions of the supplied Australian hydrogen. Additionally, Australia plans to design a regulatory framework that ensures safe operations, secured energy, and stable energy pricing both domestically and globally. Third, the Australian governments are planning to increase public awareness of hydrogen utilization and safety, addressing the social aspect of low-carbon hydrogen deployment. Finally, realizing all of these goals requires setting reasonable targets for the country to pursue as it develops and deploys low-carbon hydrogen technologies in the country. Australia plans to produce **0.5-1.5 Mt-H_2 per year by 2030, 5-12 Mt-H_2 per year by 2040, and 15-30 Mt-H_2 per year by 2050**. The country also plans to achieve low-carbon hydrogen prices of **US$1.5-3.4 per kg-$H_2$ by 2030, US$1.3-2.5 per kg-$H_2$ by 2040, and US$1.1-2.4 per kg-$H_2$ by 2050**. Overall, Australia has invested more than US$345 to support the development of hydrogen hubs, and it has progressed well in terms of hydrogen supply but still needs further progress in terms of hydrogen offtake due to cost and regulatory uncertainties.

Brunei Darussalam (BRN). Brunei currently focuses on fossil-based natural gas (NG) as a raw material for hydrogen production via steam methane reforming (SMR) coupled with carbon capture and storage (CCS) for low-carbon hydrogen production. Potentially, **this route could produce 3.6 Mt-H_2 per year**, which can cover up to 5% of the combined 2050-forecasted hydrogen demand in the Association of Southeast Asian Nations (ASEAN) countries. However, the contribution from electrolytic hydrogen is **limited to up to 0.07 Mt-H_2 per year due to limited land space and renewable energy potential**, mainly from floating solar photovoltaics (FSPV). Due to these factors, carbon dioxide removal (CDR) technologies, including biomass with carbon capture and storage (BECCS) and direct air capture and storage (DACS), could play important roles to offset residual carbon emissions from SMR-CCS hydrogen production facilities. However, these technologies could face land constraints that need to be considered in this scenario. In addition, consideration of low-carbon hydrogen as a means for decarbonizing the power, transportation, and industrial sectors could provide a promising opportunity for Brunei, especially if hydropower becomes available from Malaysia's Sarawak state. In the future, Brunei could benefit from integrated hydrogen-related strategies within its climate-related documents to ensure holistic overview of climate solutions that could be critical for achieving its 2050 net zero emissions goal. Specifically, inclusion of low-carbon hydrogen in the ten climate strategies, developed by Brunei's National Council on Climate Change, could provide this benefit.

Fiji (FJI). Fiji is committed to achieving net-zero carbon emissions by 2050. Although hydrogen was not explicitly stated in their low-emission development strategy brief, the potential for its use in power generation and renewable energy exportation could render it promising for Fiji's net-zero journey. As an island country, **Fiji expects to be a net importer of hydrogen**. Indeed, Fiji has an active international partnership with two hydrogen companies from Japan and New Zealand to deliver hydrogen to Fiji for dual-fuel power generation. Fiji is slowly pursuing hydrogen production with a recently (April 2024) announced collaboration between Hydrogen Power Fiji–a subsidiary of Hydrogène de France (HDF) Energy–and Pacific Trade Investment (PTI) Australia to develop the first electrolytic hydrogen production plant in the country, powered by a mix of solar, wind, and on-site energy storage. Future directions for Fiji could include carrying techno-economic, environmental, and social assessments of hydrogen in the power sector as one of the solutions that may help the country **generate close to 100% electricity from renewable energy by 2030, according to their National Development Plan (NDP)**. In addition, developing standards, codes, regulation, and policy around hydrogen technologies could be a priority before participating in the hydrogen market as an importer or exporter. Specifically, certificates with explicit carbon intensity for hydrogen production are expected to be an integral part of low-carbon hydrogen trades both regionally and globally. However, establishing a domestic low-carbon hydrogen market and reaching 100% renewable energy might be of a higher priority to Fiji before potential export of low-carbon hydrogen overseas. Finally, **creating a hydrogen strategy and roadmap could be useful** to guiding hydrogen investments in the country and promoting regional and global collaborations in this sector.

India (IND). India is motivated to pursue low-carbon hydrogen due to its potential of contributing to energy security and independence. In 2021, India was the world's third-largest energy importer, fourth-largest LNG importer, and third-largest coal and petroleum product importer. To ensure a well-planned entrance into the hydrogen market, India's National Green Hydrogen Mission (NGHM) report presents several key elements for pursuing low-carbon hydrogen in the country. First, India plans to localize its hydrogen supply via the pursuit of emerging low-carbon hydrogen production technologies, such as water electrolysis. Specifically, the first goal of the country is to **produce 5-10 Mt-H_2 per year by 2030** to localize a significant part of its domestic demand via localized low-carbon hydrogen processes. In parallel, India plans to **localize electrolyzer manufacturing** with a potential to **export electrolyzers** as the low-carbon hydrogen market grows. Second, India plans to develop and deploy low-carbon hydrogen in two phases starting from 2022 and ending in 2030. The first phase is planned to focus on demand and supply creation, whereas the second phase is planned to expand low-carbon hydrogen pilot projects. To help with demand creation, the government developed a bidding framework that took place in mid-2023 and selected seven hydrogen-related projects to be awarded governmental financial incentives. Third, the mission encouraged ministerial cooperation with identified specific responsibilities for every relevant Indian ministry. Fourth, the mission recommends several actions for the state and center governments regarding incentives, regulation, and policy of low-carbon hydrogen that will encourage investments and increase awareness. Finally, although the mission aims to produce **5 Mt-H_2 per year by 2030**, it reports **a potential expansion to 10 Mt-H_2 per year, depending on the growth of the hydrogen export market**. In addition, it aims to create new 600,000 jobs in the low-carbon hydrogen space and allocate approximately US$97 billion in low-carbon hydrogen investments by 2030.

Indonesia (IDN). Indonesia's hydrogen roadmap provides essential insights on how Indonesia is a promising location for low-carbon hydrogen production. Particularly, Indonesia's archipelagic location and abundance of renewable energy sources (e.g., solar and wind) presents an opportunity for the country to pursue low-carbon hydrogen production and exportation. Being the third-largest ammonia exporter in the world, Indonesia is positioned well in terms of exporting renewable energy in the form of liquid ammonia. However, the Indonesian Government recognizes the challenges regarding low-carbon hydrogen technologies, such as uncertain supply and demand, insufficient investments, and lack of clear regulations. Thus, the hydrogen roadmap presents a three-pillar strategy that depends on reducing fossil fuel dependence, developing domestic hydrogen demand, and exporting hydrogen and its derivatives to the global market. Indonesia plans to take a careful approach regarding low-carbon hydrogen development and deployment. The country plans to lower the uncertainty around low-carbon hydrogen technologies by building a hydrogen infrastructure while updating its assessment of the different hydrogen technologies. Finally, the Indonesian hydrogen strategy expects a **6.5 Mt-H_2 per year production rate to be achievable by 2060**, and it **estimates a 2040 hydrogen cost to be in the range of US$1.9-3.9 per kg H_2**, depending on the production method of low-carbon hydrogen and its power source.

Japan (JPN). Japan was the earliest country to present a low-carbon hydrogen strategy, which was announced in 2017. The strategy sets the stage for Japan and other countries to initiate commitments around clean hydrogen. The original Japanese hydrogen strategy ambitiously sets three phases for low-carbon hydrogen starting with increased hydrogen use (i.e., increasing hydrogen demand), followed by introduction of hydrogen power generation and supply chain by 2030, and ending with an established CO_2-free hydrogen supply chain by 2040. Japan's 2023 updated hydrogen strategy provides a refined vision for the country to pursue low-carbon hydrogen technologies. For instance, being a **current net importer of energy and hydrogen**, the instability of recent gas prices has motivated the Japanese Government to diversify its energy portfolio. This action could reduce the country's dependence on fossil-based energy sources and could create demand for low-carbon energy. Under the Hydrogen Society Promotion Act, enacted in May 2024, Japan will provide supporting measures to the approved hydrogen business plans to promote supply and utilization of low-carbon hydrogen and its derivatives. Japan plans to provide a 15-year support to suppliers who aim to develop a commercial-scale supply chain of low-carbon hydrogen and its derivatives, provided that such suppliers are obligated to continue their hydrogen supply for another 10 years after the support period. Additionally, Japan plans to subsidize a portion of the capital cost of low-carbon hydrogen land transportation services. Japan plans to grow demand as careful as possible to meet hydrogen supply, ensuring immediate low-carbon hydrogen utilization in power generation, transportation, and household applications. To support this effort, **the public and private sectors are investing approximately US$105 billion to develop commercial-scale supply chain for low-carbon hydrogen and its derivatives**. In addition, the government plans to develop international hydrogen standards regarding hydrogen use in fuel cells, refueling stations, and auxiliary equipment. Furthermore, Japan plans to increase its effort in public awareness and safety of hydrogen via developing a publicly available safety strategy report that is supported by scientific evidence and internationally accepted codes. Finally, Japan targets an annual low-carbon hydrogen procurement of **3 Mt-H_2 per year by 2030, 12 Mt-H_2 per year by 2040, and 20 Mt-H_2 per year by 2050**. The delivered prices of low-carbon hydrogen to Japan's ports are expected to be **US$2.3 and US$1.6 per kg-H_2 by 2030 and 2050, respectively**. Regarding electrolyzer manufacturing, Japan plans to reduce the capital costs of **alkaline water electrolyzers to approximately US$365 per kW** and **of proton exchange membrane (PEM) water electrolyzers to approximately US$456 per kW by 2030**. This effort could facilitate the commercialization of cost-competitive electrolysis-based hydrogen production.

Malaysia (MYS). With approximately 285 Gigawatts (GW) of solar and hydro power potential, **Malaysia plans to become a net exporter of renewable energy via low-carbon hydrogen and its derivatives**. Along with its renewable energy potential, Malaysia's existing hydrogen infrastructure and handling expertise makes it a suitable location for low-carbon hydrogen production and exportation. Malaysia's hydrogen roadmap provides a thorough techno-economic analysis that determines specific targets for low-carbon hydrogen deployment such as a maximum production cost of **US$4.8, US$2.6, and US$2.1 per kg-$H_2$ by 2030, 2040, and 2050, respectively**, from solar-powered water electrolysis. In addition, Malaysia's roadmap estimates production rates of **0.9-2.0 Mt-H_2, 3.6-7.0 Mt-H_2, and 6.6-15.0 Mt-H_2 per year in 2030, 2040, and 2050, respectively**. Malaysia plans to **export 0.5-1.0 Mt-H_2 per year by 2030**, expand its domestic hydrogen market by 2040, and diversify hydrogen production and utilization pathways by 2050. To achieve these goals, Malaysia is creating a governance structure with three clusters that focuses on hydrogen production and conversion, hydrogen transportation and storage, and hydrogen end-use market development. Moreover, the government of Malaysia plans to build its current and future workforce capabilities by introducing courses that build necessary hydrogen-related skills, especially for unemployed and low-income individuals. Such an effort could ensure the growth of the country in this space while increasing public awareness around low-carbon hydrogen production and safety.

New Zealand (NZL). New Zealand published a hydrogen vision in September 2019 and consulted on an interim hydrogen roadmap in August 2023, highlighting the challenges and opportunities of low-carbon hydrogen production and utilization in the country. Following a change in Government in late 2023, New Zealand recently published a Hydrogen Action Plan on 14 December 2024. In the time available, this document has not been able to be included in the present analysis. The Interim Hydrogen Roadmap outlines a proposed role for hydrogen in the energy system and role for government in supporting hydrogen. Interest in hydrogen in New Zealand has focused on decarbonization of hard-to-electrify sectors, such as heavy transport and heavy industry. New Zealand has potential to export hydrogen, with a demonstration project from New Zealand to Fiji already announced. The Government committed in the Interim Hydrogen Roadmap to undertake further work to understand the electricity system implications of hydrogen export. The Interim Hydrogen Roadmap lists several governmental actions, including but not limited to, establishing regulatory work to enable safe hydrogen operation, budgeting US$19 million over 3 years to establish a Clean Heavy Vehicle Grant, which is open to hydrogen fuel cell heavy-duty vehicles, and cooperating internationally to develop mutual recognition of hydrogen certification schemes.

Philippines (PHL). The 2023-2050 Philippines Energy Plan (PEP) highlights that natural gas consumption was fully dominated by power generation in 2022. Given the need for energy decarbonization and the availability of natural gas reserves in the Philippines, **hydrogen production via SMR coupled with CCS could present a potential bridge to achieving decarbonization**. This low-carbon hydrogen, as stated in the PEP report, can be used as a potential alternative fuel for transportation and baseload power generation. On the other hand, electrolytic hydrogen is yet to be developed in the country. To help with this effort, the national policy framework for hydrogen document was developed, outlining the creation of a Hydrogen Energy Industry Committee (HEIC) that oversees the implementation of policy, ensures the comprehensive development of hydrogen and its derivatives, and promotes investment. An announced hydrogen project is the planned HDF Energy's power plant that would utilize electrolytic hydrogen to supply **up to 45 Megawatt (MW) of power to 800,000 inhabitants** in the Zamboanga Sibugay province by 2025. So far, the Philippines' Department of Energy has not received updates on the project, and important details are still lacking regarding carbon intensity and safety measures as they relate to this project, potentially slowing down its deployment. Therefore, tracking progress as well as addressing policy and regulation gaps regarding low-carbon hydrogen projects, such as carbon intensity limits and hydrogen safety measures, could benefit the Philippines in its progress toward low-carbon hydrogen deployments. The Philippines' Department of Energy, through HEIC, has been involved in developing a strategic roadmap for hydrogen, which can address such issues around low-carbon hydrogen technologies.

Republic of Korea (KOR). In November 2021, the Republic of Korea has published the 1st basic plan for implementation of a hydrogen economy, which highlights the potential of low-carbon hydrogen to enable energy independence and accelerate the achievement of the country's climate commitments. Through demand creation and a special focus on hydrogen fuel cell developments, the Republic of Korea plans to enter the global low-carbon hydrogen market as a **net importer of hydrogen** and a **net exporter of hydrogen fuel cell technologies for transportation and power generation**. The Government of the Republic of Korea sets targets of 300,000 commercial hydrogen fuel cell vehicles and 660 installed hydrogen refueling stations by 2030. Approximately 10% and 40% of these targets, respectively, have been met in 2023, showing progress toward hydrogen fuel cell vehicle deployment. By 2040, South Korea's government plans to have **1,200 hydrogen refueling stations**, expanding the hydrogen vehicle infrastructure to encourage technology. Furthermore, the basic plan highlights that the 2030 targets for hydrogen supply are set at **3.9 Mt-H_2 per year**, which **includes 3.0 Mt-H_2 per year from low-carbon hydrogen production methods**. Out of this amount in 2030, **approximately 2.0 Mt-H_2 per year** is expected to be imported from overseas whereas the remaining amount is planned to be produced locally. **By 2050,** the supply target increases to **approximately 27.9 Mt-H_2 per year from low-carbon sources**, out of which **approximately 22.9 Mt-H_2 per year is imported to the country**. The associated local production cost targets from **electrolytic hydrogen are estimated to reach US$2.7 and US$1.9 per kg-H_2 by 2030 and 2050, respectively**. The production cost of **electrolytic hydrogen from imported routes is targeted to be US$1.0 and US$2.0 per kg-H_2 by 2030 and 2050, respectively**. To support the expansion of hydrogen production and procurement, the Republic of Korea has established the clean hydrogen certification scheme that provides a tiered system for low-carbon hydrogen produced and/or procured based on carbon intensities. The **maximum carbon intensity in this system is set at 4.0 kg-CO_2 per kg-H_2**, which covers the **well-to-gate** emissions and excludes ship and hydrogen carrier emissions temporarily. In addition to hydrogen production, the Republic of Korea's government has plans to manufacture **6.2 million hydrogen vehicles and export 3.3 million of them by 2040**. By the same year, the targets for local hydrogen-fueled taxis, buses, and trucks are set at 80,000, 40,000, and 30,000, respectively. Manufacturing of fuel cells is also considered by South Korea, with **2040 targets of 15 GW for power generation and 2.1 GW for homes and buildings**. To further support these efforts, a hydrogen safety management system is planned to be established with two bills already initiated regarding hydrogen safety. Furthermore, increasing public awareness is pursued by the government through distributing hydrogen guidebooks and establishing a hydrogen experience center that is focused on increasing awareness around hydrogen safety. Overall, the Republic of Korea has progressed significantly in terms of hydrogen fuel cells and could observe a steep expansion in the coming years regarding fuel cell deployment, hydrogen production, and hydrogen usage.

Singapore (SGP). As a densely populated and land scarce country, Singapore has limited indigenous energy sources. Singapore imports almost all its energy needs and, likewise, plans to import most of its hydrogen and renewable energy from overseas. Singapore's National Hydrogen Strategy provides insights on low-carbon hydrogen potential in the energy, transportation, and industrial sectors. Particularly, importing hydrogen in the form of ammonia can benefit Singapore, as it can either be directly combusted or cracked into hydrogen, which can be used for power generation and/or **as a bunker fuel** for ships. The last application is of particular interest to the country as it **was the largest bunkering hub in 2021**. Moreover, the Government of Singapore encourages innovation in low-carbon hydrogen technologies, especially in areas of low-carbon ammonia cracking and utilization, hydrogen and ammonia safety and regulatory standards, and hydrogen transportation and distribution, with a total funding of **more than US$130 million through the Low-Carbon Energy Research (LCER) funding initiative**. Similar to all selected Indo-Pacific countries, Singapore plans to strengthen its international collaborations by supporting GO certificates, cross-country research collaborations, and trading and financing ecosystem for low-carbon hydrogen. Finally, Singapore plans to further strengthen its workforce in the areas of handling, transportation, and storage of hydrogen and its derivatives.

United States (USA). In 2021, the U.S. announced the Bipartisan Infrastructure Law (BIL), which **included US$9.5 billion for low-carbon hydrogen technologies**. Following that, in August of 2022, the Inflation Reduction Act (IRA) was announced with a proposed hydrogen production tax credit (PTC) of **up to US$3.00 per kg-$H_2$**. These two bold actions position the U.S. well for taking over a significant portion of the low-carbon hydrogen market in the future. In June of 2023, the U.S. announced its National Clean Hydrogen Strategy and Roadmap, providing specific targets and actions that guide the U.S. hydrogen market toward achieving wide low-carbon hydrogen deployment by 2050. The U.S. plans to replace most of its current annual hydrogen production of **10 Mt-H_2 per year with low-carbon hydrogen by 2030**. With current announced low-carbon hydrogen projects, the U.S. is on track to exceed this target by an additional 2 Mt-H_2 per year, potentially opening the door for **exporting low-carbon hydrogen by 2030**. Furthermore, the U.S. plans to increase its electrolyzer manufacturing capabilities to meet associated high global demand. To do this, the U.S. invests heavily in research, development, demonstration & deployment (RDD&D) with the goal of **reducing the capital costs of alkaline, PEM, and solid oxide electrolysis cell (SOEC) electrolyzers to US$230-400, US$380-450, and US$300-500 per kW, respectively, by 2030**. Moreover, the U.S. estimates low-carbon hydrogen production to cost **US$1.6-1.8**, **US$1.2-1.4**, and **US$1.2 per kg-$H_2$ by 2030, 2040, and 2050, respectively**. Generally, the U.S. hydrogen roadmap aims to focus on three priorities: high-impact end uses for low-carbon hydrogen, cost reductions of low-carbon hydrogen, and establishment of hydrogen hubs to support lower delivered hydrogen costs. The main challenge for the U.S. is assuring the readiness and willingness of hydrogen offtakers to create demand for low-carbon hydrogen, which is supported by governmental financial incentives and credit mechanisms that lower the risk for low-carbon hydrogen offtakers.

Viet Nam (VNM). Viet Nam plans to become a **net hydrogen exporter** with low-carbon hydrogen being produced both from fossil (coupled with CCS) and non-fossil sources. **By 2030**, Viet Nam's hydrogen plan estimates the production of low-carbon hydrogen to reach **0.1-0.5 Mt-H_2 per year**. This number is estimated to expand to **10-20 Mt-H_2 per year by 2050**, presenting a significant upscaling challenge for the country that may require large investments and commitments. To accomplish this goal, Viet Nam aims to repurpose and expand existing infrastructure to enable low-carbon hydrogen production and utilization to grow. Low-carbon hydrogen is expected to enter Viet Nam's gas, power generation, transportation, and industrial markets, diversifying its use cases for wider reach. Building on these plans, Viet Nam's National Energy Master Plan summarizes the scales, potential locations, and timeline of low-carbon hydrogen projects. **Three projects are planned to be operational by 2030 with scales in the range of 0.1-0.4 Mt-H_2 per year**. **By 2050, Viet Nam plans to have three operational low-carbon hydrogen projects, each at the scale of 1-12 Mt-H_2 per year**. Finally, two low-carbon hydrogen projects have been announced so far. The first project is in the planning stage, aiming to produce approximately **60 kt-H_2 per year via a mix of alkaline and PEM water electrolysis that have a combined capacity of 1 GW**. The second project is an ammonia project that could produce **0.2 Mt-ammonia (NH_3) per year** while utilizing electrolytic hydrogen as an input in the ammonia production process. Improvements on Viet Nam's hydrogen development plan on the legal framework and regulatory provisions, as well as on the certification and target definitions, could strengthen Viet Nam's position in the new hydrogen market.

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1 Introduction

Low-carbon hydrogen (H_2) has been considered globally as a significant part of the future energy mix. It has also been considered as a clean fuel and feedstock for several applications, including transportation and ammonia production. Conventionally, hydrogen is produced via steam methane reforming (SMR) or coal gasification, in which the main product and byproduct are H_2 and carbon dioxide (CO_2), respectively. These processes are carbon emitters, with estimated CO_2-eqivalent (CO_2-eq) emissions of 11.4 kg-CO_2-eq and 22.7 kg-CO_2-eq per kg-H_2.[2] Note that these numbers include median direct and upstream CO_2 emissions, as estimated by the International Energy Agency (IEA).[2] Integrating SMR and coal gasification with carbon capture and storage (CCS) technologies could result in lower emissions of 2.6-6.1 kg-CO_2-eq and 2.3-3.1 kg-CO_2-eq per kg-H_2, respectively, depending on the CO_2 capture rate.[2]

Cleaner hydrogen production methods include water electrolysis, which splits water into H_2 and oxygen (O_2) using electricity and thus depends heavily on the price and source of electricity. Solar and wind power can supply this electricity, resulting in carbon intensities of 0.6-1.3 kg-CO_2-eq per kg-H_2.[2] It is worth noting that integrating water electrolysis with different grids can have significantly different carbon intensities. For instance, the IEA reports that integrating water electrolysis with the 2021 global grid could result in a generation-weighted average carbon intensity of 23.5 kg-CO_2-eq per kg-H_2.[2] Comparatively, integrating water electrolysis with a grid where nearly 100% of the electricity comes from hydropower generation (e.g. Paraguay), would result in an approximate carbon intensity of 0 kg-CO_2-eq per kg-H_2, as reported by the IEA.[3]

Another clean hydrogen production method is biomass gasification, which uses heat, steam, biomass, and oxygen (O_2) to produce H_2 and CO_2 in a two-step process. The product is then separated using membranes or adsorbers to provide a purified source of H_2. The process emits approximately 3.7 kg-CO_2-eq per kg-H_2 without CCS.[2] Integration of biomass gasification with CCS could make this pathway carbon-negative, with a carbon intensity of -17.5 kg-CO_2-eq per kg-H_2.[2]

Clean (or low-carbon) hydrogen can be used in many applications to lower the global greenhouse gas (GHG) emissions from several sectors. Hydrogen combustion engines and hydrogen fuel cells can mitigate the GHG emissions from the land transportation and electricity generation sectors; sustainable aviation fuel (SAF), if produced from clean sources of carbon (*e.g.*, atmospheric CO_2 or biomass) and low-carbon hydrogen, can lower the emissions from the aviation sector; and ammonia, if its hydrogen is sourced from low-carbon hydrogen production methods, can mitigate the emissions from the agriculture sector. All of these applications could contribute heavily to the decarbonization of several hard-to-abate sectors, potentially reducing the impacts of climate change worldwide. Therefore, several countries and organizations have considered hydrogen as a versatile energy carrier in their reports.[2,4,5]

The selected Indo-Pacific countries could directly benefit from hydrogen technologies as they attempt to reach their net-zero GHG goals while growing their clean economies. Indeed, these countries have identified hydrogen supply chains as the first cooperative work program (CWP) to pursue, highlighting the important role that hydrogen will play in the economic growth.

In this report, we provide a status overview of low-carbon hydrogen in the selected Indo-Pacific countries. Those countries are Australia, Brunei Darussalam, Fiji, India, Indonesia, Japan, Malaysia, New Zealand, the Philippines, Singapore, Thailand, Republic of Korea, United States, and Viet Nam. We highlight efforts in the technological, policy, and regulation spaces, as reported by those countries in their publicly announced reports. We additionally provide peer-reviewed information and data from partners to ensure the accuracy of the data reported in this work. We finally identify synergies and gaps, aiming to elevate the progress of low-carbon hydrogen assessment and deployment in the region. It is worth highlighting that this report is a snapshot of the work carried by selected Indo-Pacific countries, meaning that future progress could change some of the conclusions of this report.

2 Australia

Table 1. Quantitative hydrogen-related plans and progress in Australia.

Country	Certification / Standard Scheme	Hydrogen Incentives	Port Readiness	Storage and Transportation	Net Importer / Net Exporter
Australia	*In Progress*	*RD&D* *Per kg*	*Export* *Import*	*Exists* *Plan* *Repurp.*	*Net Exporter*

2.1 Brief Overview

In September 2024, Australia's Department of Climate Change, Energy, the Environment and Water (DCCEEW) released an update to Australia's 2019 National Hydrogen Strategy, highlighting the country's ability to co-lead the region and the world in the clean hydrogen economy.[6,7] Specifically, the strategy emphasized Australia's established hydrogen-based industry, growing hydrogen infrastructure, clean **history of exporting energy to countries in the region**, and abundant solar and wind resources, which will all play important roles in producing low-carbon hydrogen.[7] In 2020, Australia was ranked the fourth-largest fossil fuel exporter globally with 85% of its produced energy being exported to other countries.[8] This percentage was equivalent to approximately US$61 billion of energy export earnings and 18.6 exajoules (EJ) of exported energy. Most of this amount comes from the three top exported energy sources, which were black coal, natural gas (NG), and uranium.[9] Dominant companies of these markets in Australia include **BHP Group Limited** (total revenue of US$53.8 billion in 2023[10]), **Chevron** (total revenue of US$196.9 billion in 2023[11]), **Shell** (total revenue of US$316.6 billion in 2023[12]), and **Woodside Energy** (total revenue of US$14.0 billion in 2023[13]).

In its 2024-25 budget, the Australian Government unveiled a Future Made in Australia (FMIA) plan, which aims to maximize the economic and industrial benefits of the move to net-zero GHG emissions and securing Australia's place in a changing global economic and strategic landscape.[14] The budget invested approximately **US$15.5 billion over ten years**, starting from 2024, to achieve these goals, and it includes measures to help develop a viable hydrogen sector in Australia.[14] In addition, the Australian Government offers several hydrogen-related funding to researchers and project developers. From these programs, the hydrogen-specific funding make up approximately **27.4% (US$3.4 billion) of the total reported funding (US$12.3 billion)**, underscoring the key role that hydrogen is expected to play in Australia's transition to cleaner energy.[15] Although many hydrogen programs/projects have commenced since 2017–the oldest date for these programs/projects–it is still unclear when this financial support is going to be fully materialized. Clarity around the timeline of such funds could improve tracking of Australia's progress in hydrogen-related projects.

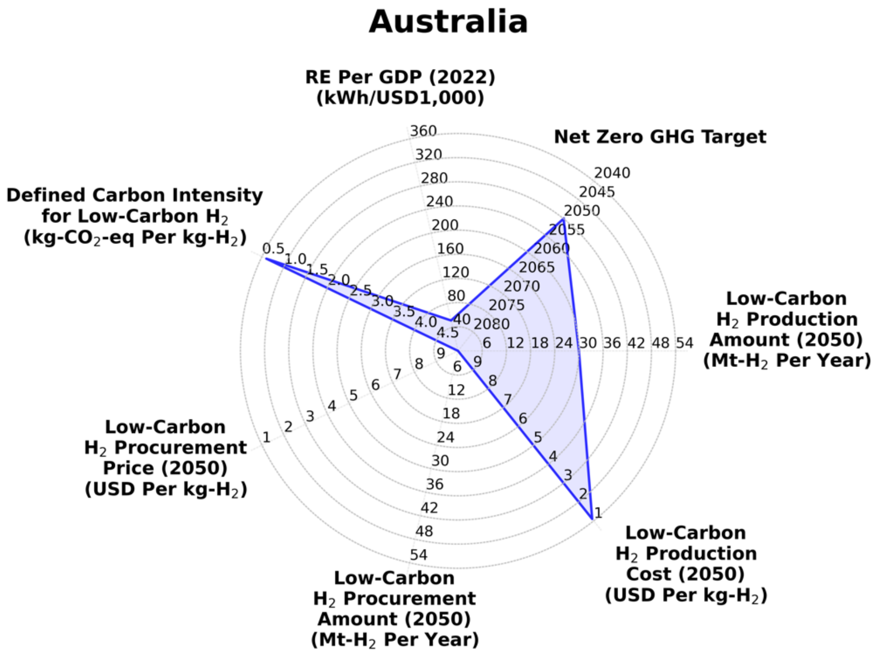

Figure 1. Radar plot of Australia's figures of merit.

Note that some metrics were missing due to the lack of available data.

