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A Report of the CSIS Energy Security and Climate Change Program

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Executive Summary

Large energy consumers in the Indo-Pacific region and their traditional energy suppliers are among a growing number of countries that are examining the potential role of clean hydrogen in energy systems as well as their own potential roles in burgeoning hydrogen supply chains. Several Asian governments are leading the charge in creating a clean hydrogen economy by releasing and executing hydrogen strategies and funding anchoring projects along hydrogen supply chains, while others are beginning to articulate visions and strategies. Many are starting to establish government-to-government cooperation and facilitate commercial projects with international partners, including traditional energy suppliers to Asian markets. Their governments are exploring opportunities and challenges that are associated with becoming a prospective supplier of clean hydrogen.

This report surveys national visions and strategies of leading Asian economies and their traditional energy suppliers and presents key implications of clean hydrogen development in the Indo-Pacific region. Below are some key observations.

Energy Security Implications

Hydrogen may not obviate energy security and geopolitical concerns that currently preoccupy countries. The energy security benefit of clean hydrogen development depends greatly on whether a country has vast indigenous resources that can be converted into hydrogen. The introduction of clean hydrogen is unlikely to significantly alter many of the factors that currently constrain a country's energy security. Hydrogen is thus likely to mirror some of the trade patterns and relationships that currently exist in hydrocarbons.

Hydrogen development could help alleviate hydrocarbon import dependence for countries with strong renewable energy potential. The domestic production of clean hydrogen could help China and India alleviate, but not solve, energy security challenges amid their rising energy demand. Insofar as these countries already have a heavy and growing import dependence for hydrocarbons such as natural gas, they appear more partial to pursuing renewable-based hydrogen, so as not to exacerbate their hydrocarbon needs. Whether the expansion of renewables can keep pace with the demand growth from both electricity generation and hydrogen production is an important question. Their large and growing energy requirements could mean that much of the clean hydrogen produced in China and India would go to satisfying domestic needs.

Hydrogen is unlikely to materially enhance energy security for countries that are currently highly dependent on energy imports and have limited, domestic renewable energy potential. The energy security value of hydrogen is highly uncertain for countries with limited hydrocarbon resources and landmass for large renewable deployment. In terms of energy security, import dependence may not see a material improvement for Japan and South Korea, both of which have limited natural resource endowments to domestically satisfy their current hydrocarbon needs, including natural gas supplies. These constraints do not portend blue hydrogen becoming an energy security solution. Also, geographical characteristics constrain the likelihood of a massive deployment of renewable capacity for hydrogen production at a level that can materially reduce their reliance on energy imports. However, the diversification of suppliers may improve energy security if hydrogen unlocks new energy ties with countries that are outside the current menu of suppliers. In particular, clean hydrogen trade that does not rely on prevailing maritime transit routes would improve the energy security of the importer countries.

Decarbonization Implications

Decarbonization is a key objective for some governments but only a co-benefit of clean hydrogen development for others. The degree and nature of interests, visions, and strategies for clean hydrogen development vary across Asia and among major energy supplier countries, but economic development and diversification are the leading common motivations for investing in capacities to produce, transport, and use clean hydrogen.

Hydrogen strategies and the actions of Indo-Pacific countries do not suggest particular preference for renewable-based hydrogen over hydrocarbon-based hydrogen, at least in the near term. Japan's and South Korea's official strategic documents acknowledge the optimal decarbonization benefits from using green hydrogen but also indicate how they view investment in blue hydrogen supply chains as a pragmatic path toward creating clean hydrogen demand and markets, which in turn can help develop green hydrogen production and markets. This approach has been mirrored by the steps being taken by major energy suppliers to Asian markets that are prospective hydrogen exporters. Going forward, however, the continued decline in cost of green hydrogen production is one key factor that could alter the economic and business assumptions that underpin these countries' approaches and investment priorities. Meanwhile, some Southeast Asian countries appear to see supplying unabated hydrogen (or "gray hydrogen") as an entry way to the budding hydrogen supply chain and an attractive stream of revenue.

The use of hydrogen in the power sector stirs a decarbonization debate. Technological research and innovation on ammonia co-combustion is an issue that has elicited varying reactions. Proponents view ammonia co-combustion as a means to reduce carbon emissions from the process of electricity generation from fossil fuels, such as coal. According to the International Energy Agency (IEA)'s *The Future of Hydrogen*, ammonia co-combustion at a 20 percent share could reduce the annual carbon emissions of coal-fired power plants by one-fifth. Yet, ammonia co-combustion technology has come under scrutiny from those who view it as means to prolong the life of coal-fired power generation assets, or hydrocarbons as electricity sources more broadly. Whether carbon emissions are abated in the process of ammonia production is an important consideration in fully evaluating the decarbonization benefit of ammonia co-combustion. For example, the emissions profile of co-combustion that uses ammonia produced from hydrocarbons with carbon capture is better than co-combustion using ammonia without carbon abatement. Countries with a relatively young fleet of coal-fired power plants could find the technology attractive once it is commercialized.