2.2 Key Objectives of Australia's National Hydrogen Strategy 2024

2.2.1 Supply

To meet hydrogen supply, Australia's 2024 national hydrogen strategy sets low-carbon hydrogen production targets from 2030 until 2050, with 5-year increments, consistent with Australia's net-zero GHG emission target.[7] Australia aims to **produce 0.5 Mt-H_2 per year by 2030, 5 Mt-H_2 per year by 2040**, and **15 Mt-H_2 per year by 2050**, with a potential to **stretch these targets to 1.5, 12, and 30 Mt-H_2 per year, respectively**.[7] The stretch potential scenario depends on future export demands of hydrogen by partner countries and external investments into Australian hydrogen projects.[7]

Additionally, Australia's national hydrogen strategy provides estimated production costs of low-carbon hydrogen for three low-carbon hydrogen production technologies, which are SMR-CCS, alkaline water electrolysis, and proton exchange membrane (PEM) water electrolysis.[7] **By 2030, the cost ranges of hydrogen produced via alkaline and PEM water electrolysis are expected to be US$1.5-2.8 and US$1.9-3.4 per kg-H_2, respectively**.[7] Comparatively, **hydrogen from SMR-CCS is expected to cost US$2.7 per kg-$H_2$ by 2030**.[7] By 2050, low-carbon hydrogen production via **SMR-CCS, alkaline water electrolysis, and PEM water electrolysis are estimated to cost US$2.4, US$1.1-2.1, and US$1.1-2.1 per kg-$H_2$, respectively**.[7] To further support this effort, Australia plans to provide a **10-year Hydrogen Production Tax Incentive (HPTI) of approximately US$1.4 (AU$2.0) per kg-H_2** for low-carbon hydrogen production facilities starting from 2027-2028 up until 2039-2040.[7] The eligibility criteria for such projects include reaching a final investment decision (FID) by 2030 and keeping the CO_2 intensity from well to production gate (well-to-gate) at **0.6 kg-CO_2-eq per kg-H_2**.[16]

Moreover, Australia plans to expand the Hydrogen Headstart Program–a program that provides support for early movers of well-developed low-carbon hydrogen projects to address the current financial gap between the production cost and sale price of low-carbon hydrogen.[7] In addition, Australia announced approximately **US$1.2 billion**, under the FMIA Innovation Fund, to support the deployment of innovative technologies linked to priority industries, including green metals and low-carbon liquid fuels.[7,14] An additional **US$345 million** is announced to support the development of hydrogen hubs in regional areas.[7] To date, funding has been announced for **seven hydrogen hubs** located in Western Australia, New South Wales, Tasmania, Queensland, and South Australia.[17,18]

2.2.2 Demand Identification and Support

Australia's hydrogen strategy focuses on use-cases for hydrogen that are **currently most prospective** and aligned with Australia's decarbonization goals. Such end uses include industry, transportation, and electricity and energy. As a chemical energy carrier, hydrogen can be considered as a fuel or a feedstock. Industrial heating, hydrogen fuel cell vehicles, and power generation can benefit from hydrogen as a fuel. Australia plans to incorporate hydrogen use as a fuel in the green metals (*e.g.*, iron and alumina), long-haul transport (*e.g.*, heavy-duty, aviation, and shipping), and electricity grid generation/support. In addition, the only viable pathway today for decarbonizing ammonia production is through hydrogen production decarbonization. Two of the most common routes that accomplish this objective are coupled SMR-CCS or water electrolysis. It is worth noting that Australia also considers ammonia as an energy carrier for exporting renewable energy overseas, which can be eventually used as a fuel (*e.g.*, for power generation) or a feedstock (*e.g.*, for fertilizer production) at the point of use.

2.2.3 Regulations and International Collaborations

From the regulatory side, Australia's hydrogen strategy shows interest in building a regulatory framework specific to hydrogen that assures safety, stable energy prices, and prolonged energy security.[6] Australia's 2019 hydrogen strategy identified **730 pieces of legislation and 119 standards** that are potentially important for the new hydrogen economy. One of the most important factors of the Australian regulatory framework around hydrogen is the regulation responsiveness, referring to adapting these regulations as the industry grows,[6] which could potentially lower the risk of clean hydrogen investments. Another essential factor of the framework is the international collaborations and outreach that enable the country to secure early partnerships with hydrogen-importing countries, build global and regional hydrogen markets, promote efficient hydrogen trades and innovation, and assure community trust and confidence.[6] **Today, Australia is an energy exporter** to Japan, the Republic of Korea, Singapore, and Taiwan.[6] Assuring a smooth transition from fossil-based energy sources to clean energy sources (including low-carbon hydrogen) will be essential for Australia to maintain established bilateral partnerships as it builds its clean hydrogen economy.

Moreover, implementing hydrogen-related policies is essential for low-carbon hydrogen to enter the market smoothly. Commitments from Australia were made at the 26th Conference of the Parties (COP) and with the G7 partners to scale up hydrogen technologies while lowering their costs and emissions.[19] In addition, Australia (along with Brunei, India, Japan, Malaysia, Singapore, Republic of Korea, United States, and other countries) was part of the COP28 Declaration of Intent, which acknowledges the need for certification schemes of low-carbon hydrogen and its derivatives.[20] These actions highlight the Australian commitments toward developing a transparent low-carbon hydrogen market globally. Executing such commitments in the coming years will be critical to the progress of low-carbon hydrogen in Australia and the Indo-Pacific region.

2.2.4 Community Benefit

Domestically, the Australian 2024 hydrogen strategy recognizes the critical role played by the community in shaping the future of hydrogen. It emphasizes the importance of increasing public awareness and education about hydrogen and its associated domestic and global benefits.[7] Specifically, the strategy highlights sharing the benefit of a hydrogen economy with First Nations, including an expansion of the First Nations Renewable Hydrogen Engagement Fund pilot.[7] This pilot is aimed to help First Nations communities that live near projects supported by the Hydrogen Headstart program to access services needed to support their engagement with hydrogen project developers.[7]

The Australian Government has also established a Net Zero Economy Authority to ensure that workers, industries, and communities affected by the transition to net zero can seize the opportunities presented by the development of a decarbonized economy.[7] The independent Australian Energy Infrastructure Commissioner will promote best practices for industry and government to adopt in the planning and operation of projects.[7] Additionally, the strategy expects the industry to understand the concerns from local communities and address them responsibly.[7] A voluntary Industry Code of Practice is expected to set clear expectations for all parties.[7]

2.2.5 Trade, Investment, and Partnerships

Australia plans to participate in regional and global hydrogen trades **as an exporter**. The 2024 hydrogen strategy sets a base export target of **0.2 Mt-H_2 per year by 2030**, with a **stretch potential of 1.2 Mt-H_2 per year**.[7] As a large country with a small population, the strategy mentions "investment attraction" as one of the pillars to build trade, investment, and partnerships in Australia.[7] The Australian Trade Commission (Austrade) and the Net Zero Economy Agency are planned to play active roles in attracting international investment in low-carbon hydrogen and its derivatives.[7] In addition, the strategy highlights the role that Australia is taking in implementing a Guarantee of Origin (GO) scheme that will provide an internationally accepted methodology of accounting for life-cycle emissions for hydrogen and its derivatives.[7] **The strategy sets 2025 as the target year for implementing the GO scheme**.[7] Initially, the scheme is expected to be applied to hydrogen and ammonia, but is planned to extend to other products like green metals.[7] It is worth noting that the GO scheme expansion is still in consultation with stakeholders.[7] Generally, the current methodology for calculating hydrogen-related carbon emissions is expected to include **upstream emissions** (i.e., extraction, production, and transport of feedstock), **direct emissions** (i.e., production of outputs from product facility), **and post-production emissions** (i.e., storage and transport of product to delivery gate).[21] The 2024-25 Australian Budget sets approximately **US$22 million to accelerate the implementation of a GO scheme**, in addition to approximately **US$26 million set in the 2023-24 Australian budget**.[14,22]

Aligned with this effort, Australia has established international partnerships related to exporting low-carbon hydrogen to Germany and Japan.[23,24] Australia and Germany signed a Declaration of Intent to invest approximately **US$450 million** to ensure Australian low-carbon hydrogen and its derivatives are considered for exportation to Germany.[24] On the other hand, Australia commissioned a project with Japan to transport liquified hydrogen from Australia to Japan using a ship called *Suiso Frontier*.[23] This project was the first global hydrogen project of its kind.[23] However, it is worth noting that this project faced an equipment (specifically, electrical solenoid valve) failure after an investigation of a hydrogen flame inside the ship.[25] Such an incident calls for further development and advancement in terms of quality control checks at equipment manufacturing facilities to ensure safe hydrogen transportation.

Overall, the established international partnerships between Australia and Japan/Germany underscores the strong role that Australia could play in international trades of low-carbon hydrogen and its derivatives.

2.3 Tracking Progress of Hydrogen Strategy

Given its history of exporting energy in the Indo-Pacific region, **Australia plans to co-establish the low-carbon hydrogen market in the region**. Australia's 2019 strategy predicted the expansion of solar and wind energy deployment in the country to 16 GW between the years 2018 and 2020,[6] a figure that was later realized with installed small-scale and approved large-scale projects.[9] Additionally, the Hydrogen Park South Australia (HyP SA)[26] and Toyota Ecopark Hydrogen Demonstration[27] projects were predicted to be commissioned in 2020.[6] Both projects went live in 2021,[26,28] with a current operation in 2024. The first project is the first renewable hydrogen production facility, equipped with a **1.25 MW PEM water electrolyzer that produces up to 20 kg-H_2 per hour (i.e., 63% energy efficient)** and supplies hydrogen to industry and residential heat applications.[26] The project blends up to 5% (recently increased to up to 10%) of electrolytic hydrogen by volume with natural gas in existing gas networks in Australia, providing heat to the residential sector without the need for consumers to change their usual cooking methods, heating methods, or appliances.[26] The second project allowed Toyota to repurpose a decommissioned manufacturing facility to become a small hydrogen hub with an education center and a commercial-scale gaseous H_2 refueling station.[27,28] Although the hydrogen production scale of this facility is small (**29.2 t-H_2 per year**),[19] it still contributes to the enabling efforts of the hydrogen economy in the country.

To track progress of the hydrogen strategy in Australia, the government initiated an effort to publish two annual reports on the status of hydrogen in Australia for the years 2021 and 2022.[19,29] The 2021 report[29] summarizes the government's actions that helped the hydrogen economy advance in Australia. In addition, it includes an assessment of the industry development signals, which was carried out by the consulting firm Deloitte. Those signals include investment, project scales, cost-competitiveness, and other categories. Particularly, the report highlights Australia's positive progress in the supply of hydrogen, especially in new investments, project-scale targets, cost-competitiveness of clean hydrogen, blending hydrogen in productions at the demonstration scale, and utilizing hydrogen in gas generators.[29] It is worth noting that three announced projects in the 2022 progress report were at **≥100-MW scale**; however, they are still in the development stage (i.e., they have not reached FID yet).[19] The 2021 status report also highlights the slow advancements in the demand side of hydrogen, such as in steelmaking, transportation, and electricity grid supports.[29] These slow advancements are expected due to the high cost and high risk of early hydrogen projects–a point that was highlighted in the 2021 status report.[29] In addition to the assessment of the industry development signals, the report mentions government actions that advanced the hydrogen economy in Australia, including:

- Building international partnerships
- Investments of approximately **US$345 million** in hydrogen hub developments
- Investment of over **US$200 million** in carbon capture, utilization, and storage (CCUS) research and development (R&D)
- Awards of approximately **US$71 million** to three 10 MW electrolyzer projects.

The 2022 status report[19] states that the Australian Government maintained fast progress in hydrogen utilization as a chemical feedstock, evidenced by its growing number of hydrogen, ammonia, and mining projects that use hydrogen as a feedstock.[19] However, the industry development signals assessment indicates that **although a substantial amount of investment was announced in 2022, only one 10-MW electrolyzer hydrogen project passed the FID stage**.[19] This outcome could indicate slow approval or technological progress in the country that could impact the overall position of Australia in the hydrogen market.

Table 2. Summary of Australian hydrogen-related project pipeline up to Dec. 2022. Data source: State of Hydrogen 2022.[19]

Announcement Period	Metric	Value
Since April 2021	Projects with FID	6
	FID-to-All Percentage	5.7%
	Materialized Funds from FID Projects	US$33.4 million
	Total Announced Fund Up to Dec. 2022	US$88,297 million
All Periods	Projects with FID	21
	FID-to-All Percentage	19.8%
	Materialized Funds from FID Projects	US$181.5 million
	Total Announced Fund Up to Dec. 2022	US$88,354 million

Indeed, the hydrogen-related project pipeline was summarized in the 2022 hydrogen status report in a table that highlights all the hydrogen-related announced projects as well as those that were announced since April 2021. From 106 active projects (before and after April 2021), only **21 reached FID**, including 6 projects announced since April 2021 (**Table 2**).[19] Out of the reported funding amounts, **0.21%** have been materialized, underscoring the **investment uncertainty** and **low technological maturity** of hydrogen-related projects in Australia.

3 Brunei Darussalam

Table 3. Quantitative hydrogen-related plans and progress in Brunei Darussalam.

Country	Certification / Standard Scheme	Hydrogen Incentives	Port Readiness	Storage and Transportation	Net Importer / Net Exporter
Brunei Darussalam	Not Reported	Not Reported	Not Reported	Not Reported	Not Reported

3.1 Brief Overview

The state of low-carbon hydrogen deployment in Brunei Darussalam (herein referred to as "Brunei") is still nascent. Recent reports from Brunei's Ministry of Energy and the Department of Energy in the Prime Minister's Office highlight the low potential of renewable power in Brunei due to the scarce wind and biomass resources.[30,31] Brunei expects low-carbon hydrogen production to come from its abundant oil and natural gas resources coupled with CCS.[31] Brunei's oil reserve was estimated to be approximately 11 trillion cubic feet (Tcf) in 2016, and its dry natural gas production was estimated to be approximately 0.4 Tcf in 2015.[32] Utilizing Brunei's dry natural gas alone has the potential to produce **approximately 3.6 Mt-H_2 per year from SMR coupled with CCS**–equivalent to about 5% of the 2050-forecasted hydrogen demand in the Association of Southeast Asian Nations (ASEAN) countries.[31] Electrolytic hydrogen is also expected to contribute to the hydrogen supply in Brunei, though at lower amounts of less than **0.07 Mt-H_2 per year** due to the **limited potential of floating solar photovoltaic (FSPV) of 3,510 GWh**,[31] equivalent to 6.8% of Brunei's total primary energy consumption in 2021.[33] Therefore, considerations around low-carbon hydrogen are still needed to assess the potential of low-carbon hydrogen market development in the country. For instance, a comparison with fossil fuel costs or renewable energy costs could elucidate the need for low-carbon hydrogen development in Brunei.

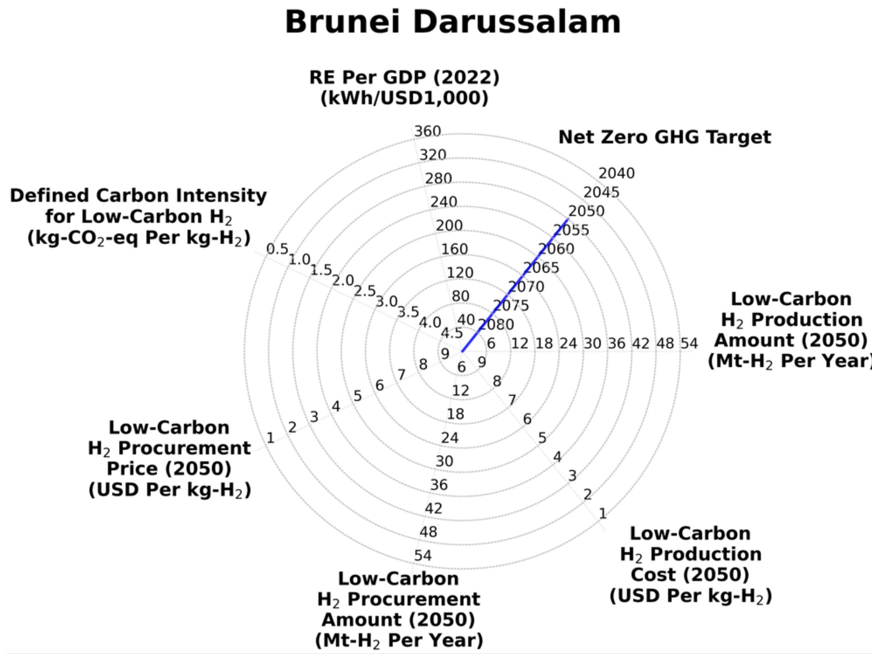

Figure 2. Radar plot of Brunei's figures of merit.

Note that several metrics were missing due to the lack of available data.

3.2 Hydrogen Production and End Uses in Brunei

In 2023, Brunei's Department of Energy in the Prime Minister's Office have published a report on low-carbon hydrogen, in collaboration with the Energy Research Institution for ASEAN and East Asia (ERIA).[31] The focus of the report was on electrolytic hydrogen production and end-uses. Brunei plans to produce most of its low-carbon hydrogen via SMR coupled with CCS due to the abundant oil and natural gas resources in the country. Indeed, considering the current maximum potential of FSPV in the country, the amount of **electrolytic hydrogen that can be produced is less than 0.07 Mt-H_2 per year**, which is merely 0.1% of the 2050-forecasted total hydrogen demand in the ASEAN region alone. **The estimated production costs of the 0.07 Mt-H_2 per year were found to be US$3.5-4.1 and US$4.6-5.2 per kg-H_2 at electricity prices of US$0.05 and US$0.07 per Kilowatt-hour (kWh), respectively**.[31] Therefore, low-carbon hydrogen production via SMR coupled with CCS could be an alternative clean hydrogen production route for Brunei as it pursues its net-zero GHG emission target by 2050.[31,34] Note that these costs do are not necessarily representative of the country's target for the production of low-carbon hydrogen. Defining decadal targets of the facility production cost or procurement price of low-carbon hydrogen could help Brunei in developing an informed strategy for hydrogen development and deployment.

Although SMR-CCS is considered as a low-carbon hydrogen production route, it is likely going to emit a residual amount of CO_2 (e.g., 10% of current SMR CO_2 emissions), potentially requiring carbon offset strategies that could include carbon dioxide removal (CDR) technologies such as biomass with carbon capture and storage (BECCS), direct air capture and storage (DACS), and direct ocean capture and storage (DOCS). CDR technologies may require large land spaces compared to the size of Brunei. Thus, carbon offset strategies could be leveraged to offset the residual emission amounts. Thus, defining a carbon intensity for low-carbon hydrogen could become necessary to participate in the global hydrogen and carbon markets as we approach 2050.

Regarding low-carbon hydrogen end uses, Brunei considers **power generation**, **road transportation**, and **industrial processes** to be the possible applications of low-carbon hydrogen in the country.[31] **By 2050**, their respective contributions to the total hydrogen demand are expected to be **50.0-78.5% (power)**, **24.7-33.8% (transportation)**, and **1.4-5.0% (industry)**.[31] The total **hydrogen demand in 2050 is expected to be in the range of 0.7-0.8 Mt-H_2 per year**.[31] Thus, developing skilled professionals, establishing interconnected infrastructure, and implementing carbon policies and regulations in Brunei could be important to realizing the targeted demand of hydrogen from low-carbon pathways.

It is worth mentioning that Japan's Advanced Hydrogen Energy Chain Association for Technology Development (AHEAD) started a pilot project to transport LNG-based hydrogen from Brunei to Japan in the form of methylcyclohexane (MCH).[35] The project was funded by Japan's New Energy and Industrial Technology Development Organization (NEDO) and was designed to have a full capacity of 210 t-MCH per year–equivalent to a hydrogen supply of 40,000 hydrogen fuel cell vehicles.[35] This project highlights the possibility for local low-carbon hydrogen production in Brunei to be transported using existing MCH land and sea infrastructure that could supply neighboring countries, such as Japan, with low-carbon hydrogen.

3.3 Potential Consideration of Low-Carbon Hydrogen in Brunei Darussalam

Brunei's forests dominate its land uses, with an estimated **71.8% land coverage in 2018**.[36] Only 25.7% of Brunei's land is used for residential and commercial uses.[36] Therefore, it is difficult for the country to install new renewable energy plants without destroying some forest land, especially when considering the country's richness in oil and gas resources. However, along with using wetlands/reservoirs as a location for FSPV, Brunei can import renewable energy via low-carbon hydrogen and/or its derivatives. For instance, the country shares borders with the Sarawak state of Malaysia, which has a hydropower potential of 87 Terawatt-hour (TWh)–1.89 times the total primary energy consumption of Brunei in 2021.[31,37] It is worth noting that hydropower imports from Sarawak was identified as one of the possibilities for Brunei in the electrolytic hydrogen study performed by the Department of Energy of the Prime Minister's Office and ERIA.[31]

Moreover, Brunei's National Council on Climate Change lists **ten strategies** for achieving a low-carbon and climate-resilient economy, including the following three strategies:[38]

- Reduction of industrial carbon emissions through zero routine flaring and As Low As Reasonably Practicable (ALARP) mechanisms
- Establishing a carbon price on excess carbon emissions by 2025
- Increasing total renewable energy share to 30% by 2035.

In the meantime, **low-carbon hydrogen is not explicitly included in these strategies**. In addition, **long-term (e.g., 2050-2060) targets are still to be defined**. Therefore, thorough assessments of low-carbon hydrogen production via SMR-CCS, biomass gasification, and renewably powered electrolysis could assist Brunei in defining meaningful targets for the country to achieve by 2050. Additionally, carbon offsetting strategies could help the country abate some of the residual carbon emissions, such as possible methane leakages and unabated CO_2 emissions from SMR-CCS. These solutions could include nature-based or engineered CDR technologies. A **transition to renewably powered water electrolysis** could also help Brunei in avoiding hydrogen-related carbon emissions but may not be cost-competitive with SMR-CCS. Moreover, participation in low-carbon hydrogen trades could present an opportunity for Brunei to decarbonize its hydrogen production chain. Such trades may require **international investments** and **certification schemes** to motivate the market and regulate the emissions associated with traded low-carbon hydrogen and/or its derivatives. Therefore, early discussions with potential low-carbon hydrogen importers could be essential for Brunei to establish international partnerships that could help the country achieve its net-zero GHG emissions target by 2050.

Hydrogen off-taking can be an issue that may require early consideration due to the multiple regulation frameworks needed for hydrogen use. For instance, passenger hydrogen-fueled vehicles require an ecosystem that depends on the existence of hydrogen refueling stations. Implementing safety measures of hydrogen in these stations may slow down their deployments, which could delay the offtake of hydrogen-fueled vehicles. Therefore, **developing hydrogen safety protocols and educating hydrogen users on them can be critical for the success of local low-carbon hydrogen technology deployment**. Although not mentioned in the electrolytic hydrogen study, hydrogen blending with natural gas for heating purposes could present an opportunity for the country to decarbonize its residential heating sources. However, this action requires effort in **technological advancements, safety measures, public awareness regarding hydrogen benefits** (e.g., mitigating air pollution, localizing energy production)**, regulations, codes, and standards**. It is worth noting that social rejection of hydrogen could impact hydrogen's supply and demand, potentially resulting in community rejection of low-carbon hydrogen deployment projects.

4 Fiji

Table 4. Quantitative hydrogen-related plans and progress in Fiji.

Country	Certification / Standard Scheme	Hydrogen Incentives	Port Readiness	Storage and Transportation	Net Importer / Net Exporter
Fiji	Non-existent	Non-existent	Export Import	Plan	Net Importer

4.1 Brief Overview

Consideration of low-carbon hydrogen production or procurement is still not public in Fiji yet. Fiji's National Development Plan (NDP) sets a target of achieving close to 100% electricity generation from renewable energy by 2030.[39] In 2021, Fiji was a net importer of primary energy that mostly relies on imported fossil fuels.[40] This situation makes the country vulnerable to fluctuating prices of fossil fuels and motivates the search for alternative fuels to generate local power in Fiji.[40–42] Low-carbon hydrogen could present an opportunity for Fiji to decarbonize and diversify its power mix. **In 2022, renewable energy contributed 58% of all electricity generation in Fiji**.[40] Out of this percentage, approximately **83% was sourced from hydropower**[40] due to the country's archipelagic nature. Low-carbon hydrogen could play an important role in storing renewable energy to stabilize Fiji's power grid across seasons or to import renewable power if land is scarce within the country.

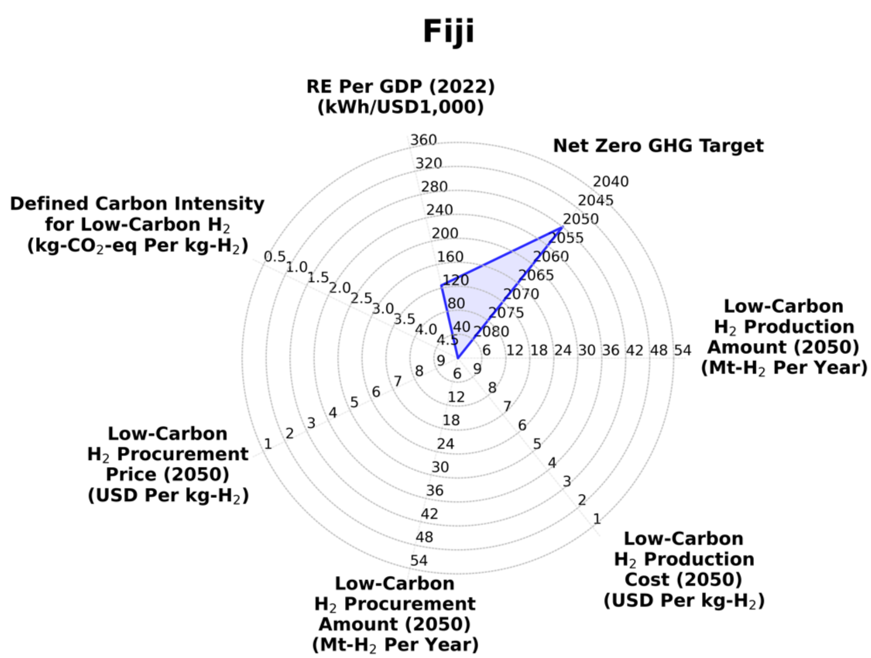

Figure 3. Radar plot of Fiji's figures of merit.

Note that several metrics were missing due to the lack of available data.

4.2 Hydrogen Considerations in Fiji

To the best of our knowledge, only two low-carbon hydrogen projects have been announced so far in Fiji. The first project is a collaboration between two industrial entities, HDF Energy and Pacific Trade Invest (PTI) Australia.[43] It aims to build a low-carbon hydrogen production facility in the Viti Levu Island; however, the project scale is still unknown.[43] We note that communicating the project scale, production rate, electricity source, and other relevant metrics may provide transparency around this and similar projects, which could help in tracking the progress of low-carbon hydrogen development and deployment in Fiji.

The second project is a hydrogen demonstration project from New Zealand to Fiji through a collaboration between Obayashi Corporation (Japan), Halcyon Power Limited (New Zealand), and Fiji Gas Pte Limited (Fiji).[44] Halcyon Power Ltd. is expected to power a 1.5 MW PEM water electrolyzer with geothermal power to produce 22.5 kg-H_2 per hour (*i.e.*, 59% electrical energy efficiency).[45] The hydrogen will then be shipped via seawater from New Zealand to Fiji, where it will be used, along with diesel, in a dual-fuel generator that was sent by Obayashi Corporation from Japan.[44] It is important to note that this pilot project tests the production of electrolysis using geothermal power, storage of hydrogen as gas in cylinders, land transportation of gaseous hydrogen to the port, port-to-port transportation of gaseous hydrogen, and the blending of gaseous hydrogen with diesel in dual-fuel power generators. This pilot ecosystem, which is one of the first of its kind, could be leveraged to inform future demonstration and commercial projects regionally and globally.

The limited amount of announced low-carbon hydrogen-related projects underscore the nascency of a low-carbon hydrogen market in Fiji. Further low-carbon hydrogen projects could help Fiji's government to understand which low-carbon hydrogen production pathway is most suitable for the country in the regional and global hydrogen markets, especially as more regulations arise in the hydrogen market globally.

4.3 Potential Consideration of Low-Carbon Hydrogen in Fiji

The highlighted two projects in the previous section set the stage for low-carbon hydrogen deployment in Fiji. However, techno-economic, environmental, and social assessment studies of low-carbon hydrogen could still elucidate the potential of low-carbon hydrogen projects in the country. For instance, Fiji's NDP sets a target of achieving close to 100% electricity generation from renewable energy by 2030, potentially requiring increasing development of energy storage.[39]For instance, Fiji's NDP sets a target of achieving close to 100% electricity generation from renewable energy by 2030, potentially requiring increasing development of energy storage.[39] The storage type will likely depend on the duration of electricity storage and the amount of electricity to be stored. With new renewable energy deployments, seasonal storage will most likely be considered, which could require advanced capabilities in low-carbon hydrogen storage, transportation, and utilization. Thus, Fiji could investigate the role of renewably powered water electrolysis in energy storage, the role of hydrogen pipelines and/or derivatives in storage and transportation, and the role of hydrogen fuel cells in backup power generation.

In addition, implementing any hydrogen-related technology will likely require standards, regulations, codes, and certificates to ensure safe handling and renewable production. Fiji could draft a plan for the development of hydrogen standards that ensures safety of handling, storing, and transporting hydrogen. Additionally, providing clear regulations around low-carbon hydrogen in the country could be beneficial to new low-carbon hydrogen projects. In parallel, hydrogen certifications, such as a "Guarantee of

Origin," may be needed if Fiji could benefit from participation in the regional and global importing/exporting market of low-carbon hydrogen.

Overall, Fiji could benefit from developing a hydrogen roadmap and/or strategy report outlining data-driven decadal pathways and targets for the country to pursue. The amount of low-carbon hydrogen necessary is still unknown to the country, which requires assessment of the current and forecasted status of low-carbon hydrogen. In addition, identifying potential end uses, standards, codes, regulations, and certifications of low-carbon hydrogen could be beneficial for the deployment of hydrogen-related technologies. Finally, aligning low-carbon hydrogen deployments with Fiji's social and economic benefit plans could improve awareness of the benefit of low-carbon hydrogen to Fiji's growth.

5 India

Table 5. Quantitative hydrogen-related plans and progress in India.

Country	Certification / Standard Scheme	Hydrogen Incentives	Port Readiness	Storage and Transportation	Net Importer / Net Exporter
India	Implemented	RD&D Per kg	Export Import	Exists Plan	Net Exporter

5.1 Brief Overview

India's National Green Hydrogen Mission (NGHM) was announced in January 2023 with two main objectives: making India a global hydrogen production hub and making India independent (i.e., Aatmanirbhar) in supplying itself with clean energy.[46,47] The first objective highlights the country's interest in becoming a **net hydrogen exporter,** while the second objective assures that India can secure its energy needs during the clean energy transition. India focuses on green hydrogen, defined as hydrogen produced using renewable energy, in its NGHM,[46] however for consistency, we refer to this hydrogen as low-carbon hydrogen throughout the report.

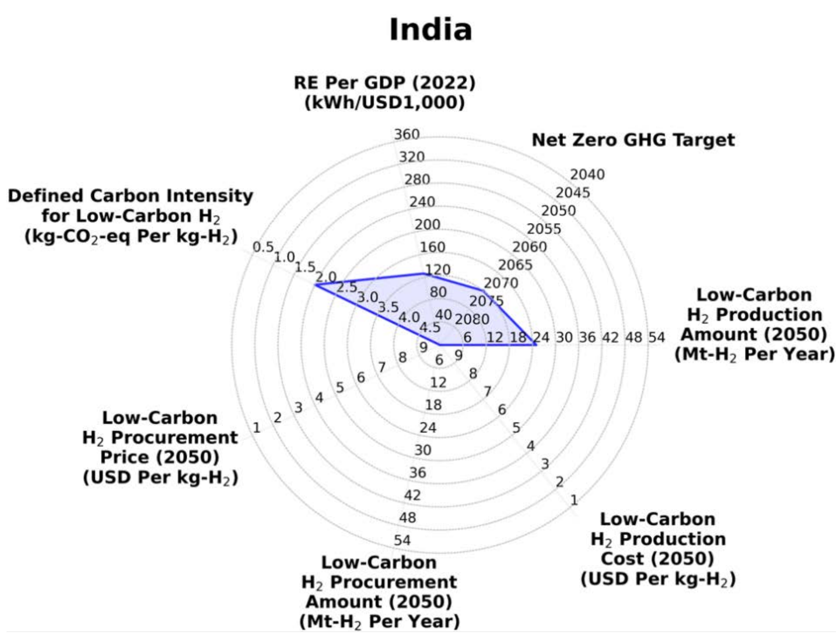

Figure 4. Radar plot of India's figures of merit.

Note that some metrics were missing due to the lack of available data.

In 2021, India was the third-largest energy importer globally, with 34% of its consumed energy being imported.[48] In the same year, India was the fourth-largest importer of LNG and third-largest importer of crude oil and petroleum products.[49,50] Consequently, the government decided to become energy-independent by 2047 and reach net-zero emissions by 2070.[46,47] India's NGHM presents goals of the Indian government to support the establishment of a clean hydrogen economy in the country, including leading the global water electrolyzer manufacturing and participating in the hydrogen trading market as an exporter.

5.2 Key Elements of India's National Green Hydrogen Mission

5.2.1 Localized Hydrogen Sourcing and Growing Hydrogen Exports

India's 2023 hydrogen consumption was estimated to be approximately **6.5 Mt-H_2 per year**, with most of the hydrogen being produced via SMR and used in industrial processes (e.g., petroleum refining, ammonia production, etc.).[46,51] **By 2030, India plans to achieve at least 5 Mt-H_2 per year for low-carbon hydrogen (green hydrogen as defined in NGHM), with potential to reach 10 Mt-H_2 per year by 2030 as the export market grows**.[46]

To support this domestic growth and to support further international growth, India plans to become a leader in electrolyzer technology and manufacturing, assuring sufficient supply of electrolyzers as the low-carbon hydrogen market grows. The mission estimates that the current global electrolyzer production of 2-4 GW_{el} per year will increase to 200 GW_{el} per year by 2030, due to commitments from governments and industrial organizations.[46] This presents an opportunity for India to manufacture and export electrolyzers overseas.

India's Ministry of New and Renewable Energy (MNRE) announced the Strategic Interventions for Green Hydrogen Transition (SIGHT) program in India's NGHM, allocating approximately **US$2.1 billion for electrolyzer manufacturing (≈US$530 million) and low-carbon hydrogen production (≈US$1.6 billion)**.[52–54] Particularly, the allocated financial incentive for electrolyzer manufacturing aims to encourage local production of electrolyzers based on both indigenously and non-indigenously developed electrolyzer stacks.[52,54] The first and second modes of this incentive reserve **at least 0.3 GW_{el} and 0.4 GW_{el} for indigenously developed stacks, respectively,** to encourage localization of electrolytic hydrogen production.[52,54] The total electrolyzer manufacturing capacity was aimed to be **3 GW_{el}** for the two announced modes by the time of writing.[52,54]

5.2.2 Hydrogen Development and Deployment Phases

India's hydrogen mission also presents a phased approach to hydrogen deployment.[46] The first phase started in January 2023 and plans to end in March 2026.[46] In this phase, both domestic demand and supply are planned to be created to allow for localized manufacturing of electrolyzers.[46] In addition, pilot projects aimed to investigate green steel, long-haul operations, heavy-duty mobility, and shipping are expected to be commenced in this first phase.[46] Lastly, initial discussions about hydrogen regulations are anticipated to align well with international standards.[46] The second phase is planned to begin in 2026-2027 and end in 2029-2030.[46] This phase would expand pilot projects to include railways and aviation sectors, and it would push low-carbon hydrogen to be commercialized in the steel, transportation, and shipping sectors.[46]

5.2.3 Ministerial Cooperation Strategy for Hydrogen

To grow the multi-sector hydrogen in domestic and international market, the mission sets expectations from ministries, departments, agencies, and both country-wide and state-wide institutions.[46] Examples of ministerial responsibilities are summarized in **Table 6**. Part of these responsibilities include skill development, international collaborations, and ease of business. Note that **Table 6** is by no means an exhaustive list of responsibilities planned by India's NGHM, but rather a subset of the full list. Interested readers of this topic are referenced to the original NGHM document.[46]

Table 6. Key responsibilities from Indian ministries, as set by the National Green Hydrogen Mission of India.[46]

Ministry Name	Key Responsibilities
Ministry of New and Renewable Energy (MNRE)	• Overall coordination and implementation of the mission • Scheme and program formulations for financial incentives • Assurances of planned deployment of renewable energy and low-carbon hydrogen capacities.
Ministry of Power	• Electricity ecosystem alignment for large-scale low-carbon hydrogen production.
Ministry of Petroleum and Natural Gas	• Facilitation of low-carbon hydrogen uptake in refineries and city gas distribution.
Ministry of Chemicals and Fertilizers	• Encouragement of adopting domestic low-carbon ammonia-based fertilizers.
Ministry of Road Transport and Highways	• Development of regulations, standards, and codes for low-carbon hydrogen technologies for heavy-duty vehicles and long-haul operations • Support of technology development via testing facilities, pilot projects, and support for infrastructure development.
Ministry of Ports, Shipping, and Waterways	• Establishment of India's exports capabilities for low-carbon hydrogen and its derivatives • Facilitation of low-carbon hydrogen and its derivatives for use as a fuel in ships.
Ministry of Finance	• Exploration of fiscal and financial frameworks for low-carbon hydrogen.
Ministry of External Affairs (MEA)	• Establishment of bilateral and multilateral partnerships in low-carbon hydrogen.
Ministry of Skill Development and Entrepreneurships	• Development of skilled human resources for employability in low-carbon hydrogen projects.
Ministry of Education	• Inclusion of hydrogen technologies in curricula at various educational levels.

5.2.4 Demand Creation

To create demand, India plans to focus on both the domestic and international hydrogen markets. Domestically, **5 Mt-H_2 per year is the set low-carbon (green as defined by NGHM) hydrogen production target by 2030**.[46] To accomplish this goal, the Indian Government is encouraging use of low-carbon (green) hydrogen by consumers–mainly, **petroleum refineries** and **fertilizer industry**–to ensure a smooth and safe transition to low-carbon hydrogen.[46] Internationally, **the Indian Government**

aspires to take over 10% of the global hydrogen market in 2030, producing 10 Mt-H_2 per year in 2030.[46] It is worth noting that this percentage is aligned with the announced electrolytic hydrogen projects by India, highlighted in **Figure 16** in the **Selective Low-Carbon Hydrogen Synergies** section. To clarify, the data highlighted in that section shows that India could make up roughly **8.1%** of the globally announced electrolytic hydrogen projects worldwide.

Additionally, under the mission, MNRE has built a competitive bidding framework that could support low-carbon hydrogen demand growth in the early stages of deployment.[46] The bidding framework is coupled with a low-carbon hydrogen certification scheme that assures the use of renewable energy in hydrogen production.[46] The mission targets to replace ammonia-based fertilizer imports with domestic *low-carbon* ammonia-based fertilizers by 2034-2035.[46]

5.2.5 Incentives, Policies, and Regulations for Low-Carbon Hydrogen

Competition of low-carbon hydrogen technologies in the global hydrogen market necessitates building strong regulations, policies, and incentives specific to this nascent field. India's NGHM specifies several factors that could position the country well in the international hydrogen market.[46] Specifically, the SIGHT program focuses on providing incentives for electrolyzer manufacturing and low-carbon (green) hydrogen production. Under this program, a total of approximately **US$2.1 billion** is allocated for electrolyzer manufacturing (**≈US$530 million**) and hydrogen production (**≈US$1.6 billion**).[52,53] The electrolyzer manufacturing incentive provides **approximately US$53**, **US$44**, **US$35**, **US$26**, and **US$18 per kW for the first five years of operation**, respectively.[52] The hydrogen production incentive pays **up to US$0.60**, **US$0.48**, and **US$0.36 per kg-$H_2$ for the first**, **second**, and **third year of operation**, respectively.[53]

In addition, to reduce the cost of production, interstate transmission charges have been waived for the renewable energy plants supplying power for low-carbon hydrogen production until 2030.[46] The Government of India may heavily focus on policies that support these goals to ensure continuous progress in this field. In terms of regulations, the mission highlights several actions for consideration by India's state and central governments.[46] Besides developing a single-window approval mechanism, the Government of India is making efforts towards harmonizing the Indian standards and regulations with international norms, standardizing technology validation methods, and assuring safety regulations are put in place.[46]

5.2.6 Expected Outcomes from the Mission

It is expected that the implementation of India's National Green Hydrogen Mission will result in the following hydrogen-related outcomes by 2030:[46]

- ≥5 Mt-H_2 per year of low-carbon hydrogen production
- ≥600,000 new full-time jobs
- ≥US$96.8 billion in total investments.

Although hydrogen production cost is not one of the explicitly stated outcomes of this mission, a study conducted on behalf of the Federation of Indian Petroleum Industry (FIPI) showed that a **low-carbon hydrogen price of approximately US$2 per kg-$H_2$ is achievable in India by 2035**, showing that low-carbon hydrogen could potentially reach cost parity with fossil-based hydrogen.[51]

5.3 Tracking Progress

Since the launch of India's NGHM, the Government of India was able to implement the hydrogen bidding system,[55] issue a green hydrogen standard,[56] and provide research and development opportunities for low-carbon hydrogen.[57] Under the SIGHT program, several low-carbon hydrogen projects were selected with a total production amount of approximately **0.4 Mt-H_2 per year** and a total maximum financial incentive of approximately US$370 million.[58] The financial incentive comes in the form of a maximum cap of **$0.60 per kg-$H_2$ in the first year, $0.48 per kg-$H_2$ in the second year, and $0.36 per kg-$H_2$ in the third year**.[59] In addition, a request for selection of low-carbon ammonia bids was issued in June 2024 with an expected scale of approximately **0.5 Mt-NH_3 per year,** which was later augmented to approximately **0.7 Mt-NH_3 per year in July 2024**.[60,61] Furthermore, India's Green Hydrogen Standard, which was announced in August 2023, sets a definition of green hydrogen as hydrogen produced via electrolysis or biomass conversion with a CO_2 intensity of **2 kg-CO_2 per kg-H_2**.[56] This standard is an essential regulating measure of low-carbon hydrogen, which will play an important role in future hydrogen trades. Finally, as promised in the hydrogen mission, the Government of India initiated research and development funding opportunities specific to the production, storage, transportation, and utilization of low-carbon hydrogen. The funding amount is planned to be approximately US$48 million, lasting until the fiscal year (FY) 2025-2026.[57]

6 Indonesia

Table 7. Quantitative hydrogen-related plans and progress in Indonesia.

Country	Certification / Standard Scheme	Hydrogen Incentives	Port Readiness	Storage and Transportation	Net Importer / Net Exporter
Indonesia	In Progress	RD&D	Export Import	Plan	Net Exporter

6.1 Brief Overview

Indonesia's National Hydrogen Strategy[62] was announced in December of 2023. The strategy identifies current and projected uses of hydrogen in the country, clarifying the demand and supply of low-carbon hydrogen as it matures in the market. Currently, **Indonesia consumes approximately 1.8 Mt-H_2 per year**, out of which 88% is demanded for urea production, 4% for ammonia production facilities, and 2% for oil refineries.[62] The strategy proposes that Indonesia could become an important player in the clean hydrogen economy due to its abundant potential of diverse renewable energy sources (including on-shore wind, off-shore wind, hydropower, solar, geothermal, and bioenergy)[63], its commitment to global climate mitigation goals, and its archipelagic location that sits on major international trading routes.[62]

The strategy estimates the potential new and renewable energy in Indonesia to be approximately 3.7 TW.[62] If 20% of this potential renewable energy was used to produce electrolysis-based hydrogen at a capacity factor of 30%, then Indonesia can theoretically produce 35 Mt-H_2 per year–i.e., 37.6% of the 2021 global hydrogen demand.[64] In addition, **Indonesia is already an ammonia exporter**, ranked the third-largest ammonia exporter globally in 2022,[62,65] which makes it a potential low-carbon ammonia exporter in the eastern Asian region and globally. **Indonesia exported approximately 1.9 Mt-NH_3 (anhydrous) in 2022**, with the largest ammonia-receiving countries being the Republic of Korea, India, and Japan that provided Indonesia with a combined exporting value of approximately **US$800 million**.[66,67] Indonesia's current ammonia infrastructure and port readiness could be leveraged to facilitate the export of low-carbon hydrogen and/or its derivatives. Indonesia's National Hydrogen Strategy[62] provides further details on how the country can achieve its low-carbon hydrogen goals to become an **exporter of low-carbon hydrogen and its derivatives**.

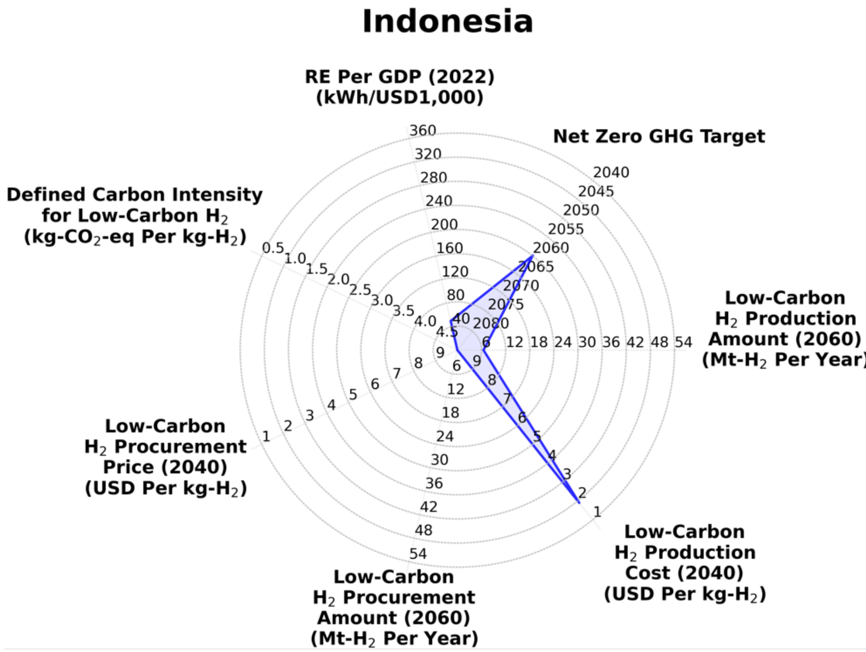

Figure 5. Radar plot of Indonesia's figures of merit.

Note that some metrics were missing due to the lack of available data.

6.2 Key Elements of Indonesia's National Hydrogen Strategy

Indonesia's hydrogen strategy acknowledges the challenges with low-carbon hydrogen, including supply and demand, lack of regulation, nascent low-carbon hydrogen market, lack of hydrogen-specific infrastructure, and limited investments.[62] To overcome these challenges, the strategy identifies several action plans that could help the low-carbon hydrogen market to mature.

6.2.1 The Three Pillars of the Hydrogen National Strategy

6.2.1.1 Reducing Dependence on Fossil Fuels

One of the pillars presented by Indonesia's hydrogen strategy is reducing the dependence on fossil fuels.[62] This pillar guides the country toward reaching energy independence and participating in the global clean energy transition. To align with this pillar, Indonesia plans to accelerate renewable energy deployment, establish reliable and efficient use of hydrogen, and facilitate access to high-quality electricity.[62]

6.2.1.2 Developing a Domestic Hydrogen Market

Indonesia plans to develop a domestic hydrogen market that can leverage low-carbon hydrogen technologies.[62] One of the main elements of this pillar is the development of a regulatory framework and certification specific to hydrogen that may include a GHG threshold for low-carbon hydrogen as well as technical and safety standards for hydrogen supply chain.[62] Although Indonesia does not have a carbon intensity threshold that defines "low-carbon hydrogen" yet (**Figure 5**), current plans in Indonesia's hydrogen strategy are directed toward creating one that aligns with global definition of clean or low-carbon hydrogen.

In addition, the strategy recommends the implementation of financial incentives such as an emission trading scheme and a carbon tax on high-carbon hydrogen production.[62] It also stresses the need for strict safety regulations.[62] Under the certification scheme, the Government of Indonesia plans to consider several market incentive factors, including research & development grants, financial infrastructure support, carbon pricing, and a trading platform.[62] These factors would improve the state of low-carbon hydrogen in Indonesia. Additionally, to facilitate growth in the hydrogen market, Indonesia plans to develop an integrated hydrogen industry (as known as hydrogen hubs) to potentially reduce transportation costs and improve the economics of low-carbon hydrogen technologies.[62]

Furthermore, the Government of Indonesia plans to ensure governance of the hydrogen market via cross-ministerial coordination that includes Indonesia's Ministry of Maritime Affairs and Investment, Ministry for Economic Affairs, Ministry of Energy and Mineral Resources, Ministry of Industry, Ministry of Transportation, and Ministry of Environment and Forestry.[62] It also plans to ensure effective communication between the government, the public, and involved stakeholders. This communication can come in the form of educational campaigns or public releases.[62]

6.2.1.3 Exporting Hydrogen and Its Derivatives to the Global Market

To maintain its exporting capabilities and to keep up with the energy transition, Indonesia recognizes a need to produce low-carbon products, including low-carbon hydrogen.[62] Accessing the global market requires Indonesia to develop low-carbon products, low-carbon fuels, and bilateral agreements with importing countries. **As a maritime country, Indonesia has the potential to be involved in international trade as a global hydrogen hub.** Indonesia passes through two shipping lanes, the Malacca Strait and the Sunda Strait. This location could make Indonesia a potential international transit center for low-carbon hydrogen and its derivatives.

Indonesia has made at least **two bilateral agreements** on hydrogen and its derivatives. In December 2023, Indonesia's national energy company, Pertamina, signed a Joint Development Agreement (JDA) with Tokyo Electric Company, majorly owned by the Government of Japan, on the development of an electrolytic hydrogen production facility that uses electricity from Lahendong geothermal power plant.[68] The pilot facility is expected to use 0.5 MW of geothermal power to produce 32 t-H_2 per year, and it is expected to be completed by the first quarter of 2027.[62] The commercial facility is expected to be using 400 MW of geothermal power to produce 0.5 Mt-NH_3 per year, which will be exported to nearby countries, including Japan.[62] The commercial facility is expected to be completed by the first quarter of 2030.[62] The second bilateral agreement is a collaboration between Indonesia and the Republic of Korea on low-carbon hydrogen and ammonia, which was highlighted in the Second Meeting of the Joint Committee on Economic Cooperation (JCEC-2), held in July 2023.[69] Although details on such projects have not been announced yet, they align well with the interest of Indonesia's Ministry of Energy and Mineral Resources on utilizing low-carbon hydrogen and ammonia as an energy carrier for future export.[70]

6.2.2 Infrastructure Plan for Hydrogen

Building a low-carbon hydrogen market/economy requires considering renewable energy generation as well as hydrogen production, transportation, and storage infrastructure. The strategy lists five means of investing in the development of low-carbon hydrogen infrastructure:[62]

- Building an electricity transmission network

- Building a hydrogen pipeline infrastructure
- Establishing seaport infrastructure for exporting hydrogen and its derivatives
- Building hydrogen storage facilities for large-scale hydrogen storage
- Developing CCS technologies for use in low-carbon hydrogen and ammonia productions.

6.2.3 Hydrogen Market Development Stages

Indonesia's hydrogen strategy proposes three levels to develop a hydrogen market. The first level was expected to start from the announcement of the strategy (December 2023) until 2030. In this level, Indonesia plans to continue developing hydrogen-specific roadmaps, policies, and regulations as well as produce hydrogen locally using SMR to better understand the hydrogen global market.[62] This level is also planned to incorporate hydrogen testing in the **electricity** and **transportation** sectors. The second level is planned to begin in 2030 and end in 2040 with a focus on **upscaled low-carbon hydrogen production**.[62] In this level, hydrogen is planned to be **sourced from renewably powered electrolysis** or from **geothermal** processes. Additionally, hydrogen is expected to be used in the **heavy-duty transportation** sector and international market entry trials will be pursued by domestic hydrogen producers. The final level is expected to start in 2040, with the key milestones being the entrance of Indonesia in the hydrogen exporting market by 2040 and the full decarbonization of the Indonesian electricity grid by 2060.[62] In addition, **the production cost of low-carbon hydrogen is expected to achieve parity with fossil-based hydrogen by 2060**.[62]

6.2.4 Target Low-Carbon Hydrogen Production Rates and Prices

Indonesia's National Hydrogen Strategy referenced an IEA report that provided projected low-carbon hydrogen production rates.[62,71] **It is shown in the strategy that by 2040, low-carbon hydrogen production could reach up to approximately 1.8 Mt-H_2**.[62] **By 2060, the production amount could exceed 6.5 Mt-H_2 per year**, allowing the country to export low-carbon hydrogen globally. Regarding the production cost of low-carbon hydrogen, Indonesia's location along the equator helps it become one of the most attractive locations for solar power. The strategy reports that **in 2040, the cost of solar-based low-carbon hydrogen production could reach $1.9-2.9 per kg-$H_2$, the cost of hydropower-based low-carbon hydrogen production could reach $2.8-3.9 per kg-$H_2$, and the cost of fossil-based low-carbon hydrogen (i.e., produced via SMR and coupled with CCS) production could reach $1.9-2.3 per kg-$H_2$**.[62] Based on these numbers, solar-based low-carbon hydrogen could compete with fossil-based low-carbon hydrogen in Indonesia by 2040.

6.3 Tracking Progress

The announcement of Indonesia's hydrogen roadmap has motivated actions relating to low-carbon hydrogen adoption. For instance, Indonesia's largest low-carbon hydrogen project was announced in December 2023, which **will produce approximately 0.2 Mt-NH_3 per year using a combined 600 MW from solar and wind**.[72] In addition, the country hosted the Indonesia International Hydrogen Summit 2024 in June of 2024.[73,74] Based on input from IDN stakeholders, the meeting resulted in actions taken by the Ministry of Energy and Mineral Resources to prepare government regulation for hydrogen that includes institutional governance, supply chain, incentive, and certification mechanisms to accelerate the deployment of hydrogen in Indonesia. Further progress in the country should be seen in terms of further studies and policy changes regarding low-carbon hydrogen uses in transportation, power, and industrial sectors to derisk adoption of this emerging market.

7 Japan

Table 8. Quantitative hydrogen-related plans and progress in Japan.

Country	Certification / Standard Scheme	Hydrogen Incentives	Port Readiness		Storage and Transportation		Net Importer / Net Exporter
Japan	Implemented	RD&D	Export	Import	Exists	Plan	Net Importer

7.1 Brief Overview

Japan's Basic Hydrogen Strategy was announced in 2017[75] and was revised in 2023.[76] The original strategy proposed a three-phase program: 1) Large expansion of hydrogen use, 2) introduction of hydrogen power generation and establishment of a hydrogen supply chain system by 2025-2030, and 3) establishment of a CO_2-free hydrogen supply chain system by 2040. Japan formulated its 6th Strategic Energy Plan in 2021, which explicitly mentions the Government's goal of **enabling hydrogen and ammonia to cover approximately 1% of the energy mix in FY2030**.[77] Moreover, Japan announced the **2050 Carbon Neutrality Declaration** in October 2020, which sets action plans to 14 relevant sectors in the energy-related (e.g., wind, solar, hydrogen, etc.), transport/manufacturing-related (e.g., semiconductors, automobiles, etc.), and home/office-related (e.g., next-generation electric power generation, resource circulation, etc.) sectors.[78] To support this effort, the **Green Innovation Fund (GIF)** was established with **US$5.6 billion** in support to hydrogen technologies.[76]

Both strategies underscore the importance of hydrogen in achieving Japan's goals of securing its energy, enhancing its economic efficiency, and prioritizing the environment while avoiding risks that relate to safety (i.e., 3E+S), which align the hydrogen strategy with the country's Strategic Energy Plan.[75,76,79] It is clear in both strategies that Japan plans to become a **net importer of hydrogen**. However, the strategy suggests that Japan can also participate in international hydrogen trades, especially in terms of hydrogen derivatives.[76] **With established importing capabilities of hydrogen and its derivatives, Japan considers itself port-ready in terms of hydrogen trades**,[76] a metric that will play a key role in positioning the country in the hydrogen economy and trading map.

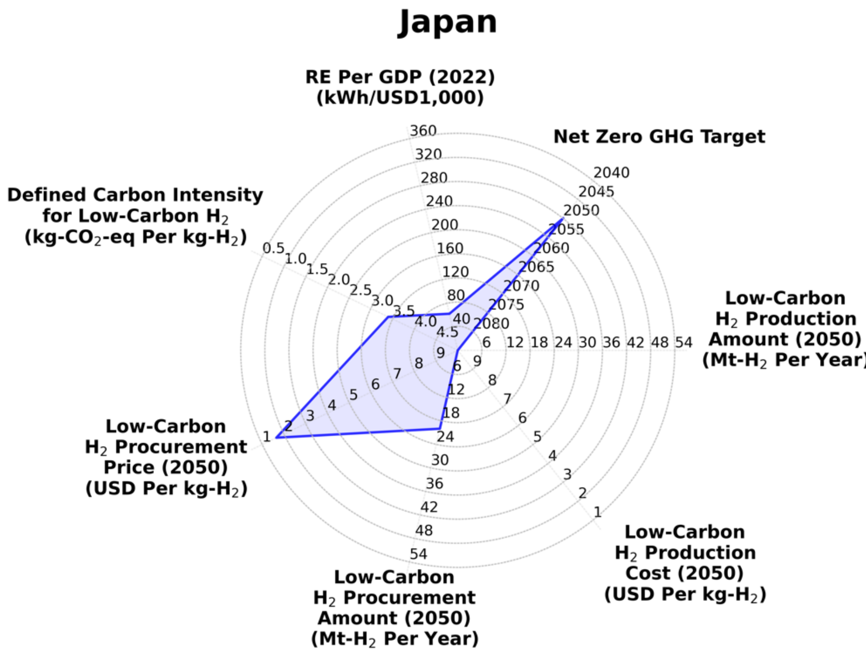

Figure 6. Radar plot of Japan's figures of merit.

Note that some metrics were missing due to the lack of available data.

7.2 Key Elements of Japan's Basic Hydrogen Strategies

7.2.1 Building an International Hydrogen Supply Chain

In 2022, Japan imported approximately 90% (crude oil; 32.6%, coal; 25.7%, natural gas; 21.1%, oil products; 9.9%, renewables; 0.7%, coal products; 0.1%) of its primary energy from overseas.[80] Japan aims to diversify its energy portfolio to lower its dependency on fossil fuel sources and ensure its energy security.[67,76] Low-carbon hydrogen and its derivatives (e.g., liquified hydrogen, organic hydrides, ammonia, methane) could be supplied by neighboring countries (e.g., Australia, Indonesia, Malaysia) and could be used as energy sources in Japan. Indeed, Japan has been collaborating with Australia on transporting liquified low-carbon hydrogen, which was sourced from coal coupled with CCS, to its ports. The first part of the project included transporting liquid hydrogen, and it was accomplished in 2022 via a ship called *Suiso Frontier*.[81,82] However, during the transportation, an equipment (i.e., electrical solenoid valve) failure was reported after an investigation of a hydrogen flame inside the ship.[25] This incident highlights the complexity of hydrogen transportation and stresses the need for detailed quality control checks at equipment manufacturing facilities to ensure safety during hydrogen transportation. Nonetheless, Japan's collaboration with Australia, under the Hydrogen Energy Supply Chain (HESC) project, sets the stage for liquid hydrogen transportation globally, enabling real-world experience in liquid hydrogen transportation via the sea.

Moreover, Japan's New Energy and Industrial Technology Development (NEDO) invested in a demonstration project for the transportation of LNG-based hydrogen from Brunei to Japan in the form of MCH.[35,76] The project involves hydrogenation of toluene in Brunei to MCH and dehydrogenation of MCH into toluene and H_2 for use in a gas turbine for electricity generation.[35] This project adds to Japan's commitment to establish a hydrogen supply chain using existing infrastructure.

7.2.2 Building a Domestic Hydrogen Demand

Japan's hydrogen strategy recognizes that establishing policies and incentives that encourage hydrogen adoption in Japan's market will be key to providing low-cost hydrogen, especially from renewable energy sources.[76] In addition, the strategy finds hydrogen demand creation to be an opportunity to expand Japan's industrial companies internationally,[76] which will provide benefits to the overall economy of Japan. The Government of Japan identified **power generation**, **transportation**, **steelmaking**, and **industrial heat and chemicals sectors** to be major end users of hydrogen.[76] To realize end uses in the given sectors, several projects and milestones have been highlighted in the strategy, including co-firing of hydrogen and ammonia (world's first demonstration testing of ammonia co-firing at a large-scale coal-fired thermal power plant conducted in 2024), wide use of fuel cells in transportation (world's first hydrogen fuel cell vehicle), and hydrogen injection into blast furnace (expected commercialization by 2030).[76]

7.2.3 Developing Standards for Hydrogen

Japan's strategy realized that developing hydrogen standards is essential to the success of building a global hydrogen economy.[75,76] Thus, Japan has been active in the international organization for standardization (ISO) technical committee (TC) 197 (ISO/TC 197) to lead hydrogen standardization for refueling stations.[75,76] The strategy expands on this effort by aiming to lead hydrogen standardization in **auxiliary equipment** (e.g., loading arms).[76] To accomplish this goal, Japan realizes the need to train delegates in this area in order to be involved in meaningful discussions about hydrogen-related auxiliary equipment standards.[76] In addition, the strategy states that Japan is interested in developing international standards for fuel cell vehicles in terms of safety and fuel efficiency.[76]

7.2.4 Addressing Hydrogen Safety and Increasing Public Awareness

Japan's hydrogen strategy included a full chapter on hydrogen safety, in which it highlights the development of an Interim Hydrogen Safety Strategy that guides the public and private sectors in developing hydrogen safety standards that are evidence-based and internationally accepted.[76] The three objectives of the safety strategy are:

- Collection of scientific data via technology development
- Revision and optimization of rules for hydrogen society development
- Development of a hydrogen utilization conditions.

7.2.5 Hydrogen-Related Investments

The Government of Japan allocated approximately **US$5.6 billion** to develop hydrogen-related technologies through the GIF.[76] In addition, under its Green Transformation (GX) policy, Japan's Government plans to invest approximately **US$140 billion in upfront costs** to lower the risk of public and private sector investments in low-carbon technologies (including low-carbon hydrogen) and to encourage a total combined investment of approximately **US$1.1 trillion over the next ten years**.[76] Japan's basic hydrogen strategy reports that the public and private sectors invested approximately **US$105 billion to develop a commercial-scale supply chain for low-carbon hydrogen and its derivatives over the next 15 years**.[83] Assuming equal distribution over the 15 years, this number is equivalent to **approximately 6.3%** of the annual investments that the Government of Japan plans to encourage in the next ten years.

7.2.6 Target Low-Carbon Hydrogen Production Amounts and Price

Japan is planning to procure 3 Mt-H_2 per year by 2030 at a price of approximately US$2.3 per kg-$H_2$, which will require the development of commercial supply chain infrastructure. By 2040, Japan plans to increase its procurement of hydrogen to 12 Mt-H_2 per year. By 2050, this amount is expected to reach 20 Mt-H_2 per year at a lower price of approximately US$1.6 per kg-$H_2$ by 2050. To reach these targets, Japan plans to contribute to technology development of low-carbon hydrogen such as renewably powered water electrolysis. One of the goals set by Japan is to reduce the capital cost of alkaline water electrolyzers to approximately US$365 per kW and of PEM water electrolyzers to approximately US$456 by 2030.[76]

7.3 Tracking Progress

Since the announcement of Japan's first hydrogen strategy, several milestones were achieved. As mentioned previously, the first global liquid hydrogen shipment from Australia to Japan was completed in 2022.[81,82] Additionally, Japan's Government has announced the GIF of approximately **US$14 billion**.[84] This fund includes approximately **US$5.6 billion** for developing hydrogen-related technologies, including hydrogen and ammonia infrastructure, hydrogen refueling stations, and hydrogen applications in steelmaking.[76] It also sets a **carbon intensity for projects to be within 3.4 kg-CO_2 per kg-H_2 for well-to-gate emissions**,[76] which could be important in the development of hydrogen certification for trade purposes.

8 Malaysia

Table 9. Quantitative hydrogen-related plans and progress in Malaysia.

Country	Certification / Standard Scheme	Hydrogen Incentives	Port Readiness	Storage and Transportation	Net Importer / Net Exporter
Malaysia	*In Progress*	*RD&D*	*Export Import*	*Plan*	*Net Exporter*

8.1 Brief Overview

The Malaysian Hydrogen Technology & Economy Roadmap (HETR) was announced in 2023. However, hydrogen has long been considered by Malaysia's Government from the early 2000s.[37] The United Nations (UN) COMTRADE database reports that **Malaysia's exported values for methanol and ammonia were approximately US$434 million and US$213 million, respectively**.[67] This data suggests the potential of using methanol and/or ammonia for hydrogen transportation from Malaysia. The HETR breaks down Malaysia's consideration of hydrogen into three phases that set the stage for today's hydrogen potential in the country.[37] These phases have focused on developing renewable energy capacity to be used in several low-carbon applications, including hydrogen production, creating legislation and financial support to speed up commercialization of hydrogen technologies, and adopting low-carbon hydrogen as a fuel source in the transportation sector.[37] From the industrial side, several projects have been considered that link hydrogen exports from Malaysia to hydrogen imports to Japan and the Republic of Korea,[37] highlighting potential bilateral agreements between Malaysia and large hydrogen-importing countries in the region. Such projects include a Memorandum of Understanding (MoU) between Petroliam Nasional Berhad (PETRONAS), through Gentari Sdn. Bhn., and two Japan-based companies (Asahi Kasei Corporation and JGC Holdings Corporation) to begin the construction of a 60-MW alkaline electrolyzer facility that would produce approximately 0.01 Mt-H_2 per year.[85] This particular project aims to establish a route that connects low-carbon hydrogen produced in Malaysia with potential suppliers in Japan and other Southeast Asian countries.[85]

Furthermore, Malaysia's location near the equator provides it with an abundant renewable energy potential of approximately 289 GW[37]–sufficient to power half of India.[86] Most of this potential power can be provided by solar photovoltaics (PV) and large hydropower (>30 MW) with potentials of approximately 269 GW and 14 GW, respectively. With this much power, Malaysia plans to enter the low-carbon hydrogen market as a net hydrogen exporter, expanding on its already-established traditional hydrogen infrastructure and expertise.[37] To maintain this status, Malaysia plans to integrate fossil-based hydrogen with CCS and introduce non-fossil-based hydrogen to the market as it increases its hydrogen production in the upcoming years. Currently, Malaysia exports fossil-based hydrogen in its gaseous form as well as in carriers (e.g., natural gas), as reported by the UN COMTRADE.[67] Continuing in this space will likely require more regional and international collaborations while shifting to non-fossil-based low-carbon hydrogen, motivating the development of the Malaysian hydrogen roadmap.

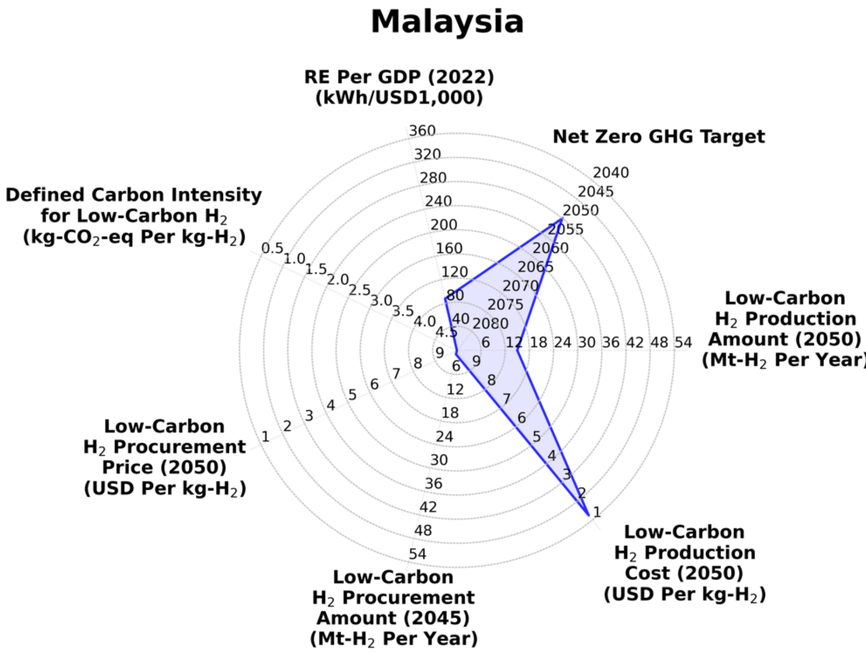

Figure 7. Radar plot of Malaysia's figures of merit.

Note that some metrics were missing due to the lack of available data.

8.2 Key Elements of Malaysia's Hydrogen Technology & Economy Roadmap

8.2.1 Techno-Economic Modeling of Hydrogen Production

The first main element that Malaysia's HETR considers is developing a techno-economic model for hydrogen production in Malaysia.[37] This model includes a hydrogen supply chain superstructure specific to Malaysia that clarifies the considered hydrogen production pathways, which are **SMR**, **biomass gasification**, **natural gas pyrolysis**, **biogas anaerobic digestion followed by SMR**, and **renewably powered water electrolysis**.[37] For the CO_2-emitting production pathways, Malaysia considers CCUS technologies to reduce their CO_2 emissions.[37] In addition, the superstructure model shows the considered end-uses of hydrogen in Malaysia, including **power generation**, **heat generation**, **direct non-energy utilization**, and **transportation**.[37] In the power and heating applications, hydrogen is planned to be blended with natural gas to lower the capital and technical risks of its introduction.[37] After its maturity in gas-blending projects, hydrogen is planned to be considered as a sole fuel for power generation and gas networks. Similarly, the direct utilization of hydrogen is planned to be sourced from fossil fuel processes without CCS in the short term before deploying low-carbon hydrogen in these applications.[37] This action is taken to derisk the entrance of hydrogen into existing markets; however, it may slow down Malaysia's transition to a low-carbon hydrogen economy. Finally, hydrogen, ammonia, and e-fuels are planned to be used for land, marine, and aviation mobility, respectively.[37]

The techno-economic model of hydrogen production in Malaysia assumes that new hydrogen projects were planned to be operational for 30 years and start between 2025 and 2050.[37] Based on this and other assumptions, the final levelized costs of non-fossil low-carbon hydrogen were estimated to be in the ranges of **US$1.4-4.8, US$1.3-2.6, and US$1.3-2.1 per kg-$H_2$ for the years 2030, 2040, and 2050,**

respectively.[37] The lowest ends of these cost ranges were associated with hydrogen produced from the biogas-SMR pathway.[37] **Solar-based water electrolysis was found to have hydrogen production cost estimates of approximately US$4.8, US$2.6, and US$1.5 per kg-$H_2$ for the years 2030, 2040, and 2050, respectively**.[37] **With financial incentives, the 2030 and 2040 cost estimates drop to approximately US$2.9 and US$2.5 per kg-H_2, respectively**.[37] The scenarios presented by the roadmap expect that by 2050, no financial incentives will be needed for solar-based hydrogen production, which is the state where solar-powered electrolysis-based hydrogen production achieves a hydrogen production cost of **US$1.5 per kg-$H_2$**.[37] Comparatively, hydrogen production from **hydropower-driven electrolysis is estimated to reach a cost of US$1.8 per kg-$H_2$ in 2050**.[37] The roadmap implies that this pathway could be easier to deploy because mini hydropower plants do not generally require significant civil infrastructure.

In addition to the cost of low-carbon hydrogen, the production capacity of low-carbon hydrogen has been forecasted in Malaysia's HETR between 2025 and 2050. It is estimated that Malaysia will produce approximately **0.9-2.0 Mt-H_2 per year in 2030, 3.6-7.0 Mt-H_2 per year in 2040, and 6.6-15.0 Mt-H_2 per year in 2050**.[37] It is worth noting that the low end of this range represents a business-as-usual (BAU) scenario, whereas the high end of this range represents an emission-driven scenario. In addition to this production amount, about **1.0 Mt-H_2 per year is forecasted to be imported between the years 2040 and 2050**.[37]

8.2.2 Three-Phase Plan of the Roadmap

As part of the Malaysian hydrogen strategies and action plans, Malaysia's HETR highlights three phases representing the 2022-2030, 2031-2040, and 2041-2050 timelines.[37] **During the first phase (2022-2030), Malaysia's hydrogen roadmap aims to begin exporting 0.5-1.0 Mt-H_2 per year** and initiate a domestic hydrogen market.[37] The second phase is planned to focus on developing a domestic low-carbon hydrogen market and establishing international standards and legislations by 2040.[37] The final phase is planned to diversify hydrogen production and utilization pathways.[37] This will ensure energy and hydrogen security that should help derisk Malaysia's economy.

8.2.3 Governance, Framework, and Regulations of Low-Carbon Hydrogen

A governance structure has been proposed in Malaysia's hydrogen roadmap to regulate and facilitate the implementation of hydrogen ecosystem via the National HETR steering committee. The committee is supported by three clusters: 1) Hydrogen production and conversion, 2) hydrogen storage and transportation, and 3) hydrogen end-use market development.[37] In addition, the roadmap plans to strengthen existing policies and regulation around hydrogen by establishing a collaborative platform for hydrogen stakeholders to come together and build the low-carbon hydrogen market in Malaysia.[37]

8.2.4 Enabling Environment and Economic Facilitation

Building a robust hydrogen economy in Malaysia requires the facilitation from both the government and industry. Malaysia's HETR states that the government plans to shift subsidies from fossil fuel technologies to renewable technologies.[37] Additionally, the roadmap specifies feasibility studies that need to be carried out, which are focused on hydrogen and ammonia supply chains, co-firing of hydrogen with natural gas, development of hydrogen hubs, and introduction of hydrogen into land-based transportation. Furthermore, Malaysia plans to perform an economic study on proven circular economy projects to accelerate the transition from a linear to a circular economy. The country also plans to assess low-carbon hydrogen as a key element to GHG mitigation and assess the consideration of low-carbon hydrogen in international carbon market mechanisms. Such assessments and enabling efforts are expected to be achieved by 2040, with most of them being targeted for the short term (i.e., by 2030 deadline).

8.2.5 Commercial Acceleration for Exports and Domestic Uptake

Since low-carbon hydrogen technologies are still not widely deployed at industrial scales in Malaysia, innovative research and development is necessary to accelerate market adoption. Specifically, Malaysia plans to follow a "**Buy-some and Build-some**" approach, in which technology evaluation becomes a key factor in deciding between buying the end-product versus building the infrastructure to produce it.[37] The roadmap elucidates the requirements to choose between the two options. Building a technology will require a proof-of-concept prototype with an **available infrastructure for pilot testing**, **ready-to-offtake consumers**, and **a lifetime-lasting use once it has been scaled up**.[37] On the other hand, buying the technology will require it to have a **clear return on investment (ROI)**, **be cost-competitive over 30 years**, **be customized for multiple end uses**, and **be certified in relation to safety and technical standards**.[37] In addition, Malaysia plans to establish **three low-carbon hydrogen hubs, one by 2030 and two by 2050**, to achieve optimal low-carbon hydrogen economics in Malaysia and to increase the economic growth of low-carbon hydrogen projects.[87]

The facilitation of low-carbon hydrogen deployment and readiness for export from Malaysia is supported by the Sarawak Economic Development Corporation (SEDC), via its subsidiary SEDC Energy. The Malaysian Investment Development Authority (MIDA) reported two projects, H2biscus and H2ornbil, that are expected to produce a **combined amount of 0.24 Mt-H_2 per year via hydro-powered water electrolysis**.[88,89] The H2biscus project is planned to produce both low-carbon hydrogen and low-carbon ammonia.[88,90] The latter will be exported to the Republic of Korea, testing the existing capabilities of transporting ammonia as a clean hydrogen carrier.[88,90] The H2ornbill project is expected to convert low-carbon hydrogen into MCH, which is planned to be exported to Japan.[89] The two projects are expected to reach FID by the second quarter of 2025. Although both projects still lack details about the plants and are still pre-FID, they highlight the strong commitment from SEDC and Malaysia's Government in facilitating hydrogen trades with two of the potentially largest clean hydrogen importers in the region.

8.2.6 Capacity-Building and Public Considerations

The Government of Malaysia acknowledges that building a local low-carbon hydrogen economy requires effort in capacity-building and talent development. The roadmap sets actions that address this necessity including developing syllabi on hydrogen technologies, enabling the low-income and unemployed individuals to access professional courses on the hard-core skills for hydrogen technologies, and enforcing local content and transfer of knowledge.[37] The roadmap identifies the years **2024-2029 to be the most important years for this talent development** to enable commissioning of small-scale hydrogen-related projects.[37]

Moreover, Malaysia's HETR includes action plans and targets to increase public awareness of hydrogen.[37] One of the action plans is to operate public transportation with hydrogen fuels, which is planned to be fully accomplished by 2038.[37] Another action plan is to encourage partnerships with local and foreign industries to enhance knowledge transfer of hydrogen-related technologies.[37] The action plans aim to introduce hydrogen-related courses in vocational education programs by 2027.[37]

8.3 Tracking Progress

Since the announcement of Malaysia's hydrogen roadmap, at least two main achievements were realized. First, an agreement of building Malaysia's largest electrolysis-based plant was established at a capacity of 60 MW per year and renewable power from floating solar PV.[91] This project attracted approximately **US$400 million and reached FID in 2024**. The second achievement was the development of the Sarawak Electrolyzer Assembly Distribution Facility (SEA-DF) also in 2024,[92] which is simply a hydrogen production hub at Demak Laut Industrial Park. The 50-MW per year facility is planned to produce approximately 25 t-H_2 per day, meeting the local demand of hydrogen in Sarawak.[92] It is still unclear whether this project has reached FID or not yet.

In addition to these two projects, H2ornbil and H2biscus comprise two of the most important projects in Malaysia, connecting the country with potential hydrogen customers in Japan and the Republic of Korea. These projects are expected to reach FID in 2025,[89] enabling the production of a combined 0.24 Mt-H_2 per year to be partially converted to MCH and ammonia that have existing infrastructure in the three involved countries.

9 New Zealand

Table 10. Quantitative hydrogen-related plans and progress in New Zealand.

Country	Certification / Standard Scheme	Hydrogen Incentives	Port Readiness	Storage and Transportation	Net Importer / Net Exporter
Malaysia	In Progress	RD&D	Export Import	Plan	Net Exporter

9.1 Brief Overview

New Zealand consulted on an initial Hydrogen Vision green paper in 2019, outlining the potential possibilities for hydrogen.[93] The green paper noted New Zealand's advantages related to high renewable electricity potential, decades of experience using hydrogen in industrial processes, and conducive regulatory settings.[93] Following this effort, the Government of New Zealand consulted on an Interim Hydrogen Roadmap from August to November 2023.[94] Following a change in government in 2023, the Minister of Energy has committed to publishing a Hydrogen Action Plan by the end of 2024, according to NZL stakeholders. The commentary below summarizes the publicly available Interim Hydrogen Roadmap.[94]

The interim roadmap was developed with input from industry consultation.[94] It outlines a proposed role for hydrogen in the energy system as well as the role for government in supporting hydrogen technologies.[94] The roadmap states that, although **renewable power** in New Zealand supplied **82% of all power** in 2021, the **final renewable energy contribution** (i.e., power and heat) was only **28% of the total energy consumption** in 2021.[94] Based on inputs from NZL stakeholders, the current government of New Zealand plans to **double renewable electricity generation by 2050**. This expansion in renewable energy contribution will likely result in the use of low-carbon hydrogen for energy generation and storage. Indeed, several low-carbon hydrogen projects were announced in New Zealand that address low-carbon ammonia production, low-carbon hydrogen refueling stations, and zero-emission aviation fuels.[94] Multiple of these projects were co-funded by the Government of New Zealand,[94] demonstrating the interest of New Zealand in low-carbon hydrogen technologies.

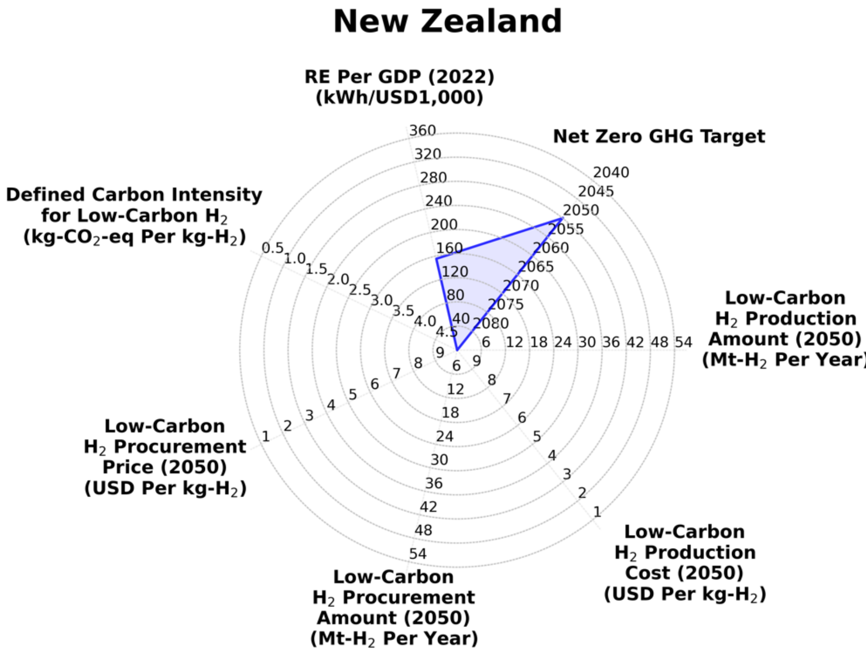

Figure 8. Radar plot of New Zealand's figures of merit.

Note that several metrics were missing due to the lack of available data.

9.2 Key Elements of New Zealand's Hydrogen Vision and Roadmap

9.2.1 Using Low-Carbon Hydrogen in the Industrial Market

Utilizing hydrogen in the industrial sector is important to satisfy countries' climate goals and commitments. For New Zealand, hard-to-abate and hard-to-electrify sectors were identified in the hydrogen roadmap as the most commonly explored areas by commercial players for hydrogen deployment.[94] Specifically, the roadmap mentions **power-to-X**, **fertilizer/urea production**, **ammonia production**, **methanol production, steel production**, **process heat**, and **heavy and specialty transportation** as sectors where hydrogen can enhance electrification and decarbonization of the country's economy.[94] In several of these applications, the Government of New Zealand highlights its involvement with hydrogen-related projects. For instance, the Kapuni Hydrogen Production Facility was supported by approximately **US$12.6 million from the government** to produce **2 t-H_2 per day** for low-carbon urea and heavy transport refueling network.[94,95] This project directly improves the economic state of New Zealand **because two-thirds of the country's current urea production is imported from overseas**.[94] Another example is the governmental support to Robinson Research Institute at Victoria University of Wellington and NZ Steel to utilize hydrogen in the iron reduction process with a locally sourced iron sand.[94] It is worth highlighting that the research, science, and innovation system, under New Zealand's Ministry of Business, Innovation, and Employment, invested **approximately US$28 million in hydrogen-related research**, as of September 2024.[96]

Moreover, the roadmap identifies stakeholder interest in using low-emissions hydrogen to decarbonize ammonia and methanol production. Particularly, although low-carbon ammonia has not been considered so far as a fuel for power generation, the roadmap recognizes that neighboring countries have considered ammonia as a hydrogen/energy carrier for safe transportation purposes.[94] This opportunity could enable New Zealand to enter the hydrogen exports market regionally and internationally. However, according to New Zealand's Vision for Hydrogen Green Paper, **New Zealand is currently not an ammonia exporter**,[93] meaning that new ammonia-related infrastructure is likely needed before participation in ammonia trades as a hydrogen carrier. On the other hand, **methanol is a potential hydrogen carrier with an established infrastructure in New Zealand**.[93] Theoretically, 1.0 kg of H_2, coupled with 7.3 kg of CO_2, can produce 5.3 kg of methanol and 3.0 kg of H_2O. Alternatively, New Zealand could consider biomass gasification as a potential pathway of bio-methanol production locally. Extracting H_2 from low-carbon methanol using methanol reforming would theoretically emit 7.3 kg-CO_2 per kg-H_2 of process emissions. Therefore, effort in point-source CO_2 capture may be required when extracting hydrogen from methanol (or bio-methanol). Consequently, consideration of carbon removal strategies, including the deployment of DAC and BECCS, may be needed to offset residual CO_2 emissions from the CO_2-emitting methanol production processes, even when such processes are coupled with CCS technologies.

In the transportation sector, New Zealand considers hydrogen applications in land, marine, and air transportation.[94] Several case studies were mentioned in the roadmap on the governmental and industrial efforts put into hydrogen application in the transportation sector. The main government-related highlights were the co-investment of three trial projects with industrial partners.[94] One of these projects is in collaboration with HW Richardson Group and focuses on trialing **six dual-fuel trucks that take both diesel and hydrogen**.[94] An initial truck was delivered in early-to-mid 2023, which carried **25 kg-H_2 at 350 bar**.[97] Another project, in collaboration with Hyundai New Zealand, tests five fuel cell truck vehicles in real-world operation.[94] Each truck is equipped with two **95-kW fuel cell stacks** with **a storage tank capacity of approximately 32 kg-H_2 at 350 bar**.[98] A third trial project is in collaboration with Ports of Auckland Ltd and Auckland Transport and focuses on hydrogen fuel cell electric buses. This trial project was commissioned in 2021 to test the operation and cost of hydrogen-fueled buses relative to diesel-fueled and electric buses.[99] The first hydrogen bus cost was approximately **US$0.7 million**, and it was deployed in March 2021 with a seating capacity of 43 adults and a standing capacity of 31 adults.[99]

Industrial involvement has also been critical in advancing New Zealand based hydrogen applications in marine and air-based transportation. The roadmap highlights that Maersk planned to utilize low-carbon methanol as a ship fuel in one of their container ships in 2023.[94] **This milestone was later achieved by Maersk in December 2023**, and it was enabled by a vessel built by Hyundai Heavy Industries (HHI) that has a **nominal capacity of 16,000 shipping containers**.[100] It is worth highlighting that **Maersk has placed 24 orders of the methanol-fueled vessel** from South Korea's HHI.[100] Moreover, Fortescue Future Industries and Channel Infrastructure were highlighted in the roadmap to explore low-carbon hydrogen production in electrochemically synthesized sustainable aviation fuels (SAFs) on a site that is directly connected to Auckland Airport.[94] Such a project could clarify the potential of low-carbon hydrogen in the aviation fuels market in New Zealand. However, it is important to note that the current SAF production cost in the U.S. is estimated to be 1.3 to 11.7 times higher than petroleum-based jet fuel under optimistic economic conditions.[101,102] Therefore, significant cost reduction in SAF production may be necessary for SAF to be cost-competitive with petroleum-sourced jet fuel.

9.2.2 Using Low-Carbon Hydrogen in the Electricity Market

New Zealand plans to reach a net-zero carbon economy by 2050, and decarbonization is likely going to play an important role in achieving this goal.[93] The roadmap acknowledges the risks associated with the volatility of renewable systems in terms of unpredictable demand peaks.[94] Therefore, low-carbon hydrogen has been identified as a potential solution to **decarbonize electricity generation using**

hydrogen-fueled fuel cells and open cycle gas turbine generators. In addition, the roadmap considers the replacement of diesel-based electricity generators with low-carbon hydrogen and fuel cell electricity generators to provide power backup services in case of outages due to emergencies or power disruptions.[94]

9.2.3 Exporting Low-Carbon Hydrogen

Although New Zealand has an excess renewable energy potential, the government plans to undertake further work to assess the electricity system implications of large-scale hydrogen export. The roadmap notes that New Zealand welcomes private interest in hydrogen export but is **currently not financially supporting the development of a hydrogen export market in the country**, prioritizing efforts to support a facilitative regulatory environment and encouraging and exploring ways to increase investment in New Zealand, particularly in renewable energy.[94] It is worth noting that this approach is similar to that taken by countries that have advanced in low-carbon hydrogen deployment (e.g., Australia, United States) since an establishment of a **domestic hydrogen market may be of higher priority than the participation in low-carbon hydrogen trades in the short term**. This approach is usually justified by reducing the risk associated with the high production costs of low-carbon hydrogen. In the future, New Zealand could become a net hydrogen exporter, given there is a hydrogen demand in the region.

9.2.4 Government Position and Actions Regarding Low-Carbon Hydrogen

The Government of New Zealand plans to ensure that hydrogen deployment is safe and meets supply-demand objectives.[94] To this end, New Zealand aims to understand electrification and the deployment of low-carbon fuels, including low-carbon hydrogen.[94] The country plans to implement low-carbon hydrogen technologies only when there is a **clear efficiency and cost improvement** relative to alternative fuels (including conventional ones).[94] Additionally, New Zealand realizes that building a hydrogen economy is a significant challenge that requires multi-sector effort. Associated tasks to this challenge include, but not limited to, building regulatory and governance framework, investing in early-stage projects, investing in research and development, increasing public awareness, building a new hydrogen-related infrastructure, and establishing international partnerships. Accomplishing these tasks could facilitate and monitor the low-carbon hydrogen applications in the country, enabling tracking of the progress related to hydrogen deployment in New Zealand.[94]

In addition, the roadmap lists several governmental actions, including but not limited to:[94]

- Establishing regulatory work regarding safe hydrogen operation
- Budgeting **US$19 million over 3 years** to establish a Clean Heavy Vehicle Grant, which will include hydrogen fuel cell heavy-duty vehicles
- Cooperating internationally to develop mutual recognition of hydrogen certification schemes.

9.3 Tracking Progress

In April of 2024, Hiringa announced the commissioning of the first hydrogen refueling network in the region with a **governmental loan support of US$10.16 million**.[103] The network is currently composed of **three hydrogen refueling stations** located in Auckland, Hamilton, and Tauranga.[103] In addition, several projects have been undertaken in the country. Based on input from NZL stakeholders, the projects include hydrogen generation using geothermal electricity at Halcyon Energy's power plant; deployment of a range of dual fuel and fuel cell heavy vehicles and buses; development of a pilot plant for green urea production; and the establishment of a hydrogen aviation consortium to explore the requirements for using hydrogen to power domestic flights in the future.

New Zealand could benefit from further assessments of low-carbon hydrogen in the country as well as defining decadal (or semi-decadal) low-carbon hydrogen production targets, similar to several other selected Indo-Pacific countries. In addition, ensuring low-carbon hydrogen would require the development of regulations, codes, standards, and certificates related to hydrogen. Although this effort was highlighted in the interim roadmap, explicit definition of the carbon intensity associated with low-carbon (or clean) hydrogen is still missing. New Zealand could strengthen its role in low-carbon hydrogen development and deployment by setting a definition of low-carbon hydrogen based on a defined carbon intensity limit(s).

10 Philippines

Table 11. Quantitative hydrogen-related plans and progress in the Philippines.

Country	Certification / Standard Scheme	Hydrogen Incentives	Port Readiness	Storage and Transportation	Net Importer / Net Exporter
Philippines	*In Progress*	*RD&D*	*Not Reported*	*Not Reported*	*Undecided*

10.1 Brief Overview

Low-carbon hydrogen technologies are still in the assessment stages in the Philippines. Hydrogen production from electrolysis and natural gas with CCS are still lacking in the country. Indeed, in 2022, produced natural gas was not used for hydrogen production but rather for power generation, according to the 2023-2050 Philippine Energy Plan (PEP), which was announced in November of 2023.[104] The plan covers conventional and renewable energy, energy efficiency and conservation, power development, and alternative fuels.[104] Hydrogen was considered a potential alternative fuel in the plan, especially for future transportation and baseload power purposes.[104] **In 2022, the Philippines imported approximately 50% of its primary energy, mainly from imported coal and oil**.[105] Such imported energy came mostly from **Indonesia** and **the Middle East**.[105] With a renewable energy potential of approximately **5.7 GW** from geothermal (34.0%), solar (24.3%), wind (7.8%), hydropower (20.5%), and biomass (13.4%),[106] low-carbon hydrogen has the potential to be produced in the Philippines rather than imported from overseas. Some of the main elements to ensure its success, however, are the low cost of production, implemented carbon policies, and established standards and regulations.

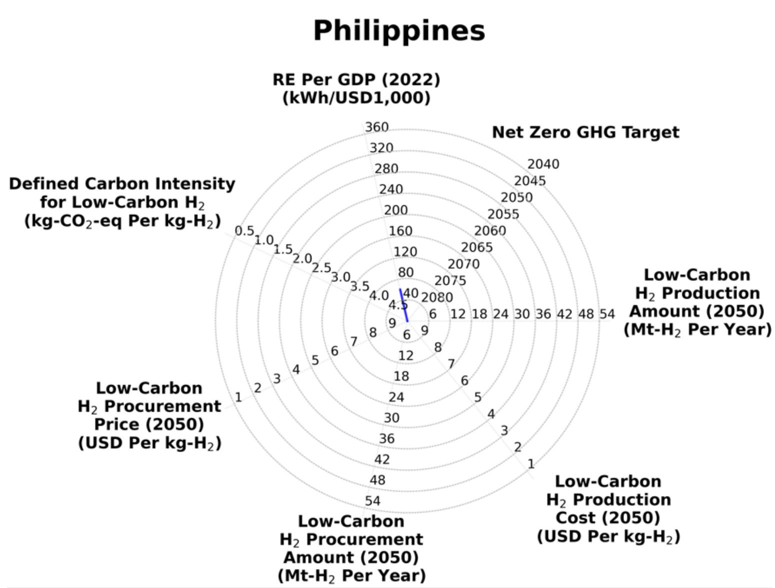

Figure 9. Radar plot of the Philippine's figures of merit.

Note that several metrics were missing due to the lack of available data.

10.2 Hydrogen Considerations in Philippines

The 2023-2050 PEP highlights the Philippines' interest in exploring low-carbon fuels, including hydrogen.[104] The plan states that the Philippines' Department of Energy has been studying hydrogen use in the **power and transportation sectors**, and it has established collaborations with international companies to assess hydrogen use in natural gas-fired power plants and hydrogen fuel cells.[104] In addition, the PEP underscores the importance of developing policies relevant to hydrogen and its derivatives to guide the development and deployment of hydrogen technologies in the country.[104] Furthermore, the PEP provides a strategic roadmap for hydrogen and its derivatives that focuses on **pursuing policy and research development** (2023-onwards), **establishing a national policy framework** (2023-2024), **institutionalizing development partnership** (2023-onwards), and **developing support infrastructure** (2028-2035).[104] So far, the national policy framework document was announced in early 2024, highlighting definitions and incentives regarding hydrogen activities in the Philippines.[107]

The national policy framework document (i.e., Department Circular No. 2024-01-0001) sets the stage for the hydrogen value chain, including production, transportation, distribution, storage, utilization, and importation/exportation.[107] Moreover, it establishes a Hydrogen Energy Industry Committee (HEIC) that will oversee the implementation of the national policy, manage the assessment of hydrogen-related technologies, develop capacity-building programs and collaborations, and conduct quarterly meetings.[107] The HEIC is also tasked with establishing technical working groups (TWGs) that will develop and update facility standards, safety codes, product quality, environmental standards, waste disposal management, and hydrogen energy certification mechanisms.[107] Moreover, the **HEIC is expected to develop a comprehensive strategic hydrogen roadmap** to provide clear definitions of the overall vision and strategy, industry targets, and necessary support systems.[107]

The Department Circular also provides guidance on hydrogen industry activities and incentives. For instance, it establishes an intent-to-engage system that requires all current and future hydrogen projects in the country to submit letters of intent before engaging in any hydrogen-related project.[107] In addition, the Department Circular explicitly states incentives for hydrogen energy projects, including, but not limited to, **income tax holidays**, **accelerated depreciation**, and **tax exemption of carbon credits**.[107]

Industrially, HDF Energy has been active in the Philippines with a signed Memorandum of Cooperation (MoC) and an MoU with governmental entities in the Philippines to explore the use of multi-MW hydrogen power plants in the country.[108,109] Indeed, HDF Energy is currently developing a **hydrogen power plant that will supply up to 45 MW** of power to **more than 800,000 inhabitants** in the Zamboanga Sibugay province and that is **expected to be operational in 2025**.[108–110] In this project, hydrogen is expected to be produced via **electrolysis**[111]; however, the carbon intensity of the electrolysis power consumption is still unclear. To the best of our knowledge, this project is the only one of its kind and size in the Philippines, which represents one of the first hydrogen production deployments in the country.

10.3 Potential Considerations of Low-Carbon Hydrogen in the Philippines

As the Philippines pursues the development of low-carbon hydrogen regulations, it could benefit from setting a threshold for carbon emissions associated with 'clean' hydrogen. Current hydrogen-related policy documents in the Philippines still lack definition regarding the carbon intensity limit for low-carbon hydrogen production. This gap may encourage fossil-based hydrogen to enter the hydrogen market and discourage investments in low-carbon hydrogen production facilities. Moreover, investments in research and development of low-carbon hydrogen derivatives for transportation purposes could benefit the country in speeding up the deployments of local low-carbon hydrogen projects. For instance, the newly built infrastructure for receiving liquified natural gas (LNG) in Batangas[104] can be integrated with local low-carbon hydrogen production facilities to produce hydrogen via SMR while capturing the emitted CO_2 using a CCS technology. In addition, assessments of hydrogen storage and transportation solutions could address potential challenges for the deployment of hydrogen fuel cells or internal combustion engine vehicles in the country. One of the main challenges of this topic will be ensuring safe handling, storage, and transportation of hydrogen, which will require thorough policy developments that address these aspects holistically. Finally, hydrogen deployment can be a social concern for the public. Therefore, the health benefits associated with low-carbon hydrogen projects as well as transparent and accessible educational programs on hydrogen considerations (including safety measures) could improve the probability of public acceptance of low-carbon hydrogen projects in the Philippines.

Overall, the Philippines has shown clear interest in clean hydrogen for use in at least the power and transportation sectors. So far, multiple assessments have taken place by the Philippines' Department of Energy. However, further progress is still underway, especially in the areas of policy development, comprehensive roadbooks, safety standards development, and production pathway assessment specific to low-carbon hydrogen. With the potentially upcoming strategic hydrogen roadmap, these elements could be addressed by the government, ensuring progress in the development and deployment of low-carbon hydrogen technologies in the Philippines.

11 Republic of Korea (KOR)

Table 12. Quantitative hydrogen-related plans and progress in the Republic of Korea.

Country	Certification / Standard Scheme	Hydrogen Incentives	Port Readiness	Storage and Transportation	Net Importer / Net Exporter
Republic of Korea	*Implemented*	*RD&D*	*Export* *Import*	*Exists* *Plan* *Repurp.*	*Net Importer*

11.1 Brief Overview

In November of 2021, the Government of the Republic of Korea published the 1st basic plan for implementation of a hydrogen economy, highlighting the need for low-carbon hydrogen to pursue carbon neutrality, enhance industrial competitiveness, stabilize power systems, and strengthen energy independence.[112] In this basic plan, insights on Korea's assessment of major trends in the hydrogen economy both globally and domestically were provided.[112] In addition, the current status, limitations, and future direction of hydrogen production, storage, transportation, utilization, and ecosystem were discussed in the plan.[112] Four major strategies were highlighted that ensure hydrogen supply, distribution, and use while developing workforce, practicing safe measures, and leading global cooperation. Finally, several promotion tasks were stated that address the strategy in more detail to guide the country toward co-leading the hydrogen economy globally.[112]

In 2021, the Republic of Korea consumed approximately 3.5 Petawatt-hour (PWh) (≈3,500 TWh) of primary energy (i.e., raw energy inputs), out of which 15.1% were sourced from hydroelectric (0.2%), renewables (3.5%), and nuclear (11.4%).[113] In 2019, the country **imported 93.5% of its total energy in the form of petroleum, bituminous coal, LNG, nuclear power, and hard coal**.[112] The three largest energy resources were petroleum (38.7%), bituminous coal (25.6%), and LNG (17.7%), which were mostly imported in 2019.[112] As a **current net energy importer**, the country is planning to explore the possibility of including hydrogen as an energy source in their energy mix to reach higher energy independence, potentially deriving **48 TWh and 288 TWh of its 2030- and 2050-forecasted energy demand from hydrogen, respectively**.[112] Additionally, the Republic of Korea plans to expand its hydrogen refueling infrastructure by building **660 refueling stations by 2030** and **1,200 refueling stations by 2040**.[112] Some of these refueling stations are expected to utilize liquid hydrogen, requiring advancements in liquefaction technologies.[114–116]

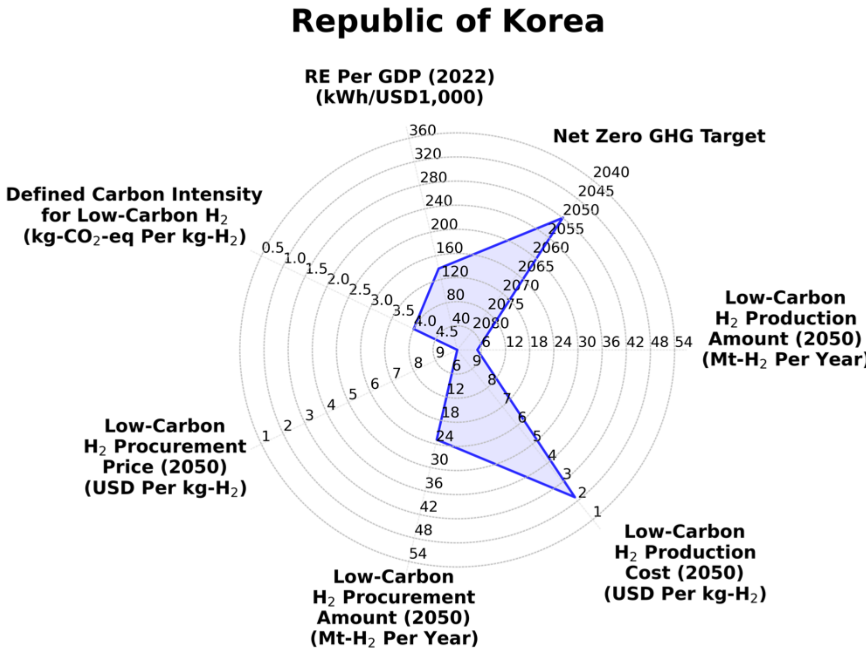

Figure 10. Radar plot of the Republic of Korea's figures of merit.

Note that the Republic of Korea plans to produce low-carbon hydrogen locally and procure the remaining demand from overseas. The targeted procurement amount of low-carbon hydrogen is 22.9 Mt-H_2 per year, whereas the targeted full supply is 27.9 Mt-H_2 per year. The extra 5 Mt of low-carbon H_2 per year will be supplied from local low-carbon hydrogen production facilities. Also note that some metrics were missing due to the lack of available data.

11.2 Key Elements of Hydrogen Development in the Republic of Korea

11.2.1 Low-Carbon Hydrogen Targets in the Republic of Korea

South Korea's hydrogen roadmap includes a national vision regarding hydrogen deployment. This vision encompasses targets regarding the number of hydrogen fuel cell vehicles, the number of refueling stations for hydrogen, the supply of hydrogen, the price of hydrogen, and the amount of hydrogen-derived power.[116] This vision has been updated in the 1st Basic Plan for the Implementation of Hydrogen Economy in November 2021,[112] and further refined by proposed targets set by the 5th and 6th Hydrogen Economy Committee, which were convened at the end of 2022 and 2023, respectively.[117]

During the 6th Hydrogen Economy Committee convened at the end of 2023, the government set targets to achieve **300,000 commercial hydrogen fuel cell vehicles** and **660 installed hydrogen refueling stations by 2030**.[117] The basic plan also provides a **2040 target** for the number of **installed hydrogen refueling stations to reach 1,200**.[112] Additionally, according to the basic plan, the amount of supplied hydrogen (**both low-carbon and fossil-based**) is expected to reach **3.9 Mt-H_2 per year**, including approximately **3.0 Mt-H_2 from SMR-CCS and renewably-powered electrolysis by 2030**. **By 2050, hydrogen supply** is expected to increase to **27.9 Mt-H_2 per year**, completely from low-carbon routes.

The basic plan also provides targets for the domestic production cost of low-carbon hydrogen as well as for the price of procured low-carbon hydrogen. It is **targeted that electrolytic hydrogen is produced domestically at a cost of approximately US$2.7 per kg-$H_2$ by 2030** and **US$1.9 per kg-$H_2$ by**

2050.[112] **The production cost of imported low-carbon hydrogen is targeted to be in the range of US$1.0-2.0 per kg-$H_2$ by 2030**.[112]

Such targets could expand the hydrogen market in the Republic of Korea while diversifying the energy portfolio of the country that will help improve its energy independence and security in the future. However, building the infrastructure that will enable the achievement of these goals could be a major challenge for establishing a hydrogen ecosystem in the country.

11.2.2 A Special Focus on Hydrogen Fuel Cells in the Republic of Korea

In January 2019, the Government of the Republic of Korea published the Hydrogen Economy Roadmap, which focuses on hydrogen fuel cells for both transportation and energy needs.[116] In mobility, the government considers hydrogen passenger cars, taxis, buses, trucks, ships, trains, drones, and small machinery.[116] The South Korean Government plans to **manufacture 6.2 million hydrogen vehicles** and **export 3.3 million of them by 2040**,[116] signifying the country's interest in becoming an exporter of hydrogen-fueled vehicles globally.

The numbers of **hydrogen-fueled taxis, buses,** and **trucks** are planned to achieve **80,000, 40,000, and 30,000, respectively, by 2040**.[116] Achieving these targets will likely require the establishment of a land-based hydrogen refueling infrastructure.[116] The roadmap highlights that the South Korean Government plans to build **1,200 hydrogen refueling stations by 2040** while expanding financial support, ensuring a stable power supply, deregulating hydrogen refueling systems, and improving hydrogen safety.[116] The roadmap reports that hydrogen ships, trains, drones, and small machinery are mostly still in the research and development stage, except for hydrogen-fueled drones and forklifts, which are in the demonstration and commercialization stages, respectively.[116]

In the energy sector, hydrogen fuel cells are planned to supply power to the grid, homes, and buildings. **In power generation**, the South Korean Government expects to rely on economies of scale to help establish fuel cell supply to the grid.[116] The country's **2040 target** is to manufacture **15 GW of hydrogen fuel cells** (including 8 GW for domestic supply and 7 GW to be exported overseas) **for power generation** and **2.1 GW of hydrogen fuel cells for homes and buildings**.[116] For context, the 2023 global fuel cell manufacturing was **12 GW**, with Japan and the Republic of Korea leading the supply market.[118] Therefore, achieving the targets set by the Korean government could keep the country as one of the largest suppliers of hydrogen fuel cells globally.

11.2.3 Hydrogen Supply and Industrial Ecosystem

The Republic of Korea plans to ensure stable and sufficient supply of hydrogen as it builds the hydrogen economy in the country.[116] Particularly, South Korea plans to source hydrogen from the existing petrochemical industry (as a byproduct), hydrogen extraction (e.g., SMR or marine bio-hydrogen production[119]), water electrolysis, or overseas.[116] **In 2030, approximately 3.0 Mt of clean hydrogen per year are targeted for domestic use**. The roadmap and basic plan imply that South Korea plans to **import clean hydrogen by 2030**, with a **target procurement amount of approximately 2.0 Mt of clean hydrogen per year**.[112,116] Thus, the establishment of international procurement collaborations and the development of a hydrogen ecosystem in the country and the region could be important to realizing these targets.

The basic plan emphasizes the need for establishing an industrial ecosystem before being able to build the hydrogen economy.[112] To accomplish this objective, specific targets from ministries are stated in the basic plan that address the localization of core hydrogen fuel cell technologies, the link between research and demonstration activities, and the safety of hydrogen-related applications.[112] To encourage these activities, the Government of South Korea plans to establish training programs for future hydrogen professionals in the areas of safety and technology development.[116] Additionally, the government plans to be active in international hydrogen-related standardization activities.[116] Of particular interest is the establishment of **hydrogen clusters** and **hydrogen cities**,[116] which enable local governments to implement a hydrogen economy and test localized hydrogen technologies.

11.2.4 Hydrogen Safety

The Republic of Korea's hydrogen economy roadmap considers hydrogen-related safety issues when it comes to hydrogen transportation and storage.[116] The Government of the Republic of Korea plans to establish a **hydrogen safety management system** that allows hydrogen to be trusted by the public as much as natural gas, which is used in homes and buildings today.[116] Indeed, **two bills** have already been initiated regarding hydrogen safety in South Korea.[116] Moreover, the government plans to improve current hydrogen standards that are related to refueling stations, tube trailers, and fuel cells for power generation.[116] According to inputs from KOR stakeholders, South Korea established the Hydrogen Products Test and Evaluation Center in March 2024, which is used to enhance the safety of relevant parts to hydrogen technologies.

11.2.5 Clean Hydrogen Certification

South Korea's Ministry of Trade, Industry, and Energy (MOTIE) initiated the clean hydrogen certification to address **investment uncertainty** and ensure **transparent deployment** of clean hydrogen.[120] A life-cycle analysis (LCA) platform is planned to be utilized to facilitate this process, and MOTIE is expected to manage this platform.[120] For a hydrogen production facility to obtain a certification of clean hydrogen under this system, they are required to maintain a carbon intensity of **4.0 kg-CO_2-eq per kg-H_2 or less**. It is worth noting that this carbon intensity is based on "well-to-gate" GHG emissions, which include emissions from feedstock extraction and hydrogen production and **exclude hydrogen carrier and ship emissions** temporarily. Future updates to this LCA calculation are expected to be based on "well-to-port" or "well-to-wheel" GHG emissions, providing more accurate carbon intensities for clean hydrogen certifications.

11.2.6 Public Awareness

Based on input from KOR partners, South Korea's government distributed "**hydrogen safety manuals**" as of November 2022 that are key to gaining the trust of the society as hydrogen technologies are developed and deployed. Such manuals aim to ensure knowledge transfer to the public regarding hydrogen, its uses, and its safety. Additionally, the government plans to incorporate hydrogen safety knowledge in school curricula to ensure early-stage understanding of the importance and safety of hydrogen.[116] Moreover, Korea Safety Gas established the "**Hydrogen Safety Museum**" in **December 2022** in Chungbuk Province, which aims to spread reliable knowledge about hydrogen safety.[121]

11.3 Tracking Progress

In 2020, the Republic of Korea invested more than **US$95 million** in hydrogen production (18.1%), storage and distribution (14.4%), mobility (16.1%), power generation (29.1%), and safe environment infrastructure (22.3%).[122] This funding came from **five ministries** in support of research and development effort. In addition, the Republic of Korea initiated efforts for **liquid hydrogen** to be used in storage and distribution. In fact, liquid hydrogen and liquefaction research have been listed as key research topics in both the country's public and private sectors.[122] Moreover, it has been reported that regional governments in South Korea have invested **at least US$1.7 billion over 2020-2031** in building a fuel cell manufacturing complex, establishing residential fuel cell infrastructure, and supporting a hydrogen production cluster program.[123]

Korea's hydrogen basic plan and the 6th Hydrogen Economy Committee report published short-term (by 2030), mid-term (by 2040), and long-term (by 2050) goals.[112,117] Some of the **2030 goals** are supplying **300,000 commercial hydrogen fuel cell vehicles** and building **660 hydrogen refueling stations**.[116] **By 2040**, the number of hydrogen refueling stations is targeted to reach **1,200 stations**. In the end of 2023, the number of hydrogen fuel cell vehicles reached **34,217 vehicles** and the number of refueling stations reached **247 stations**.[117] **These numbers show that the Republic of Korea achieved approximately 11% and 37% of its 2030 targets, respectively**. Faster deployment of hydrogen vehicles and refueling stations may be required to achieve the 2030 goals on time.

Regarding power generation, the Republic of Korea plans to **utilize 3.5 Mt-H_2 per year by 2030 and 13.5 Mt-H_2 per year by 2050**, equivalent to **48 TWh and 288 TWh, respectively**. Relevant milestones for these targets may include utilizing ammonia and hydrogen to contribute approximately 70% to the total Korean power generation by 2050. **In 2018**, the total installed capacity of fuel cell power generation facilities in the Republic of Korea was approximately **300 MW**, and it has increased to approximately **680 MW** and **more than 1,000 MW** in **2021** and **2024**, respectively.[112,124] According to data from the Electric Power Statistics Information System, the average annual additional fuel cell capacity is approximately **130 MW per year**. At this growth rate, the total fuel cell capacity will be limited to below **2 GW** (i.e., 2,000 MW) **in 2040**.[124] Thus, achieving **South Korea's 2040 target of 15 GW** installed fuel cell capacity for power generation could benefit from expansion in fuel cell manufacturing capacity, which is one of the tasks set by the government in the hydrogen basic plan.

Recognizing the importance of hydrogen in the power sector to meet its Nationally Determined Contributions (NDCs), the Republic of Korea has built an institutional framework to support clean hydrogen power generation in creating large hydrogen demand. In 2023, the 10th Master Plan for Power Supply and Demand set a **2030 target of achieving 2.1% contribution from low-carbon hydrogen and ammonia to the national power supply, increasing to 7.1% by 2036**.[125] Accordingly, as of May 2024, South Korea launched a clean hydrogen bidding market **for up to 6,500 GWh per year** of electricity production over a **15-year period, starting in 2028**.[126] Potentially, this market could cover up to 1% of the 2023 electricity generation in South Korea per year.[127]

Furthermore, the Republic of Korea recently expanded tax support for clean hydrogen through the amendment of "**The Act on Restriction on Special Cases Concerning Taxation**" **in 2024**, where hydrogen technology is newly designated as the national strategic technology.[128] The act stipulates the detailed technologies and facilities eligible for R&D and investment tax credits. For national strategic technologies, **the maximum R&D tax credit rate is capped at 50%, and investment tax credits at 25%**.[128]

Finally, fuel cells have been used in homes and building in Korea. A recent hydrogen project in this area is the Yuldong-With-U in the city of Ulsan, which is a 437-household apartment complex that is fully powered by the hydrogen byproducts from a petroleum facility. The project has a **full capacity of approximately 1.3 MW** and **electrical energy efficiency of 65%** (i.e., can generate 25.7 kWh per kg-H_2). However, the city of Ulsan has not announced the carbon intensity of this project yet, which raises some uncertainties around the cleanliness of the consumed hydrogen.

12 Singapore

Table 13. Quantitative hydrogen-related plans and progress in Singapore.

Country	Certification / Standard Scheme	Hydrogen Incentives	Port Readiness	Storage and Transportation	Net Importer / Net Exporter
Singapore	In Progress	RD&D	Export Import	Plan Repurposed	Net Importer

12.1 Brief Overview

As a land-limited country, alternative energy sources in Singapore are scarce. Thus, Singapore's challenge in transitioning to a cleaner future highly depends on developments in renewable technologies.[129] In October 2022, Singapore's Ministry of Trade and Industry (MTI) published the country's first hydrogen roadmap, beginning with a special highlight of the background effort that the government has already implemented for pursuing its climate targets.[129] One of the key achievements under this umbrella is the transition away from oil-based fuels to natural gas, which is the cleanest form of fossil fuel today.[129] Additionally, previous published reports by the Government of Singapore identified low-carbon hydrogen to be a potential fuel source in the 2050 fuel mix.[129] With a limited solar potential of 8.6 GW_p–equivalent to up to 10% of the country's 2050-forecasted electricity demand–Singapore plans to **import low-carbon hydrogen for power generation**.[129] Achieving this goal could require the development of new infrastructure and a low-carbon hydrogen certification scheme that may facilitate such an critical transition of the energy system in Singapore.

Moreover, 2020 GHG emissions in Singapore reached **approximately 49.7 Mt-CO_2-eq,** with the industrial (44.4%), power (39.8%), and transportation (13.7%) sectors accounting for 97.9% of the total emissions.[129] Low-carbon hydrogen technologies (e.g., hydrogen-compatible combined cycle gas turbines, hydrogen fuel cells, and hydrogen-fed industrial processes) could contribute to reducing the total GHG emissions associated with these carbon-emitting sectors.[129] Singapore's National Hydrogen Strategy provides insights and guidelines on how the Government is considering low-carbon hydrogen applications to help with the energy transition to a low-carbon economy.

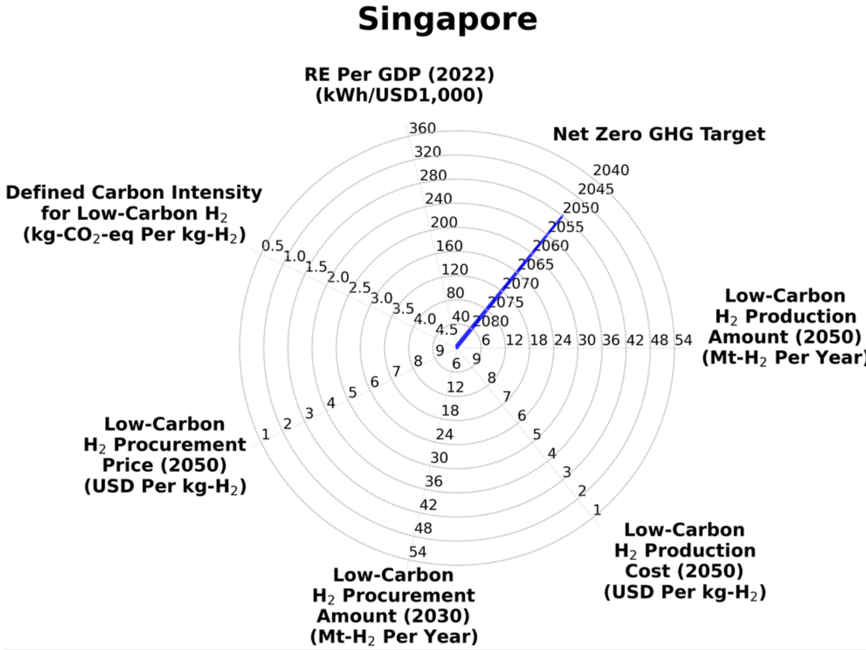

Figure 11. Radar plot of Singapore's figures of merit.

Note that some metrics were missing due to the lack of available data.

12.2 Key Elements of Singapore's National Hydrogen Strategy

12.2.1 The Potential of Low-Carbon Hydrogen in Singapore

Singapore's National Hydrogen Strategy recognizes that hydrogen can be used in the **power**, **industrial**, and **transportation** sectors as a fuel or a feedstock that could generate power, produce chemical commodity, or generate electricity for vehicles.[129] In the power sector, hydrogen fuel cells, hydrogen gas turbines, and blended hydrogen-natural gas combined cycle gas turbines (CCGTs) are considered by the Government of Singapore.[129] Out of the three technologies, CCGTs are identified as commercially available, with hydrogen being able to contribute 30-50% of the total gas feed composition.[129] The roadmap states that original equipment manufacturers (OEMs) are exploring CCGTs that can take hydrogen as the sole feed, potentially providing a cleaner way to combustion for power generation by 2030.[129] On the other hand, the government is exploring the adoption of hydrogen fuel cells for maritime, land, and industrial users.[129]

Industrially, Singapore identifies that hydrogen can be used in heating and chemical conversion applications because of its potential to be used in fuel cells or in hydrogen-fed reactors (e.g., ammonia reactors or reverse water gas shift reactors).[129] This feature benefits the industrial sector in terms of building a shared, rather than separate, infrastructure for importing and distributing low-carbon hydrogen for both power generation and chemical conversion processes.[129] Additionally, Singapore considers decarbonizing hydrogen production via **coupling with carbon capture technologies** or by **replacing current hydrogen production methods with imported low-carbon hydrogen**.[129]

Finally, Singapore's hydrogen strategy highlights that the transportation sector can benefit from low-carbon hydrogen in maritime, aviation, and land transport applications.[129] Having the world's **busiest container transshipment port and being the world's largest bunkering hub in 2021**, Singapore considers transporting hydrogen in the form of **ammonia** due to the potential use of ammonia as a possible bunker fuel by 2050.[129] To support this effort, the Maritime and Port Authority (MPA) of Singapore has been exploring feasibility projects of using ammonia as a bunkering fuel in terms of technical, economic, and regulatory aspects.[129] The aviation sector in Singapore can also benefit from low-carbon hydrogen as a feedstock for **SAF production**. In the medium term, hydrogen fuel cells could be used for airside ground vehicles and aircraft propulsion, with liquefied hydrogen as a potential fuel source for hydrogen-powered aircraft in the long term. The Government of Singapore, through the Civil Aviation Authority of Singapore (CAAS), has been involved in multiple projects covering the use of SAF in aircrafts and the development of aviation-related supply and infrastructure.[129] Lastly, hydrogen applications in land transport can come in the form of hydrogen fuel cells that may decarbonize vehicle segments that require higher power and mileage. The Government of Singapore plans to continue exploring this avenue through partnerships with industry and research institutions to build an understanding of hydrogen fuel cell vehicle development.[129]

12.2.2 Cross-Sectoral Collaborations Through Pathfinder Projects

As a potential **net importer of hydrogen**,[130] Singapore plans to focus their initial effort on ammonia, as it could be used for both hydrogen transport or as a shipment bunker fuel. To this end, Singapore's Government plans to build its capabilities in importing, handling, transporting, and distributing low-carbon ammonia.[129] **Singapore plans to innovate in ammonia utilization processes and in ammonia regulations as a bunker fuel for ships**.[129] Based on input from SGP stakeholders, Singapore is working on an ammonia pathfinder project that is expected to produce **0.25 Mt-NH_3 per year**, which will expect to see the direct combustion of ammonia for power generation and maritime bunkering. In alignment with this data, the roadmap states that ammonia-fueled electricity generators are expected to be commercialized by 2050.[129]

12.2.3 Investments in R&D of Low-Carbon Hydrogen Technologies

To build Singapore's capabilities around low-carbon hydrogen technologies, Singapore's Government plans to coordinate between industry and the research community to maximize the understanding of key areas for Singapore's development. For instance, the Low-Carbon Energy Research (LCER) funding initiative was introduced in 2020 with an **initial funding of approximately US$43 million to research, development, and demonstration (RD&D) projects on low-carbon technology solutions**.[129] Under Phase 2 of the LCER funding initiative, an additional approximate amount of US$100 million was allocated to develop low-carbon technologies, of which around **US$34 million has been awarded to mid technology readiness level (TRL) projects under the Directed Hydrogen Program**.[129,131] Additionally, the roadmap specifies potential research and development key areas that include ammonia cracking as well as liquid hydrogen transportation and storage.[129]

12.2.4 International Collaborations Relevant to Low-Carbon Hydrogen

Singapore recognizes the importance of international partnerships to the effective scaling up and deployment of sustainable solutions. In this regard, Singapore's hydrogen strategy mentions three foci of Singapore's government as part of international collaborations, which are:[129]

1. Establishing an ecosystem for **trading and financing** low-carbon hydrogen projects
2. Supporting the **development of Guarantee of Origin certificates** to align well with jurisdictions and cross-border trading regulations

3. Supporting **research collaborations** in low-carbon hydrogen technologies.

In addition, the roadmap highlights the government's involvement in government-to-government (G2G) agreements regarding low-carbon hydrogen issues, which cover topics such as certification, hydrogen supply chain, and technology development.[129]

12.2.5 Low-Carbon Hydrogen Infrastructure and Workforce Development

Although Singapore's low-carbon hydrogen production is expected to be limited, developing an infrastructure for transporting and storing hydrogen and/or its derivatives can still be critical. Due to the nascency of the hydrogen supply chain, the Government of Singapore does not plan to build a large infrastructure of hydrogen in the near term.[129] However, to achieve long-term targets, the country plans to "gradually build up the necessary infrastructure" for low-carbon hydrogen transportation and storage.[129] Additionally, upskilling and reskilling the existing workforce in the energy and chemicals, chemical storage, marine bunkering, power generation, and aviation sectors could be critical due to the expected growth in the use of hydrogen and hydrogen-relevant applications.[129] The country also realizes that developing a new hydrogen workforce will also be needed, as the hydrogen-relevant applications are expected to grow in Singapore's energy, industrial, and transportation sectors.[129]

12.3 Tracking Progress

Singapore's National Hydrogen Strategy states that hydrogen has the potential to play an important role in decarbonizing its power and industry sectors. However, large-scale hydrogen deployment could face several challenges in the short term. Notwithstanding, the country has achieved a significant milestone with regards to **the utilization of ammonia as a bunkering fuel or a power generation fuel**. In March 2024, Fortescue announced that it was able to use ammonia, blended with diesel, in a combustion process to power a vessel in the port of Singapore.[132] This project was supported by the MPA of Singapore, government agencies, research institutions, and industry partners.[132] In addition, this project marks the **world's first ammonia-powered vessel trial**, demonstrating Singapore's commitment to consider ammonia as a bunker fuel.

Furthermore, an MoU was signed in March 2024 by Vopak and Air Liquide to develop and operate an ammonia infrastructure for importing, cracking, and hydrogen distribution in Singapore.[133] The Government of Singapore is also embarking on an ammonia pathfinder project for direct ammonia combustion and maritime bunkering. Completing such projects and developing many more could position Singapore as a clean ammonia hub that could be attractive to the region.

13 Thailand

Table 14. Quantitative hydrogen-related plans and progress in Thailand.

Country	Certification / Standard Scheme	Hydrogen Incentives	Port Readiness	Storage and Transportation	Net Importer / Net Exporter
Thailand	Not Reported	Not Reported	Not Reported	Not Reported	Not Reported

13.1 Brief Overview

Thailand's GHG emission development strategy highlights that hydrogen deployment is among the necessary solutions to enable the country to reach its net-zero GHG emission target by 2065.[134] **In 2022**, the domestic hydrogen production rate was **approximately 0.03 Mt-H_2 per year**, all sourced from biogas-fed SMR.[135] Assuming constant operation throughout the year, this rate translates to approximately **82 t-H_2 per day**, which can power only about **2,000 hydrogen-fueled buses** (operating at 10 kg-H_2 per 100 km and driving about 400 km per day) that can serve a mere **0.14% of the total population** (total population = 71.7 million). Expansion of the hydrogen production rate could entail the diversification of the hydrogen production method, likely requiring low-carbon hydrogen production technologies, including biomass gasification, SMR-CCS, and water electrolysis. Thailand plans to **increase its renewable energy contribution in its final energy consumption mix by 24% before 2027**–equivalent to approximately 26 TWh.[136,137] Additionally, the International Renewable Energy Agency (IRENA) predicts that renewable energy share in Thailand could reach as high as **37% of the total final energy consumption by 2036**–equivalent to approximately 20 GW of installed capacity.[138] Therefore, hydrogen can play a significant role in **power generation**, **seasonal storage**, **heating**, and **transportation** to help the country achieve these targets.

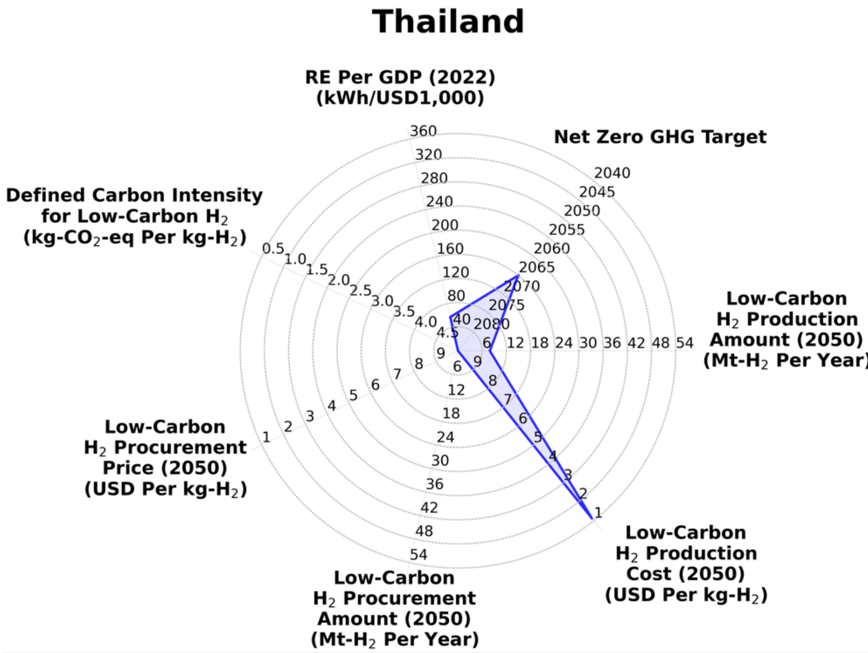

Figure 12. Radar plot of Thailand's figures of merit.

Note that some metrics were missing due to the lack of available data.

13.2 Hydrogen Considerations in Thailand

Thailand's Energy Policy and Planning Office (EPPO) in the Ministry of Energy has conducted several studies on hydrogen-related activities since 2021.[139,140] The studies consider end uses of hydrogen in the power generation, industry, and transportation sectors.[139,140] The results of such studies have motivated the country to pursue a **commercial hydrogen production and utilization development plan, which is in-progress today**.[139] The plan highlights Thailand's goals of utilizing hydrogen in the energy sector by 2030 and growing to other sectors by 2050. To achieve these goals, Thailand's government plans to promote hydrogen in the country, following four strategies: 1) market and incentive development, 2) R&D promotion and domestic industry support, 3) infrastructure development, and 4) law and regulations development.[139]

The first and second strategies plan to provide financial and investment support to hydrogen users, including entrepreneurs.[139] Under these two strategies, Thailand plans to develop **hydrogen pricing**, **carbon market**, and **trading mechanisms** to support the growth of hydrogen-related activities in the country.[139] Additionally, development of new research and business cases followed by pilot projects is also considered under the first two strategies.[139] The third strategy focuses on **developing an infrastructure** that could enable hydrogen transport and use within the country.[139] For instance, Thailand plans to develop hydrogen refueling stations that will facilitate the use of hydrogen fuel cell vehicles.[139] Additionally, Thailand plans to develop blended-fuel pipelines to enable blends of hydrogen in the gas network.[139] The fourth strategy plans to c**reate a regulatory and policy support for hydrogen within the existing energy framework**.[139] This strategy is yet to be developed further to include explicit aspects of hydrogen regulation, such as safety and related emissions.

To achieve the four strategies, Thailand's hydrogen development plan includes explicit short-term (2020-2030), medium-term (2031-2040), and long-term (2041-2050) targets.[139] These decadal targets are expected to be driven by international policy pressure and net-zero commitments.[139] In the short term (2020-2030), Thailand's hydrogen development plan shows a focus on developing pilot projects, new business models, and an import/export plan.[139] In addition, it includes establishment of safety standards of hydrogen production and use by 2030.[139] The plan reports that the estimated low-carbon hydrogen production cost range was **US$1.3-4.7 per kg-$H_2$ in 2021**, with the low end representing hydrogen from SMR-CCS and the high end representing hydrogen from water electrolysis.[140]

In the medium term (2031-2040), Thailand plans to focus on hydrogen blending and fuel cell vehicle project deployments, requiring development of gas quality standards and a hydrogen storage depot.[139] To enable this effort, tax incentives, investment support, and infrastructure modifications are planned to be pursued during this decade.[139] Thailand plans to blend **10-20% of hydrogen in gas pipelines** and build at least **70 refueling stations** that are within 400 km from each other **by 2040**.[139]

The long-term (2041-2050) targets expand on these goals by increasing the blending percentage to between **25% and 75%**, building more than **110 additional hydrogen refueling stations**, and achieving **27,000 light and heavy duty hydrogen-powered vehicles**.[139] It is worth noting that the number of refueling stations may not be the optimal choice regarding the cost of hydrogen transportation from the production facility to the refueling station. Therefore, careful early planning could avoid potentially high prices for the end user. The 2040-2050 decade is also expected to establish a carbon market and trading mechanisms and achieve a hydrogen production cost of **US$1.1 per kg-$H_2$ via SMR-CCS** and **US$2.3 per kg-$H_2$ via electrolysis**.[140] In parallel, Thailand plans to develop hydrogen road and pipeline transportation mechanisms and establish fuel cell and refueling station standards.[139]

It is worthwhile to note that several selected Indo-Pacific countries (e.g., Australia, Malaysia, and the U.S.) have estimated electrolysis-based hydrogen *production* costs in the range of **US$1.1-2.1 per kg-$H_2$ by 2050** compared to Thailand's estimated *production* costs of electrolytic hydrogen of **US$2.3 per kg-$H_2$ by 2050**.[140] The success of these potential low-carbon hydrogen exporters in achieving a low-carbon hydrogen production costs of **US$1.1** could present an opportunity for Thailand to import low-carbon hydrogen at a lower price than domestic electrolytic hydrogen. Therefore, assessing potential hydrogen import routes that provide the lowest costs of delivered hydrogen might be of interest to Thailand.

In addition to production cost targets, Thailand's hydrogen development plan includes liquefaction, shipping, pipeline transportation, road transportation, and CO_2 capture costs as well as carbon taxes.[140] By 2050, the total price of hydrogen from SMR-CCS including all of the mentioned costs is estimated to be **US$3.9 per kg-$H_2$**, whereas that from electrolysis is estimated to be **US$6.0 per kg-$H_2$**.[140] By 2060, the total price of SMR-CCS and electrolysis-based hydrogen is estimated to be **US$2.8 and US$4.2 per kg-H_2**, respectively.[140]

At the industrial level, there are several hydrogen-related projects announced to date. The IRENA Renewable Energy Outlook (REO) report on Thailand highlights two local hydrogen energy storage projects as of 2017.[138] The first one, developed by CNX Construction, utilizes Anion Exchange Membrane (AEM) electrolyzers to produce hydrogen. It also uses both batteries and hydrogen to store excess solar power for four single-family houses in the Phi Suea House development.[138,141] This system is capable **of producing approximately 0.2 kg-H_2 per hour**[142], **storing 90 Nm^3 of hydrogen** (i.e., roughly 7.5 kg-H_2[143]), and **generating approximately 80 kWh** using a hydrogen fuel cell to meet the night demand of this housing development project. To the best of our knowledge, this project is still operational today. The second project is a **1-MW** water electrolysis facility that stores excess wind-generated electricity in hydrogen during off-peak hours and uses it in fuel cells to generate **300 kW of power** during peak hours.[138,144] This project was awarded to Hydrogenics Corporation and Phraram 2 Civil Engineering Co. Ltd. by the Electricity Generating Authority of Thailand (EGAT), and it costs **approximately US$4.8 million**.

In addition to power storage, PTT Public Company Limited (PTT) –a state-owned oil and gas company in Thailand–has signed an MoU with the Saudi ACWA Power in November 2022 to build a low-carbon hydrogen and ammonia plant in Thailand that produces approximately **0.23 Mt-H_2 per year** (equivalent to **1.2 Mt-NH_3 per year**) at a cost of approximately **US$7 billion**.[145–147] The produced hydrogen and ammonia are planned to be used in energy production and export.[145,147] PTT also have existing plans with the Japanese Mitsubishi Heavy Industries (MHI) to explore the development of a carbon-neutral petrochemical complex that utilizes low-carbon hydrogen or ammonia as a fuel to power generators.[147] In line with this partnership, MHI signed an MoU with EGAT to research co-firing of hydrogen with natural gas in gas turbine power generation facilities.[148] The project is set to achieve a blending of **20% hydrogen with natural gas**,[148] contributing to meeting one of the goals set by Thailand's government for the 2031-2040 decade.[139] The feasibility study for this project is expected to be ready by **mid-2025**, which will set the stage for project deployment right after.

13.3 Potential Considerations of Low-Carbon Hydrogen in Thailand

Existing plans in Thailand should prepare the energy, transportation, heating, and industrial sectors for the introduction of low-carbon hydrogen use in the country. However, there are at least four improvements that could strengthen Thailand's hydrogen strategy further.

First, **forecasting primary energy costs from non-hydrogen-based electricity sources, diesel, and gasoline** could be relevant to compare against defined hydrogen production cost targets. Such a comparison can be informative when deciding on relevant technologies for Thailand to meet its climate goals. Second, **development of regulations, codes, standards, and policies around low-carbon hydrogen** could enhance the transparency and safety of hydrogen projects. For instance, a **limit to carbon intensity** (in kg-CO_2-eq per kg-H_2) that goes into internationally accepted certification schemes could align the hydrogen market with Thailand's net-zero targets. In addition, structured tax schemes could speed up deployment efforts, enabling Thailand to participate early in the hydrogen market. Third, **increasing the public awareness around hydrogen safety and deployment, as well as around hydrogen-associated health benefits,** via the development of government-sponsored programs could ensure a smooth introduction to hydrogen in residential areas. These programs can come in the form of school curricula development, hydrogen-specific workshops, and publicly available governmental reports. In parallel, **holistic assessments** that consider household equipment (e.g., oven) compatibility for blended hydrogen-gas mixtures could be beneficial for end users of hydrogen in residential areas. Fourth, **developing a highly skilled workforce** could be important in establishing a hydrogen market in the country while creating new employment opportunities for local communities. This effort can be accomplished by establishing government-sponsored vocational education programs that prepare skilled professionals for the low-carbon hydrogen market. In addition, embedding employment opportunity creation within **low-carbon hydrogen roadmaps and strategies** could elucidate the community benefit associated with low-carbon hydrogen deployment in Thailand.

Overall, Thailand's plans for hydrogen development are underway, which include a hydrogen production and utilization development plan that covers the production pathways and end uses of hydrogen in the country. It additionally outlines strategic targets to build the low-carbon hydrogen market by 2050, contributing to the 2065 net-zero target of Thailand. These plans are still missing relevant information, such as explicit production amount targets, workforce development plans, and social aspects of hydrogen deployment in Thailand. Considering these aspects, among the outlined strategies in Thailand's hydrogen development plan, the country could strengthen its position in the hydrogen market domestically, regionally, and globally.

14 United States

Table 15. Quantitative hydrogen-related plans and progress in the United States.

Country	Certification / Standard Scheme	Hydrogen Incentives	Port Readiness	Storage and Transportation	Net Importer / Net Exporter
United States	Implemented	RD&D Per kg	Export Import	Exists Plan	Net Exporter

14.1 Brief Overview

The United States (U.S.) Government has implemented several actions towards clean hydrogen and its deployment. In November of 2021, the Bipartisan Infrastructure Law (BIL) was introduced that includes **US$9.5 billion for low-carbon hydrogen**.[149,150] Additionally, the Inflation Reduction Act (IRA) was passed into law in August 2022, and it included a hydrogen production tax credit (PTC) of **up to $3.00 per kg-$H_2$** to encourage early investments in low-carbon hydrogen production technologies.[150,151] In March of 2023, the U.S. Department of Energy (DOE) published the Pathways to Commercial Liftoff – Clean Hydrogen report, which focuses on deployment considerations for upscaling low-carbon hydrogen supply and demand in the U.S.[152] In June of 2023, the U.S. Government announced the U.S. National Clean Hydrogen Strategy and Roadmap, highlighting the potential of low-carbon hydrogen development and deployment in the U.S. and laying out specific strategies and guiding actions that could maximize the benefits of low-carbon hydrogen in the country.[150] The roadmap sets ambitious goals of replacing CO_2-intensive hydrogen production methods with low-carbon hydrogen production methods.[150]

In 2018, the U.S. produced approximately 10 Mt-H_2, accounting for about 14% of the global hydrogen production.[153] Additionally, the U.S. has installed **1,600-mile** long hydrogen pipelines, 50 open retail hydrogen refueling stations, and over 500 MW of fuel cells for stationary and backup power generation.[150] Moreover, the U.S. introduced 50,000 fuel cell forklifts, more than 80 fuel cell buses, and more than 15,000 hydrogen fuel cell vehicles.[150] These facts highlight the existence of some hydrogen infrastructure in the U.S. that could accelerate deployment efforts in this space.

With today's planned and announced low-carbon hydrogen production projects, the U.S. is on track to achieve a low-carbon hydrogen production rate of 12 Mt-H_2 per year by 2030.[150,152] However, the demand side of hydrogen projects is still underway,[150] restricting the commissioning of several of these projects. This is caused by the high cost of low-carbon hydrogen production, which may be reduced after the recent finalization of the hydrogen PTC (i.e., 45V tax credit) and as the projects scale up their nominal capacities. The DOE announced the Hydrogen Demand Side Initiative in January of 2024, to improve the confidence of hydrogen offtakers, increasing the demand for low-carbon hydrogen.[154]

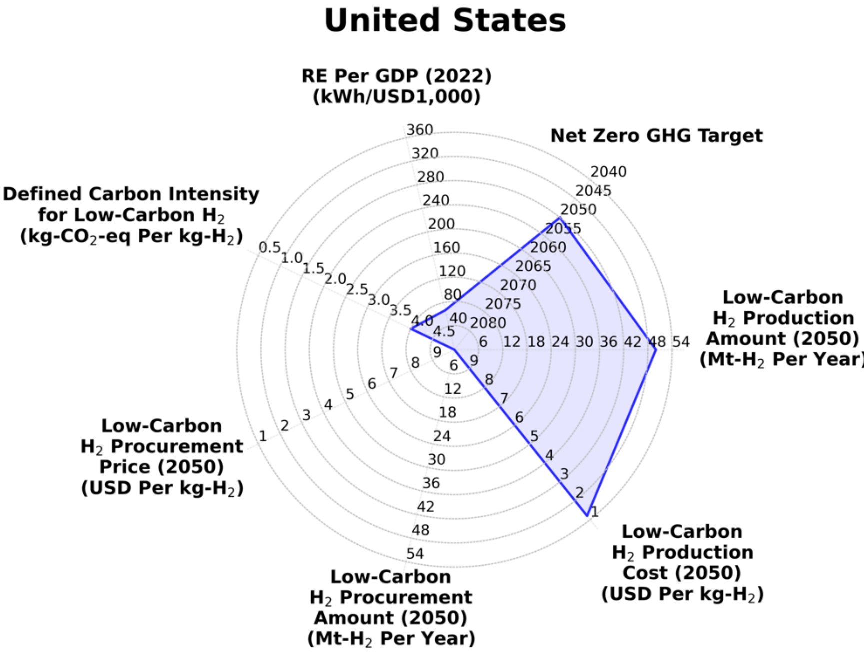

Figure 13. Radar plot of the United States' figures of merit.

Note that some metrics were missing due to the lack of available data.

14.2 Key Elements of the U.S. Approach to Low-Carbon Hydrogen Adoption

14.2.1 Low-Carbon Hydrogen Production and Relevant Costs

The U.S. hydrogen strategy and roadmap and the 2023 commercial liftoff report provide targets for low-carbon hydrogen production and costs. **By 2030**, DOE expects the annual low-carbon hydrogen production in the U.S. to reach **10 Mt-H_2 per year**, and it aims to reduce the production cost of low-carbon hydrogen to approximately **US$1 per kg-$H_2$** to achieve the targeted Hydrogen Shot (i.e., $1 per kg-$H_2$ in one decade, starting from 2021).[150,152,155] In parallel, an **interim** target of **US$2 per kg-$H_2$** has been set by the BIL for **2026**.[150] To put this target into context, SMR-based hydrogen (without CCS) production is estimated to cost **US$1.3 per kg-$H_2$** and electrolytic hydrogen production (without the hydrogen PTC) in different U.S. tariff structures has been estimated to fall in the range of **US$2.6-12.3 per kg-$H_2$**.[152,156] The U.S. DOE reports that the levelized cost of hydrogen (LCOH) produced via electrolysis ranges from **US$5 to US$7 per kg-H_2**, depending on the capacity factor, which ranges from 50% to 70% in the referenced analysis.[157]

The DOE has set an ambitious target to enable the cost of low-carbon hydrogen production to achieve **parity** with fossil-based hydrogen production by 2031 (i.e. the Hydrogen Shot). **By 2040** and **by 2050**, the low-carbon hydrogen amount is targeted to reach **20** and **50 Mt-H_2 per year**, respectively.[150,152] Considering both alkaline and PEM water electrolysis, the 2023 liftoff report estimates the production costs of electrolytic hydrogen **by 2030, 2040, and 2050 to be US$1.6-1.8, US$1.4, and US$1.2 per kg-$H_2$, respectively**.[152] Comparatively, hydrogen produced via SMR-CCS is estimated to cost **US$1.6, US$1.2, and US$1.2 per kg-$H_2$ by 2030, 2040, and 2050, respectively**.[152] Moreover, the 2023 Pathways to Commercial Liftoff Report estimates the 2030 industrial forecasts for the system capital costs of **alkaline**, **PEM**, and **solid oxide electrolysis cell (SOEC)** electrolyzers at

US$230-400, **US$380-450**, and **US$300-500 per kW**, respectively.[152] These forecasts correspond to 60%, 60%, and 80% cost reductions, respectively, relative to 2022 cost estimates.[152]

14.2.2 Three Priority Strategies for Low-Carbon Hydrogen

14.2.2.1 High-Impact Uses of Low-Carbon Hydrogen

To accelerate the deployment of low-carbon hydrogen in the U.S., the government plans to focus on utilizing low-carbon hydrogen for high-value applications, such as in the industrial, transportation, and power sectors.[150] Industrially, hydrogen can be used as a feedstock in the **production of ammonia and methanol**.[150] As of May 2024, the U.S. has **four operational** bio-methanol plants that collectively have a full capacity of approximately **0.4 Mt of methanol (CH_3OH) per year** as well as **one operational** low-carbon methanol plant (i.e., produced from CO_2 and non-renewable H_2) with an approximate capacity of **0.1 Mt-CH_3OH per year**.[158] In addition, **three** e-methanol (i.e., produced from CO_2 and renewable H_2) plants with a combined full capacity of **0.5 Mt-CH_3OH per year** and **one** bio-methanol plant with a full capacity of **0.4 Mt-CH_3OH per year** are in the **pre-feasibility or feasibility** stages.[158] DOE is funding several research projects that assess the techno-economics of producing low-carbon hydrogen carriers (e.g., ammonia, methylcyclohexane, and methanol) as well as other projects that develop novel methods for extracting hydrogen back from ammonia.[150] Additionally, the U.S. could utilize hydrogen in **steelmaking**, which is partially (25-30%) imported from overseas.[150] DOE is currently supporting two projects around hydrogen utilization in steelmaking that aim to optimize the direct reduction of iron and **potentially produce 5 kt of steel per day**.[150] Furthermore, the U.S. Government considers **blending hydrogen with natural gas** to produce industrial heat via combustion.[150] For instance, DOE's HyBlend initiative explores several research projects in related topics including material compatibility, blending cost and emissions, and hydrogen appliances.[150]

In the **transportation** sector, hydrogen is considered for medium and heavy-duty trucks and buses as well as maritime applications, aviation, and rail, requiring fuel cell technology development.[150] DOE is supporting a project, through its Super Truck Program, to demonstrate hydrogen-fueled medium and heavy-duty vehicles by 2028.[150] Moreover, both methanol and ammonia are considered as alternatives to conventional bunker fuel in ships.[150] Indeed, the international maritime organizations (IMO) have enforced a **0.5% limit to the sulfur content in conventional bunker fuels**,[159] providing methanol and ammonia an opportunity to be used as bunker fuels. In addition, low-carbon hydrogen can be used to produce SAFs.[150] The U.S. DOE, Department of Transportation (DOT), and Department of Agriculture (USDA) established a SAF Grand Challenge that set **3 billion gallons (11.36 billion liters) and 35 billion gallons (132.49 billion liters) of SAF by 2030 and by 2050, respectively**.[150,160] However, it is important to be aware that SAF production costs are **estimated to be 1.3-11.7 times higher** than conventional jet fuel production costs,[101,102] which could increase the investment uncertainty in SAF. Lastly, in rail transport, hydrogen can be used directly in hydrogen fuel cells, such as in California's hydrogen fuel cell passenger train that was expected to be in service in early 2024.[150] The train is not operational yet but recently arrived in San Bernando, California, on June 20, 2024, after several months of testing.[161] It is expected that the train will begin operation in late 2024 or early 2025.[161]

The **power** sector can also benefit from low-carbon hydrogen in backup power and energy storage applications.[150] The U.S. government, through its federal departments, funded several projects in these areas, including the following:[150]

- The world's first trigeneration (i.e., combined cooling, heat, and power (CCHP)) system
- First-of-a-kind demonstration of hydrogen fuel cells for data center applications
- Reversible fuel cell research, development, demonstration, and deployment (RDD&D)
- Hundreds of fuel cell deployments for power backup
- 220 MW alkaline water electrolyzers for the Intermountain Power Project (IPP) Renewed in Delta, Utah[162,163]
- Five nuclear-powered electrolyzer demonstration projects with a total electrolyzer capacity of 2.4-3.4 MW.[164,165]

14.2.2.2 Cost Reduction of Low-Carbon Hydrogen

Reducing the cost of low-carbon hydrogen is the biggest hurdle for electrolytic hydrogen deployment due to the need for electrolysis-based hydrogen plants to operate at low renewable electricity prices and high capacity factors (i.e., high annual operating hours), which is typically not achievable using islanded solar- or wind-powered electrolysis. The U.S. hydrogen roadmap recognizes that component cost reductions will only be achievable with R&D innovations and high-volume manufacturing.[150] Thus, encouraging demand should be an effective way to reduce the capital cost of hydrogen. In addition, innovative integration of electrolyzers with the grid is recognized as a key area for cost reduction of electrolytic hydrogen.[150]

Renewably powered water electrolysis is not the only low-carbon hydrogen production method. The U.S. BIL instructed DOE to consider conventional hydrogen production pathways coupled with CCS, such as SMR with CCS or autothermal reforming (ATR) with CCS.[149,150] It is worth noting that the clean hydrogen liftoff report estimates the cost of hydrogen via SMR+CCS or ATR+CCS to be around **US$1.6 per kg-$H_2$**, without the U.S. hydrogen PTC.[152] Biomass gasification is also considered by the U.S. Government due to its cost-efficiency as a carbon-negative pathway throughout its life cycle.[150]

In addition to reducing the cost of hydrogen production methods, reducing the cost of components across the hydrogen value chains is also considered by the U.S. Government.[150] Indeed, approximately **US$4 billion** is allocated by the U.S. Treasury and Internal Revenue Service (IRS) for projects that expand the clean energy supply chain, including the low-carbon hydrogen supply chain.[150] This and similar funds will be critical to reducing the cost of transporting and storing low-carbon hydrogen. For instance, **building hydrogen pipelines might be less expensive than liquifying hydrogen** and transporting it to consumers, depending on the end use.[152] In the U.S., the former is estimated to cost an additional **US$0.2-1.7 per kg-$H_2$** to hydrogen production costs, whereas the latter will add **US$3.1-3.2 per kg-$H_2$**.[150] However, it is vital to consider the willingness-to-pay price since transportation applications may be willing to pay a higher price for low-carbon hydrogen than industrial processes, which require production costs close to the $1 per kg-$H_2$ mark to be competitive with fossil-based hydrogen.[150]

14.2.2.3 Regional Supply and Demand Networks

To enable the deployment of low-carbon hydrogen in the U.S., the government issued the Regional Clean Hydrogen Hub under the U.S. BIL, which aimed to create several hydrogen hubs around the U.S. by the end of 2023 with a total funding amount of **US$8 billion**.[149,150] The U.S. Government summarized 200 responses from stakeholders in the hydrogen roadmap, and had been analyzing the potential of integrating such hubs with hydrogen offtakers to ensure demand creation for low-carbon hydrogen in the

U.S.[150] In addition, the U.S. hydrogen roadmap mentions that DOE is expected to consider issues around low-carbon hydrogen deployment, such as the availability of water and other domestic resources.[150] Finally, regarding conventional production methods that are coupled with CCS, the U.S. Government plans to account for the regional storage potential to assure rational placement of low-carbon hydrogen projects throughout the states.[150]

14.2.3 Manufacturing at Scale

Driving down cost of low-carbon hydrogen will likely require component cost reductions, which could be achieved with high-volume manufacturing. The U.S. Government has announced **US$500 million** for clean hydrogen manufacturing and recycling RDD&D.[150] This effort is coupled with several commitments of localizing manufacturing of hydrogen-related technologies (e.g., fuel cell electric vehicles, refueling infrastructure, and electrolyzers). For instance, the government plans to build a **3-GW-per-year** electrolyzer manufacturing capacity in the U.S. by 2028 and deploy manufacturing facilities for low-carbon hydrogen technologies in disadvantaged communities.[150]

14.2.4 Certification, Clean H_2 Production Tax Credit, and Social Considerations

The verification processes implemented by the U.S. government to ensure clean hydrogen production are embedded within tax credits. For instance, California's Low Carbon Fuel Standard (LCFS) is an incentive that aims to reduce the emissions of transportation fuel in California.[166,167] Facilities that produce more kilograms of carbon dioxide equivalents per mega joules (kg-CO_2-eq per MJ) than targeted by the state will need to purchase LCFS credits to offset their emissions.[167] The price of one LCFS credit, which allows for 1 t-CO_2-eq to be emitted, is fluctuating with a value of approximately **US$54 per t-$CO_2$** in August 2024.[168] Similarly, the H_2 PTC enables a hydrogen credit of **US$0.12-0.60 per kg-$H_2$** depending on the carbon intensity of the hydrogen production facility according to **Table 14**.[169] This credit is multiplied by **five** if the facility meets the **prevailing wage and apprenticeship requirements**.[169,170] For instance, a hydrogen production facility with a life cycle GHG emission ratio in the range of 2.5-4.0 kg-CO_2-eq per kg-H_2 would be qualified to get US$0.60 per kg-$H_2$ instead of $0.12 per kg-$H_2$, given that they meet the prevailing wage and apprenticeship requirement.

In January of 2025, the U.S. Department of the Treasury and the IRS announced the final rules for the 45V tax credit to consider three pillars: **incrementality** (i.e., the use of **new** clean power), **temporal matching** (i.e., the use of clean electricity **within the same generation hour**), and **deliverability** (i.e., electricity use from **the same region** as the low-carbon hydrogen production facility) in the H_2 PTC.[169,171] These final rules could have an effect on the FID of planned hydrogen production facilities, although certain conclusions are yet to come. Notably, the rules are set to ensure the low-carbon intensity of hydrogen production (up to 4.00 kg-CO_2-eq per kg-H_2) that qualify for the 45V tax credit of up to US$3.00 per kg-$H_2$.

Table 16. Hydrogen PTC amount depending on life cycle GHG emission ratios and prevailing wage and apprenticeship requirements.

Life Cycle GHG Emission Ratio (kg-CO_2-eq per kg-H_2)	Credit Amount (per kg-H_2)	Credit Amount if Prevailing Wage and Apprenticeship Requirements Met (per kg-H_2)
<0.45	US$0.60	US$3.00
0.45 to <1.5	US$0.20	US$1.00
1.5 to <2.5	US$0.15	US$0.75
2.5 to ≤4.0	US$0.12	US$0.60

14.3 Tracking Progress

The U.S. was active in the low-carbon hydrogen space before announcing the country's hydrogen roadmap. For instance, the U.S. announced the hydrogen PTC of up to US$3.00 per kg-$H_2$ in August 2022.[151] Additionally, the U.S. has set the hydrogen shot, aiming to reduce the production cost of low-carbon hydrogen to **US$1 per kg-$H_2$ by 2031**.[155] These policy changes and commitments, among others, indicate the strong interest of the U.S. Government to enable low-carbon hydrogen technology deployments.

Since the announcement of the U.S. hydrogen roadmap, the most important milestone that has been achieved is the selection of **seven U.S. hydrogen hubs for negotiation**. These hubs include the Appalachian, California, Gulf Coast, Heartland, Mid-Atlantic, Midwest, and Pacific Northwest hydrogen hubs, covering a total of 16 states.[172] The combined permanent job amount from all hydrogen hubs totals approximately **112,000 permanent jobs**.[172] In addition, a multiyear program plan has been published by DOE's Hydrogen and Fuel Cells Technologies Office (HFTO), which reiterates set targets in the roadmap and adds several others (e.g., **US$500 per kW high-temperature electrolyzer system cost by 2026** and **delivered hydrogen price for heavy-duty vehicles of US$7.0 per kg-$H_2$ by 2028**).[173] As of October 2024, the reported delivered hydrogen price in California was **approximately US$34.6 per kg-$H_2$**, which is higher than the hydrogen price at refueling stations in South Korea (US$5.7-9.0 per kg-$H_2$), Japan (US$7.7 per kg-H_2), and Germany (US$12.0-16.7 per kg-$H_2$).[174–177] This fact underscores the U.S. challenge in lowering and stabilizing the delivered hydrogen price to consumers in refueling stations.

Moreover, the U.S. Government continues to announce additional funding for low-carbon hydrogen technologies projects. In March 2024, DOE announced funding of the amount of **US$750 million** for more than 50 projects to help reduce the cost of low-carbon hydrogen.[178] In addition, **up to US$6 billion** was announced in the same month, with two iron and steel projects (totaling up to **US$1 billion**) that will investigate hydrogen utilization in iron and steel plants.[179] Finally, verification of hydrogen low carbon intensity has been emphasized in both federal and state programs that aim to reduce the GHG emission rates as much as possible. Those programs include California's LCFS and clean hydrogen PTC.

15 Viet Nam

Table 17. Quantitative hydrogen-related plans and progress in Viet Nam.

Country	Certification / Standard Scheme	Hydrogen Incentives	Port Readiness		Storage and Transportation		Net Importer / Net Exporter
Viet Nam	In Progress	RD&D	Export	Import	Plan	Repurposed	Undecided

15.1 Brief Overview

In 2020, Viet Nam locally produced around 0.5 Mt-H_2 from local sources of fossil fuels (i.e., natural gas and coal), and has used the same amount in the same year. Most of the hydrogen production in Viet Nam depends on localized natural gas and imported fossil fuels. Viet Nam has 24.7 Tcf of natural gas reserve, allowing the country to localize hydrogen production via SMR.[180] The natural gas contribution to the energy consumption mix in 2023 was only 5.3%, whereas refined oil and coal contributed 24.4% and 47.5%, respectively, of the country's total energy consumption mix in 2023.[181] Viet Nam is a net importer of coal–its major source of energy–with an imported amount of approximately 39.5 Mt-coal and an exported amount of only about 1 Mt-coal in 2022.[180] In the same year, this amount of coal emitted 219 Mt-CO_2, equivalent to approximately 73.5% of the total energy-related CO_2 emissions in the country.[180] Thus, reducing the energy-associated greenhouse gas emissions in Viet Nam and achieving energy independence will most likely rely on the ability of the country to transition away from coal toward localized natural gas with CCS and renewables as sources of primary energy.

In an effort to accomplish this goal, Viet Nam issued several strategies that cover energy, oil & gas, and climate change, among other topics. These strategies formed the basis for the National Hydrogen Development Strategy by 2030 with a Vision to 2050, which was approved by the Prime Minister in February 2024 (Decision No. 165/QD-TTg), highlighting plans for hydrogen production, storage, transportation, distribution, and utilization.[182] The objective of the strategy was to develop an ecosystem for hydrogen that helps with energy security, national climate goals achievements (e.g., net-zero GHG emissions target in 2050), and green growth strategies.[182]

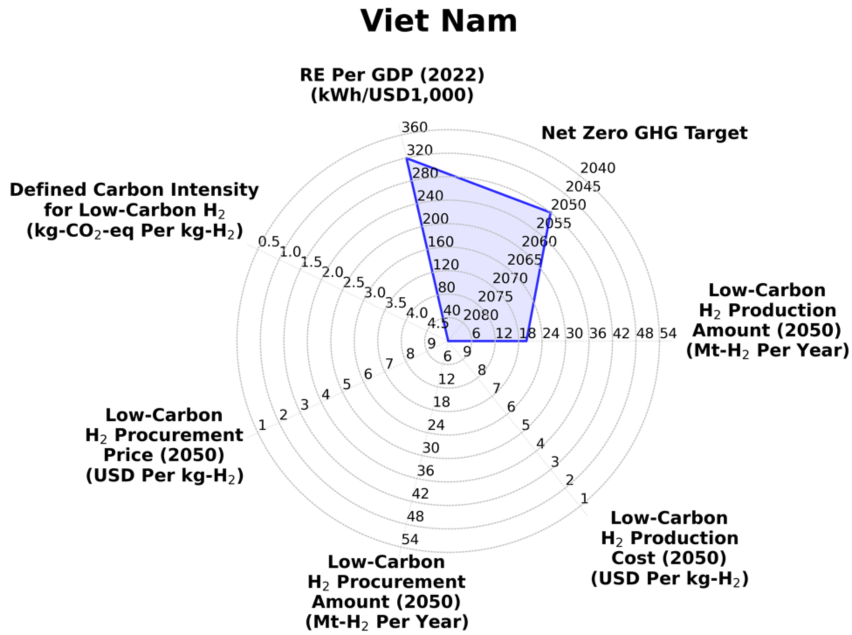

Figure 14. Radar plot of Viet Nam's figures of merit.

Note that several metrics are missing due to the lack of available data.

15.2 Key Elements of Viet Nam's Hydrogen Development Strategy

15.2.1 Low-Carbon Hydrogen Ecosystem in Viet Nam

Viet Nam's ample renewable energy resources, including wind and solar power, makes it a promising location for low-carbon hydrogen production. This abundance makes Viet Nam a **potential exporter of renewable energy via hydrogen and/or its derivatives**. As a **potential net exporter of low-carbon hydrogen**, Viet Nam plans to produce both fossil-based (e.g., via SMR-CCS) and non-fossil-based (e.g., via water electrolysis) hydrogen. The country plans to produce low-carbon hydrogen at a rate of **0.1-0.5 Mt-H_2 per year by 2030** and expand to **10-20 Mt-H_2 per year by 2050**. To realize these targets, Viet Nam plans to repurpose existing infrastructure and build new infrastructure as necessary to distribute hydrogen-derived energy to the points of use. **By 2030**, the country expects to **establish several pilot centers** that utilize existing infrastructure and produce special equipment for hydrogen transportation and storage needs. **By 2050**, Viet Nam expects the infrastructure to be **scaled up to tolerate 10-20 Mt-H_2 transport per year**.

Regarding the use of low-carbon hydrogen, Viet Nam plans to explore blending of hydrogen with NG and ammonia with coal for power generation to create a bridge for the transition from fossil-based to non-fossil-based fuels for power. Viet Nam targets the use of **hydrogen and its derivatives for energy generation to account for 10% of the final energy consumption demand by 2050**. Additionally, low-carbon hydrogen and its derivatives are considered to be used in rails, roads, maritime, and aviation for transportation purposes. Finally, industrial applications, such as steel, cement, chemicals, and oil refining, are potential applications for low-carbon hydrogen that are explored by Viet Nam's government.

Regarding low-carbon hydrogen export, Viet Nam's hydrogen strategy states that by 2030, the country plans to leverage its abundant renewable energy resources, such as wind and solar, to attract investments in low-carbon hydrogen for export applications. **By 2050, Viet Nam plans to become a net hydrogen exporter in the region**, contributing to the transition of clean energy regionally and globally.

15.2.2 Priority Low-Carbon Hydrogen Projects for Investment

In parallel with Decision No. 165/QD-TTg, Viet Nam's National Energy Master Plan for the period 2021-2030, with a vision to 2050 (Decision No. 893/QD-TTg), provides specific targets for the country to ensure energy security and planned new energy deployments (including deployment of renewables).[183] Hydrogen is identified as a clean energy carrier to be explored by Viet Nam. Two phases (2021-2030 and 2031-2050) are specified to include a total of **six high-priority low-carbon hydrogen production projects**.[183] **The first phase (2021-2030) is expected to include three projects, each at a scale of 0.1-0.4 Mt-H_2 per year**.[183] **The second phase (2031-2050) is planned to include three projects, each at a scale of 1-12 Mt-H_2 per year**.[183] The projects are planned to be potentially located in the Northern, Central, and Southern regions of the country, with no specific locations determined yet.[183] Defining the specific locations could influence the electricity/energy prices, which could impact the production cost of low-carbon hydrogen associated with these projects.

15.2.3 Tasks and Implementation Solutions

To ensure the development of a clean hydrogen economy in Viet Nam, the hydrogen development strategy states several key tasks for the government to facilitate the transition from fossil-based hydrogen to low-carbon hydrogen production and use. Policy mechanisms include **establishing legal frameworks for low-carbon hydrogen production and use**, which could help facilitate the transition away from fossil-based hydrogen.[182] Additionally, **investments and finance of low-carbon hydrogen are planned to take place at small-scale pilot projects (0.1-0.4 Mt-H_2 per year) in the short term (by 2030) followed by large-scale commercial projects (1-12 Mt-H_2 per year) in the longer term (by 2050)**.[182,183] It is worth noting, however, that most relevant policies and funding are still in the development stage.

The technology for producing, transporting, distributing, and storing green hydrogen is still relatively new for Viet Nam. Thus, the pool of experienced and specialized workforce in this field could be limited. Viet Nam realizes that low-carbon hydrogen deployment necessitates advancements in science and technology as well as in workforce development. Thus, the hydrogen development strategy highlights the Government of Viet Nam's role in encouraging low-carbon hydrogen investments by local fossil-energy businesses, developing training plans for key technology fields (including hydrogen), and attracting highly skilled workers in the hydrogen field.[182]

Viet Nam also recognizes the role of international collaboration and communication in the development of a low-carbon hydrogen economy. Viet Nam's hydrogen development strategy sets governmental action points regarding the promotion of international cooperation in hydrogen-related R&D, the establishment of strategic partnerships in the hydrogen energy sector, and the active engagement in international forums, such as COP, Just Energy Transition Partnership (JETP), and Asia Zero Emission Community (AZEC).[182] In addition, Viet Nam aims to engage with the public by co-coordinating several educational programs that raise awareness about the benefits and policies of the hydrogen economy.[182] Lastly, international collaborations with countries that have advanced in low-carbon hydrogen deployment (e.g., Australia, Japan, etc.) could benefit Viet Nam as the country builds its presence in the low-carbon hydrogen economy regionally and globally.

15.2.4 Relevant Organizations for Implementation

Viet Nam's national hydrogen development strategy facilitates ministerial cooperation by defining several tasks for six ministries, as summarized in **Table 18**.[182] In addition to ministerial cooperation, People's Committees of Provinces and Cities are expected to manage the selection of investors in hydrogen energy projects, arrange land funds for hydrogen energy projects, and coordinate with investors on site clearance, compensation, immigration, and resettlement for hydrogen-related projects.[182]

Finally, Viet Nam's strategy sets tasks for businesses and corporations in Viet Nam's energy sector that emphasize the alignment with the country's goal of achieving **net-zero GHG emissions by 2050**.[182] Such tasks include developing hydrogen blending projects with gas and coal, leveraging existing talent and special equipment for hydrogen storage and transportation, and expanding international partnerships in hydrogen production technologies.[182] The companies mentioned in the strategy include **Viet Nam Electricity Group (EVN), Viet Nam Oil and Gas Group (PVN), Viet Nam National Chemical Group (Vinachem), Viet Nam Coal and Mineral Industries Group (Vinacomin; TKV), and Viet Nam National Petroleum Group (Petrolimex)**.[182]

Table 18. Key responsibilities from Vietnamese ministries, as set by Viet Nam's hydrogen strategy.[182]

Ministry Name	Key Responsibilities
Ministry of Industry and Trade	• Chairing and coordinating the hydrogen strategy • Monitoring and implementation of hydrogen-based energy projects.
Ministry of Planning and Investment	• Coordination with relevant ministries to develop policies and mechanisms that attract investments of hydrogen-related projects.
Ministry of Science and Technology	• Development of programs that promote scientific research activities related to hydrogen production, storage, distribution, and utilization.
Ministry of Natural Resources and Environment	• Coordination with relevant ministries regarding climate change prevention programs, including GHG emission reduction.
Ministry of Transport	• Development of policies regarding low-carbon transportation solutions, including hydrogen fuel cells.
Ministry of Education and Training	• Development of a national training program for the new energy industry, especially hydrogen-sourced energy.

15.3 Tracking Progress

Since the announcement of Viet Nam's hydrogen development strategy, the largest electrolytic hydrogen production project entered the planning stage in March 2024.[184] The project plans to produce **60 kt-H_2 per year via 1 GW of both alkaline and PEM water electrolyzers that are powered by a 1.2-GW wind plant and 800-MW solar plant**.[184] In addition, The Green Solutions Group Corporation (TGS) of Viet Nam has begun construction of the first electrolytic hydrogen plant that will supply low-carbon hydrogen for low-carbon ammonia production.[185] The plant is expected to produce **approximately 0.2 Mt-NH_3 per year with a capacity factor of 87% and a combined power source of 600 MW from wind, solar, and battery energy storage system (BESS)**.

More rigorous **legal framework** and **regulatory provisions** that are related to hydrogen technologies as well as improvements to the local science and technology regarding low-carbon hydrogen technologies could enhance Viet Nam's hydrogen development plan and strengthen its position in the regional and global hydrogen market. In addition, Viet Nam's strategic location along international and regional maritime routes with numerous seaports makes it an attractive destination for sustainable energy investments. These are favorable factors that could attract foreign investments in low-carbon hydrogen development projects, potentially exporting to net importers of hydrogen (e.g., Japan, the Republic of Korea, and some European Union countries). Therefore, defining decadal targets that are based on technological assessments could be helpful in providing a holistic picture to potential hydrogen-related investments in Viet Nam. Such targets can pave the way for the development of a low-carbon hydrogen ecosystem in the country. Finally, Viet Nam could benefit from adopting carbon intensity limits for low-carbon hydrogen to ensure its cleanliness for potential importers of the hydrogen.

16 Selective Low-Carbon Hydrogen Synergies

The low-carbon hydrogen roadmaps and strategies of selected Indo-Pacific countries collectively highlight the main uses of hydrogen as a fuel and a feedstock for the future energy, transportation, and industrial sectors. Hydrogen is seen as a vector that could shift electrons with time and space, enabling decarbonization efforts in the transition from fossil-based to non-fossil energy sources. Indeed, decarbonization has been highlighted by several reports as a strategy that considers hydrogen as an essential player. In the context of low-carbon hydrogen in selected Indo-Pacific countries, there are several synergies that could be identified from the summarized hydrogen plans and effort in this report.

Table 19. Summary of physical properties of potential hydrogen carriers that were mentioned in selected Indo-Pacific countries' hydrogen reports.

Green trading symbol indicates that the carrier is traded in most selected Indo-Pacific countries. Yellow trading symbol indicates that the carrier is traded in some selected Indo-Pacific countries. Orange trading symbol indicates that the carrier is not traded maturely yet. *MCH is not typically used as a fuel, which is why we exclude its lower and higher heating value in this table. **Trading data of MCH is lacking, which is why we are not including an assessment of its trading in selected Indo-Pacific countries; however, we note that MCH is considered by Japan and Brunei to be a hydrogen carrier. ***Note that natural gas varies in quality and composition, which impact its physical properties. The shown properties of natural gas aim to cover the full spectrum of natural gas. **Data sources:** UN COMTRADE[67], Boundy et al.[186], Pacific Northwest National Laboratory's (PNNL) Hydrogen Tools[187], and Air Liquide[188].

Hydrogen Carrier	Density (kg/m^3)	Lower Heating Value (MJ/kg)	Higher Heating Value (MJ/kg)	Boiling Point (˚C)	Traded in selected Indo-Pacific countries?
Liquid Ammonia	681.7	18.6	22.5	-33.3	⇆
Liquid Methanol	824.2	20.1	22.9	65.4	⇆
Methylcyclohexane*, **	769.4			100.9	?
Compressed Gaseous H_2	20.3 (300 bar) 25.0 (400 bar)	120.2	142.2	-253	⇆
Liquid H_2	70.8	120.1	141.8	-253	⇆
Liquid Natural Gas***	428.2	48.6	55.2	≈ -162	⇆

Selected Indo-Pacific countries could leverage the use of existing hydrogen-related transportation infrastructure by establishing plans that utilize their optimal use for low-carbon hydrogen trades regionally and globally. For instance, New Zealand's interim hydrogen roadmap reports that a methanol infrastructure is well-established in the country.[94] Similarly, Indonesia's hydrogen roadmap highlights the existence of an ammonia infrastructure in the country that could be used for hydrogen transportation.[62] Existing MCH and LNG infrastructure could also facilitate hydrogen transportation and distribution.[6,76] These examples provide potential solutions to safe regional and global hydrogen transportation. It is important to note that methanol and ammonia can be potentially used as bunker fuels for ships. Particularly, methanol vessels have been ordered by several large shipping companies, including Maersk and CAM CGM.[100,189] Ammonia-fueled vessels have been slower in terms of adoption compared to methanol-fueled vessels due to regulatory challenges, but they are being pursued by several groups, including Maersk.[190] In addition, MCH and liquified hydrogen port-to-port transportation has been tested in, at least, Japan-Brunei, Japan-Malaysia, and Japan-Australia partnerships,[35,81,89] suggesting potential technical maturity in the region as we get closer to 2050.

Moreover, the fourteen selected Indo-Pacific countries collectively aim to utilize renewable energy in their energy mixes, which could require hydrogen to be used as either a fuel or an energy storage solution. For instance, fluctuating renewable energy (e.g., solar, wind) requires energy storage to maintain full capacity and ensure continuous energy supply to customers. The use of batteries provides a solution to short-term energy storage; however, hydrogen could be applied for long-term energy storage (e.g., seasonal energy storage), enabling optimal utilization of fluctuating renewable energy throughout the year. Water electrolysis, hydrogen fuel cells, and hydrogen-fueled electricity generators could be integrated with the grid to provide stable renewable energy supply to customers. **In this context, multiple selected Indo-Pacific countries are considering fuel cell manufacturing and deployment in their hydrogen roadmaps and strategies (e.g., Japan, the Republic of Korea, and the United States)[76,112,150], whereas some selected Indo-Pacific countries (e.g., India and New Zealand)[46,94] are more focused on the deployment of hydrogen fuel cell vehicles. This synergy presents potential hydrogen fuel cell trades within the selected Indo-Pacific countries in the upcoming future.** However, there is a lack of defined targets regarding the import and export of hydrogen fuel cells across most hydrogen roadmaps of selected Indo-Pacific countries potentially causing a lack of clarity regarding the possible scale of this hydrogen-related trade route in the region.

Furthermore**, the supply and demand of low-carbon hydrogen within the selected Indo-Pacific countries could be satisfied, given the announced production and procurement targets, by those countries.** By 2030, the low-carbon hydrogen production amount is targeted to reach approximately 17-25 Mt-H_2 per year. The target increases to 36-52 Mt-H_2 per year by 2040 and 113-147 Mt-H_2 per year by 2050. Out of these amounts, Japan and the Republic of Korea plan to procure a combined total of approximately 5 Mt-H_2 per year by 2030, 14 Mt-H_2 per year by 2040, and 44 Mt-H_2 per year by 2050. The given numbers suggest that 20-29% of the planned low-carbon hydrogen production amount in 2030 could be traded between selected Indo-Pacific countries. This percentage increases to 27-39% by 2040 and 30-39% by 2050, suggesting a growth in the hydrogen trading market between selected Indo-Pacific countries. Alternatively, this point could suggest potential partnerships with non-selected Indo-Pacific countries that may satisfy the remaining demand of low-carbon-hydrogen-importing countries in the selected Indo-Pacific countries (e.g., Japan, Singapore, the Republic of Korea). For instance, the Middle East and North Africa (MENA) region could export low-carbon hydrogen to some selected Indo-Pacific countries, given the region's related investment amount in low-carbon hydrogen that have reached FID (≈US$5 billion out of US$29 billion globally[118]), strong interest in participating in hydrogen trades,[191] and close proximity to several selected Indo-Pacific countries that may become net importers of low-carbon hydrogen.

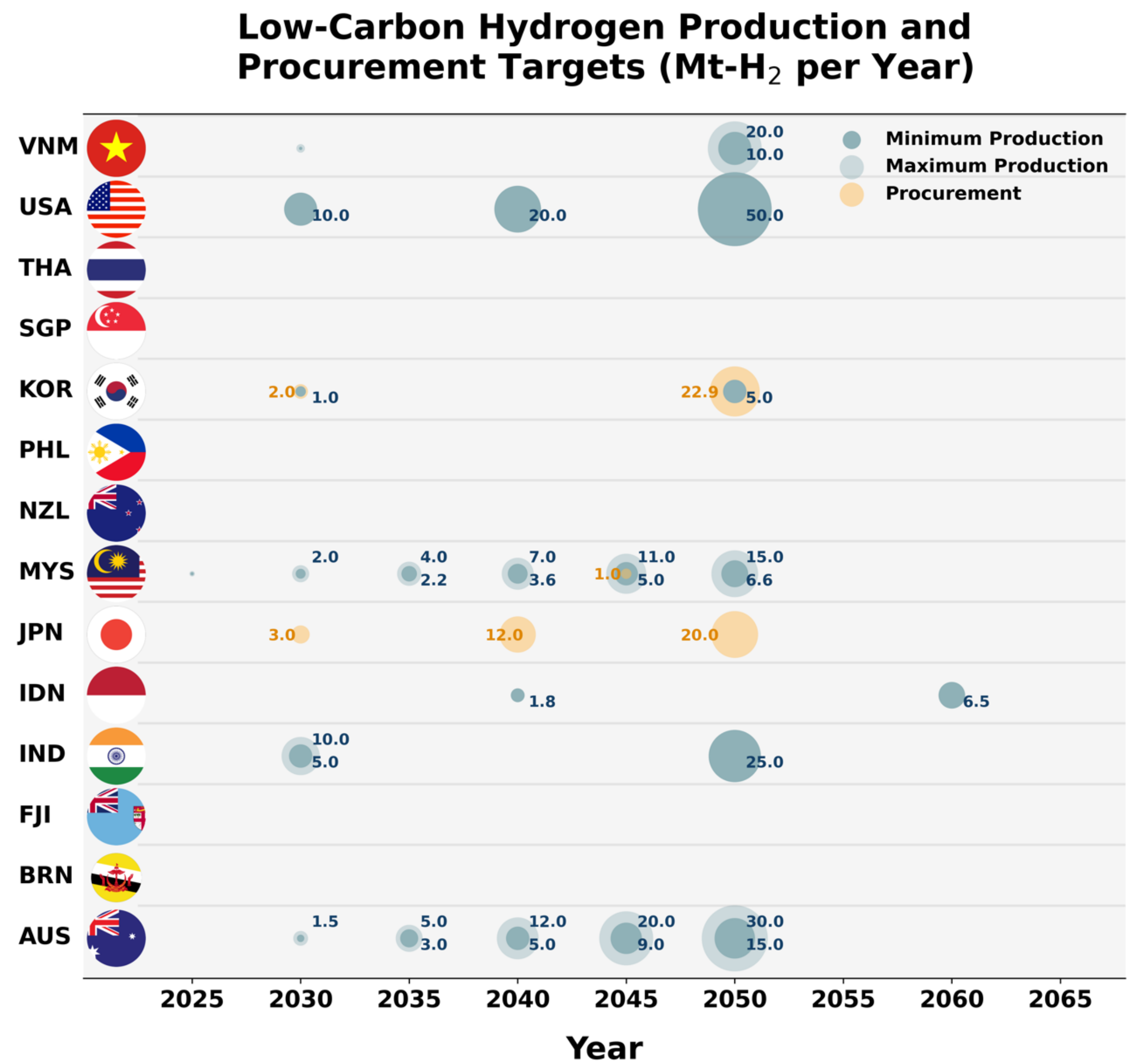

Figure 15. Target low-carbon hydrogen production and procurement amounts in selected Indo-Pacific countries.

Note that the light and dark blue circles refer to the minimum and maximum production amounts, respectively. The yellow circles represent the procurement amounts of potential H_2-importing selected Indo-Pacific countries. Values include hydrogen produced via any low-carbon hydrogen production method (including at least SMR-CCS and electrolysis).

Data sources: Countries' roadmaps/strategies and countries' presentations in Hydrogen CWP workstream meetings.

Selected Indo-Pacific countries could leverage the advancements of several countries in the development of hydrogen-related policies, standards, regulations, certificates, and incentives. For instance, the announced electrolytic hydrogen projects in selected Indo-Pacific countries have a total capacity of approximately 143 GW_{el} (including current and planned hydrogen and hydrogen derivative projects by 2030) (**Figure 16**).[192] The development and deployment of such projects have likely contributed to the development of policies, standards, regulations, and certificates that could facilitate the deployment of new electrolysis-based hydrogen production facilities in the selected Indo-Pacific countries. Additionally, financial incentives (e.g., production tax credits), similar to those proposed by Australia (US$1.4 per kg-$H_2$)[7], India (US$0.4-0.6 per kg-H_2)[46], and the United States (US$0.6-3.0 per kg-$H_2$)[150], could attract international investments of low-carbon hydrogen in the region and build a global hydrogen hub that could supply a large portion of the planned low-carbon hydrogen demand in the future.

Indeed, an IEA dataset shows that the selected Indo-Pacific countries could take about 28% (143 GW_{el} out of 513 GW_{el}) of the globally **announced** electrolytic hydrogen production projects in terms of scale (in GW_{el}) by 2030,[192] suggesting that **selected Indo-Pacific countries could form a large electrolysis-based hydrogen hub globally** (**Figure 16**). From this reported data, Australia, India, and the United States make up 52%, 29%, and 14%, respectively, which is 95% of the total announced and planned electrolytic hydrogen projects in the selected Indo-Pacific countries.[192] It is worth highlighting that this data is dependent on the *reported* project scales, which may not reflect *actual* project scales worldwide due to the possible lack of data. Therefore, **standardizing reporting methodologies could improve tracking of the progress of electrolytic (and, generally, low-carbon) hydrogen projects in selected Indo-Pacific countries.**

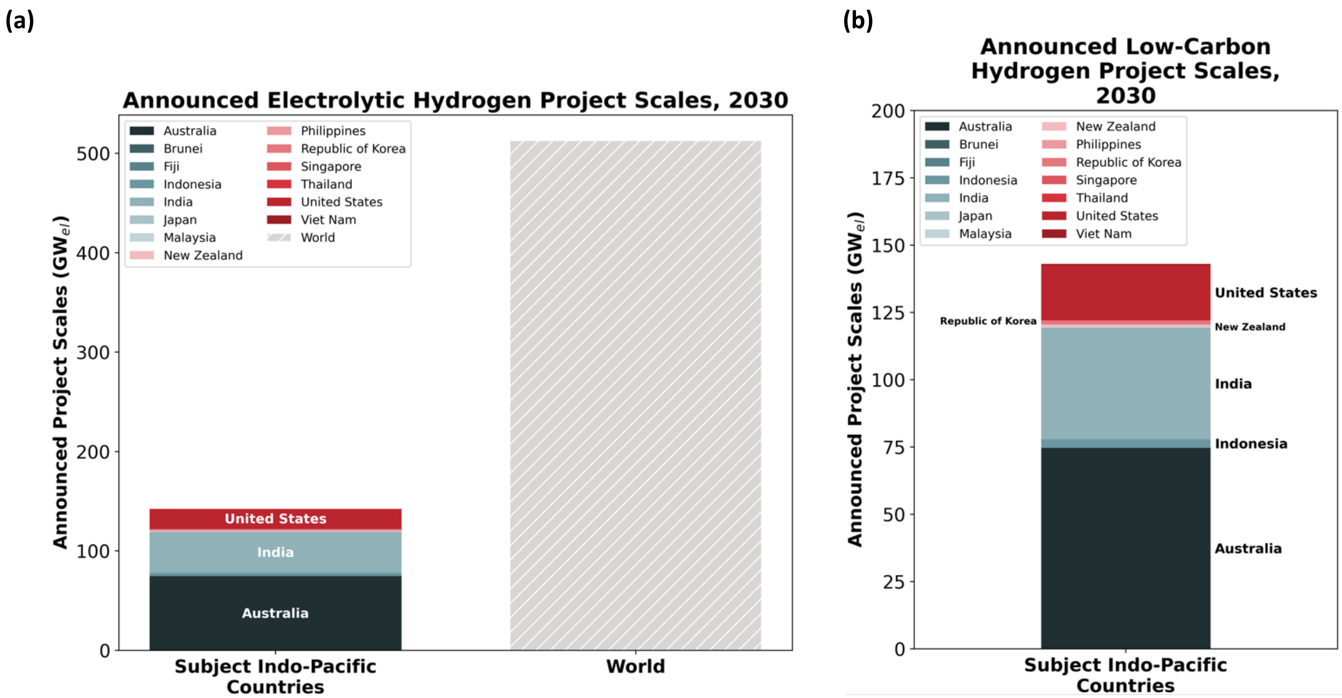

Figure 16. Planned and announced electrolysis-based hydrogen project scales in 2030 of selected Indo-Pacific countries as a comparison to the world's planned and announced electrolysis-based hydrogen project scales.

(a) Announced scales of planned electrolytic hydrogen projects in the selected Indo-Pacific countries and the world, broken down by country. **(b)** A zoomed-in version of the announced scales of planned electrolytic hydrogen projects in the selected Indo-Pacific countries. It is worth noting that these projects include currently operational projects and hydrogen-derivative projects (e.g., low-carbon ammonia).

17 Potential Gaps in Hydrogen Strategies

Developing a low-carbon hydrogen market within the selected Indo-Pacific countries most likely requires significant collaborative efforts between partners in terms of technology, certification, regulation, policy, partnership development, and knowledge-sharing that could strengthen the position of low-carbon hydrogen in the region. Several international hydrogen forums have already been established to help with these efforts, such as the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE),[193] and the International Hydrogen Trade Forum (IHTF)[194]. Within the selected Indo-Pacific countries, there still exist some gaps that could be filled by partners to strengthen the position of selected Indo-Pacific countries in the low-carbon hydrogen market.

Agreement on a certification scheme that enhances the transparency of low-carbon hydrogen production methods could ensure the low-carbon intensity of the traded hydrogen. Addressing this gap is particularly important for all selected Indo-Pacific countries because it influences the achievements of net-zero GHG or CO_2 emissions targets. Several selected Indo-Pacific countries have already established policies and regulations around the life cycle GHG emissions from low-carbon hydrogen production. For instance, **Figure 17** summarizes the well-to-gate carbon intensity set by Australia, India, Japan, the Republic of Korea, and the United States for low-carbon hydrogen certifications as well as the well-to-gate carbon intensities associated with three different hydrogen production methods (i.e., SMR, coal gasification, and water electrolysis). The figure shows that the well-to-gate carbon intensity that qualifies hydrogen to be low-carbon (or clean) in the five selected Indo-Pacific countries falls in the range of 0.6-4.0 kg-CO_2-eq per kg-H_2. **This wide range demonstrates that the definition of clean hydrogen is still not consistent across countries, potentially causing low-carbon hydrogen trade issues.** Therefore, unifying the definition of clean or low-carbon hydrogen could be a necessary step to ensure smooth hydrogen flows between selected Indo-Pacific countries.

Another important aspect to consider from **Figure 17** is the hydrogen production processes that qualify to produce low-carbon hydrogen. **Figure 17** shows that the current carbon intensity limit, set by Japan, the Republic of Korea, and the United States, could enable SMR-CCS, coal gasification with CCS, and water electrolysis powered by renewables (i.e., solar and onshore wind) to qualify for low-carbon hydrogen benefits. On the other hand, the allowable carbon intensity limit for low-carbon hydrogen in India could limit this choice to SMR-CCS and water electrolysis powered by renewables to benefit from low-carbon hydrogen support in the country. Notably, Australia's carbon intensity limit for low-carbon hydrogen could restrict most of the benefits of low-carbon hydrogen in the country to the facilities that produce hydrogen from non-fossil sources. In the context of the given three hydrogen processes in **Figure 17**, onshore wind-powered water electrolysis presents the only solution (out of the given three pathways) that could produce low-carbon hydrogen in Australia, according to the definition of low-carbon hydrogen having a carbon intensity of 0.6 kg-CO_2-eq per kg-H_2 or less. It is worth noting, however, that there are other hydrogen production technologies that could qualify for the low-carbon benefits, such as biomass gasification, which could have an overall negative carbon intensity.

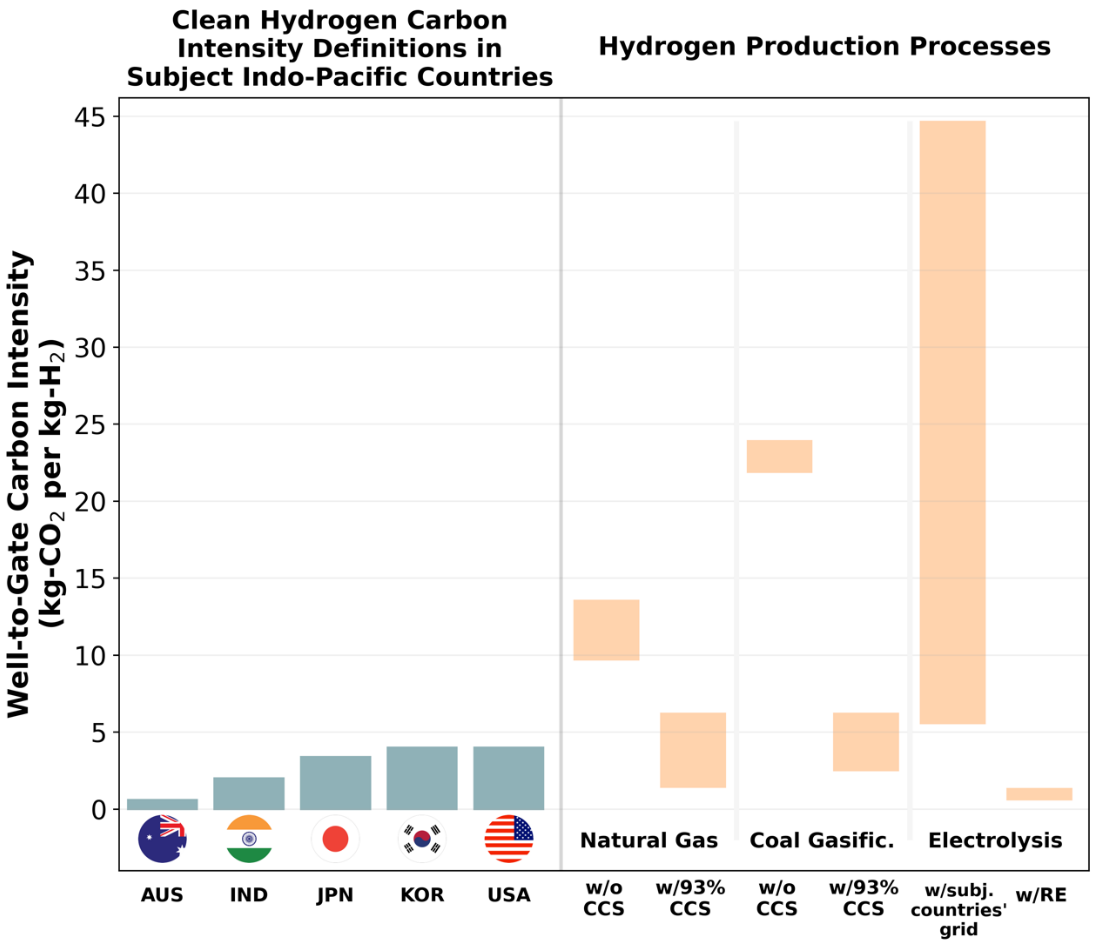

Figure 17. A comparison of defined carbon intensity of low-carbon hydrogen as set by some selected Indo-Pacific countries with the carbon intensity of three hydrogen production processes.

Left: Carbon intensity definitions for clean hydrogen in some selected Indo-Pacific countries (Australia, India, Japan, Republic of Korea, and the United States). **Right:** Carbon intensity of hydrogen production processes, which includes natural gas reforming, coal gasification, and water electrolysis. Note that the carbon intensity limits set by selected Indo-Pacific countries follow a well-to-gate system boundary that includes electricity consumption.

Data sources: CO_2 emissions associated with natural gas reforming and coal gasification are taken from an IEA report and refer to the year 2021.[195] We assume an electrolysis electricity consumption of 50 kWh per kg-H_2. selected Indo-Pacific countries' grid emission factors were taken from the Statistical Energy Review for 2022 of all selected Indo-Pacific countries. Renewable energy (RE) is limited to onshore wind and solar power plants.[196] Their associated CO_2 emissions are assumed to be 27 g-CO_2-eq per kWh and 12 g-CO_2-eq per kg-H_2, respectively.

A hydrogen supply chain, in the given context, includes equipment manufacturing as well as hydrogen production, storage, transportation, and distribution. **Collaborations within the selected Indo-Pacific countries in the full hydrogen supply chain could be strengthened by developing a consistent data reporting methodology that encompasses relevant and consistent metrics.** So far, ten selected Indo-Pacific countries have published their hydrogen roadmaps and strategies, which mostly include commitments, tracking, and definition of some target milestones to achieve by 2030, 2040, 2050, and/or 2060. However, several of these reports lack data about supply chain targets that could facilitate planning of the overall supply chain in the region. For instance, not all selected Indo-Pacific countries report decadal targets of low-carbon hydrogen production and/or procurement amounts. Reporting such targets could enable both exporters and importers of low-carbon hydrogen to plan international investments, propose international trading routes, and form optimal collaborations to ensure smooth deployment of low-carbon hydrogen in the region. Another important metric to report is the potential scale of low-carbon hydrogen export and import targets by each country. The Republic of Korea's 1st basic plan for hydrogen sets a positive example in this aspect by reporting potential demand of fossil-based hydrogen without CCS, fossil-based hydrogen with CCS, and low-carbon hydrogen in 2030 and 2050.[112] The plan additionally includes 2030 and 2050 targets of imported low-carbon hydrogen amount and domestically produced low-carbon hydrogen amount.[112] Such details are missing in most hydrogen roadmaps and strategies of selected Indo-Pacific countries. Furthermore, to achieve these ambitious supply goals, the Korean government is actively fostering demand through strategic policy directions. For instance, during the 6th Hydrogen Economy Committee in 2023, the government set targets of deploying 300,000 hydrogen vehicles and achieving clean hydrogen production of 13TWh by 2030, which corresponds to a maximum of 400,000 tons for vehicles and approximately 800,000 tons of clean hydrogen demand respectively. To facilitate this process, we provide a suggested list of relevant metrics that could initiate the consistent data reporting effort, aiming to enhance future iterations of hydrogen roadmaps and plans both regionally and globally (**Table 20**). It is worth noting that this list is not exhaustive but contributes to the standardization of data reporting relevant to hydrogen roadmaps and strategies.

Table 20. Suggested list of metrics to be reported by countries in their hydrogen roadmaps and strategies.

This list is by no means exhaustive, and it is suggested to initiate consistent data reporting across countries in low-carbon hydrogen.

#	Metric	Potential Impact
1	Carbon intensity limit for low-carbon (or clean) hydrogen (in kg-CO_2-eq per kg-H_2)	• Facilitation of internationally-accepted certification scheme development • Ensuring low-carbon intensity of hydrogen • Transparent communication about low-carbon hydrogen .
2	Decadal or semi-decadal targets for low-carbon hydrogen production amounts (in mass per year; e.g., Mt-H_2 per year)	• More accurate forecasting of regional and global low-carbon hydrogen supply chain • Transparent guidance of domestic policy and industrial development • Establishment of data-informed bilateral agreements on low-carbon hydrogen and its derivatives • Identification of optimal trading routes of low-carbon hydrogen.
3	Decadal or semi-decadal targets for low-carbon hydrogen procurement amount (in mass per year; e.g., Mt-H_2 per year)	
4	Decadal or semi-decadal targets for low-carbon hydrogen export (in mass per year; e.g., Mt-H_2 per year)	
5	Decadal or semi-decadal targets for low-carbon hydrogen import (in mass per year; e.g., Mt-H_2 per year)	
6	Decadal or semi-decadal targets/forecasts for domestic supply and demand of low-carbon hydrogen (in mass per year; e.g., Mt-H_2 per year)	• More accurate production amount and procurement amount targets.
7	Decadal or semi-decadal targets for low-carbon hydrogen production cost (in currency per mass; e.g., US$ per kg-H_2)	• More accurate techno-economic assessments related to low-carbon hydrogen • Establishment of a willingness-to-pay price for low-carbon hydrogen on a country level • Guidance on the distribution of funding to low-carbon hydrogen technologies • Identification of optimal trading routes based on production cost and procurement price.
8	Decadal or semi-decadal targets for low-carbon hydrogen procurement price, *including storage and transportation* (in currency per mass; e.g., US$ per kg-H_2)	
9	Targeted low-carbon hydrogen production technologies (e.g., water electrolysis, SMR with CCS)	• More accurate planning of potential equipment supply.

10	Targeted hydrogen end-user applications locally, regionally, and internationally (e.g., power generation, heavy-duty fuel cell vehicles)	• Clarification of supply chain gaps • Development of derisking plans for low-carbon hydrogen.
11	Targeted hydrogen transportation solutions (e.g., specific hydrogen carriers, liquefaction, compression)	• Clarity in communication regarding the development of hydrogen transportation solutions.
12	Established and in-progress hydrogen-related infrastructure, *including hydrogen derivative infrastructure*	• Maximizing the lifetime of existing infrastructure • Facilitating the introduction of low-carbon hydrogen in the local market.
13	Potential port entries of low-carbon hydrogen in the existing port infrastructure	• Leveraging existing port infrastructure for low-carbon hydrogen trades.
14	Number, funding amounts, and TRLs of low-carbon hydrogen-related projects that are in the feasibility, construction, and operational stages	• Transparent funding distribution • Accountable tracking of hydrogen-related projects • Identification of mature routes for low-carbon hydrogen.
15	Nominal capacities of hydrogen-related projects that are in the feasibility, construction, and operational stages	• Tracking of scale capabilities of all partners.
16	Existing and planned low-carbon hydrogen bilateral agreements	• Knowledge sharing of technology and policy development relevant to low-carbon hydrogen.
17	Existing and planned policies, regulations, standards, and codes relevant to low-carbon hydrogen	• Public acceptance of low-carbon hydrogen technologies.
18	Considerations of low-carbon hydrogen certification schemes in current and/or future policies and regulations	• Alignment of international efforts around hydrogen-related certificate scheme development.
19	Renewable energy capacity expansion coordinated with the electricity grid and low-carbon hydrogen production	• More accurate forecasted life cycle emissions analyses associated with grid-connected hydrogen production.

Furthermore, early consideration of equipment supply of emerging technologies could avoid future supply chain issues. For example, several selected Indo-Pacific countries have announced the production of low-carbon hydrogen for both domestic use and export. Part of this hydrogen production is planned to come from water electrolysis facilities, requiring electrolyzers and power electronic equipment to be manufactured at a comparable scale to current announcements. By 2040, the total low-carbon hydrogen production amount in selected Indo-Pacific countries is targeted to reach 36-52 Mt-H_2 per year. If 10 Mt-H_2 per year is produced via electrolysis throughout the year at a capacity factor of 90%, then more than 60 GW of installed added electrolyzers would be required (at 50 kWh/kg-H_2 electricity consumption). **Figure 18 (left)** shows that a 10% growth rate in the annual added electrolyzer manufacturing capacity would require approximately 1.8 GW of electrolyzer manufacturing per year in 2025, whereas a 40% growth would correspond to 0.1 GW per year in 2025. This data underscores that delayed actions will result in larger electrolyzer manufacturing investments to satisfy a higher annual growth rate, whereas early actions can spread out investments and demand a lower annual growth rate. In addition, the electrolyzer manufacturing rates increase as we near 2040 to meet the **potential** electrolyzer demand within selected Indo-Pacific countries (i.e., 10 Mt-H_2 per year via new electrolysis facilities in this scenario). **Figure 18** also exhibits the potential rate profile for meeting 20, 30, 40, and 50 Mt-H_2 per year via electrolysis at the two chosen growth rates, demonstrating the substantial growth of electrolyzer manufacturing that could be associated with these scenarios.

It is equally important to consider the expected electrolyzer capacity factor (i.e., low operating days) in each of these scenarios. Lower electrolyzer capacity factors would increase the demand for electrolyzers, shifting the profiles upwards (**Figure 18 (right)**) and indicating higher electrolyzer manufacturing capacity demand. It is worth noting that these calculations are restrictive to electrolyzers alone. Further considerations of the demand of power electronics equipment could provide broader consideration of potential challenges faced by the growth of the low-carbon hydrogen market within selected Indo-Pacific countries.

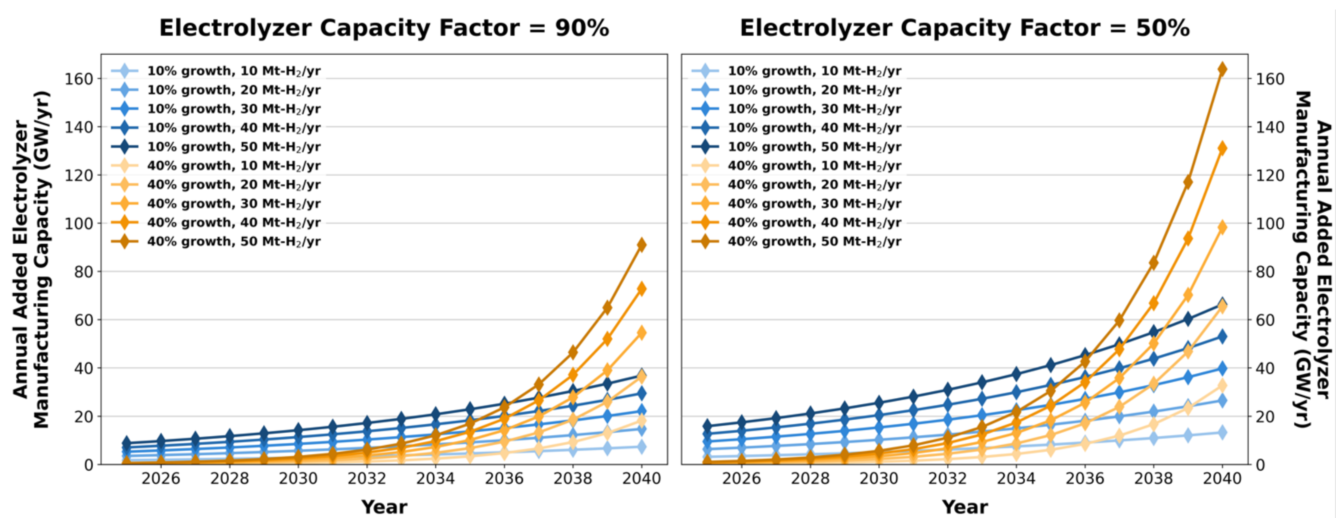

Figure 18. Predicted annual added electrolyzer manufacturing capacities (in GW per year) for two scenarios and two electrolyzer capacity factor assumptions.

Blue lines and points refer to a scenario with 10% growth of the annual added electrolyzer manufacturing capacity. Yellow lines and points refer to a scenario with 40% growth of the annual added electrolyzer manufacturing capacity. Note that the color shade indicates a specific low-carbon hydrogen production rate met by selected Indo-Pacific countries in the given context. Two assumptions of average electrolyzer capacity factors are assumed: 90% (left) and 50% (right), to account for differences in operational needs between the different applications of water electrolysis. An electrolyzer electricity consumption of 50 kWh per kg-H_2 was assumed, and the generalized reduced gradient (GRG) nonlinear method was used to solve the optimization problem in Excel.

Two examples of electrolyzer manufacturing capacity considerations in selected Indo-Pacific countries can be shown by India and the United States. As of 2024, India's MNRE has awarded funding to 21 projects at a combined total electrolyzer capacity of 3.0 GW per year under the first and second tranche of the SIGHT program, which aims to establish electrolyzer manufacturing capabilities in India.[46,52,54] The SIGHT program is expected to award more funding to projects until FY2030.[52,54] The United States awarded eight RD&D projects with a total of US$316 million to advance local electrolyzer manufacturing capabilities and achieve the U.S. target set by 2028, which is to manufacture at least 3 GW of electrolyzers per year.[150,197] Expanding this effort to include transparent planning of electrolyzer manufacturing in selected Indo-Pacific countries may be required to meet the significant low-carbon hydrogen production demands of 2040 and 2050. The speed at which electrolyzers are manufactured could play a major role in enabling the low-carbon hydrogen market to grow regionally and globally. **This point could also be assessed for other hydrogen technologies, such as fuel cells, hydrogen combustion, and others, to ensure their upscaling matches existing and planned capabilities in equipment manufacturing**.

18 Conclusion

Several selected Indo-Pacific countries have published their hydrogen roadmaps and strategies that cover wide topical areas associated with low-carbon hydrogen. Decadal production cost and procurement price targets exhibit the need for cost-price matching efforts that consider midstream costs, including storage and transportation. Decadal production and procurement amount targets highlight that selected Indo-Pacific countries could satisfy projected low-carbon hydrogen demand by hydrogen-importing selected Indo-Pacific countries (e.g., Japan, Republic of Korea, etc.) in the short term (i.e., closer to 2030) but may fall short in the longer term (i.e., closer to 2050). However, this finding is reliant on available data, which may not capture planned, but unannounced, projects. Therefore, one of the important next steps in this effort is ensuring reporting and tracking of hydrogen-related projects and plans to ensure proper analysis of low-carbon hydrogen supply chains. To overcome this challenge, this report provides suggested metrics that could align regional and global hydrogen efforts.

Synergies between selected Indo-Pacific countries could accelerate the establishment of a low-carbon hydrogen economy in the region. Existing infrastructure and knowledge of hydrogen carriers, such as ammonia, methanol, or liquified natural gas, provides one solution to overcoming hydrogen transportation and storage hurdles. In addition, the presented synergy analysis shows that approximately 28% of the globally announced water electrolyzer capacity for projects that are either operational today or expect an operation before 2030 are contributed by selected Indo-Pacific countries. This finding suggests that the selected Indo-Pacific countries could form a global electrolysis-based hydrogen production hub that makes up 28% of the global electrolytic hydrogen capacity demand in 2030.

Several gaps between selected Indo-Pacific countries have also been highlighted in the report. Of particular importance to the hydrogen trade is the definition of low-carbon hydrogen, which was missing in most selected Indo-Pacific countries. Although five selected Indo-Pacific countries have defined low-carbon (or clean) hydrogen using a "well-to-gate" life cycle carbon intensity, their definitions span a wide range of 0.60 to 4.00 kg-CO_2-eq per kg-H_2, potentially causing issues for future low-carbon hydrogen trades. This range may also exclude some technologies that are typically referred to as low-carbon hydrogen production methods, such as grid-powered electrolysis, coal gasification with 93% CCS, or SMR with 93% CCS. Future hydrogen planning should set a clear definition of low-carbon hydrogen based on a carbon intensity (e.g., implementation of certification schemes) that is agreed upon regionally or, more preferably, internationally. This effort will likely require collaborations between several governmental and industrial groups that ensure alignment of low-carbon hydrogen plans.

Early action regarding equipment manufacturing was also found to be critical for establishing a low-carbon hydrogen supply chain in the region. In particular, accelerating the scale up of electrolyzer manufacturing could contribute to reducing electrolyzer costs and avoiding delayed larger investments and growth requirements. Although most hydrogen-producing selected Indo-Pacific countries report the potential use of electrolysis as a hydrogen production method, only two of them communicated their plans to manufacture electrolyzers. This finding suggests that electrolyzer trading will be essential in the hydrogen supply chain; however, most selected Indo-Pacific countries did not report electrolyzer importing targets yet, presenting a data gap that needs to be filled in next iterations. Thus, comprehensive planning that considers the supply chain of necessary equipment could be appropriate in this situation.

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