Geopolitical Implications

Hydrogen technology innovation and manufacturing capacities may not be immune from the ongoing geoeconomic competition. The access to technology to convert resources into various forms of hydrogen is a key license to participate in clean hydrogen value chains. Major economies are increasingly investing in hydrogen technology development and equipment manufacturing to ensure access to the stable supply of clean hydrogen and to safeguard energy transitions against foreign dependence that could become politically or economically untenable. This is a new industrial area with opportunities to shape supply chains and mitigate the supply chain concentration in China seen in other clean energy technologies.

Clean hydrogen trade could alter some bilateral energy ties. There are also ways in which clean hydrogen may alter some of the existing energy relations. One such bilateral relationship is between Australia and China. Against the backdrop of rising geopolitical tension with China, the Australian government has explored a number of low-emissions energy partnerships that incorporate hydrogen commitments with traditional partners, such as Japan, South Korea, and Singapore, as part of its effort to minimize its economic exposure to China. Clean hydrogen is emerging as a key vehicle to help Australia rebalance its relations with Asian markets that had become dominated by China. Additionally, energy ties between individual Asian importer countries and Russia could undergo a notable change in the coming years. Many advanced industrialized democracies have responded to the Russian invasion of Ukraine with commitments to reduce reliance on Russian energy. Russia's growing isolation has significantly complicated its ambition and capacity to become a clean hydrogen supplier in the near future.

Key Recommendations

In light of the rising clean hydrogen interest in the Indo-Pacific region, U.S. policymakers have several important considerations:

- **Ensure resilience and robustness in clean hydrogen supply chains.** It is strategically important for the United States to ensure that an emerging clean hydrogen sector is resilient to supply-chain disruptions. Hydrogen supply chains entail technologies to produce, transport, and consume hydrogen, as well as the capacity to manufacture necessary related equipment and components. The security of supply chains for clean hydrogen is essential if the United States is to attain the triple benefit of decarbonization, energy security, and industrial competitiveness from creating a clean hydrogen market at home. It is also essential for U.S. regional partners if hydrogen is to meet its decarbonization potential in the Indo-Pacific region. The United States should work with like-minded countries to create a regional clean hydrogen supply chain with diverse participants and resilience to geopolitical tensions.

- **Recognize the energy security benefit of clean hydrogen exports from the United States.** Some of the Asian importing countries are concerned whether global hydrogen supply capacity will grow quickly enough to meet their anticipated demand. This concern may lead to growing calls for the United States' emergence as a supplier of clean hydrogen and its derivatives to help enhance regional energy security, as the United States has done with liquefied natural gas (LNG). Although clean hydrogen development is in its very early stages in the United States, this concern from some key Asian importer countries merits attention if the United States seeks to promote the use of clean hydrogen as a decarbonization tool in the region.

- **Ensure the environmental sustainability in hydrogen value-chain creation.** The U.S. approach to hydrogen development, as per the Infrastructure Investment and Jobs Act, is technology neutral with a stringent carbon intensity requirement. This approach is similar to that of advanced industrialized Asian economies as well as most of the prospective hydrogen suppliers to the region that were examined in the report. To the extent that some Southeast Asian countries may seek to emerge as hydrogen suppliers without requisite capacities to abate carbon emissions during the production process, however, U.S. energy engagement in the Indo-Pacific region should explore ways to speed up capacity development in producing and supplying clean hydrogen.

Introduction

Hydrogen is an energy carrier that is gaining attention globally as a non-carbon-emitting energy source, whether burned in an engine to produce heat or used in a fuel cell to produce electricity. Hydrogen is also uniquely flexible. It can take various forms for transport, including ammonia, liquid hydrogen, and liquid organic hydrogen carriers.[1] Also, various types of energy sources can be used in producing hydrogen, including hydrocarbons such as natural gas and coal, renewables such as wind and solar, and nuclear energy. In this report, the term "clean hydrogen" refers to hydrogen from non-carbon-emitting sources such as renewables and nuclear energy and production processes that produce low to no carbon where fossil fuels are reformed or gasified and carbon dioxide is captured.[2]

A growing number of countries are starting to either examine the potential role of clean hydrogen in their energy systems or consider their own role in growing hydrogen supply chains. According to the IEA, 17 governments have released hydrogen strategies and over 20 additional governments have announced that they are developing strategies.[3]

Hydrogen has emerged as a major focus among the Indo-Pacific economies, some as a potential producer and exporter and others as a growing consumer and importer. Specifically, Asian economies in the region increasingly view hydrogen as a useful energy to help meet energy demand while decarbonizing their energy systems. Several Asian governments have released hydrogen strategies and roadmaps to support the use of clean hydrogen, while others have expressed official interest in examining the economic viability of hydrogen use.

Several global energy supplier countries have expressed interest in producing and supplying hydrogen to Asian markets. Many of these countries are traditional hydrocarbon suppliers to Asia. These supplier governments have shown strong interest in the economic opportunities associated with exporting hydrogen.

The aims of these strategies and their associated action plans have important implications beyond their respective national borders. The hydrogen strategies of key Asian consumer governments and their supplier governments could affect not only inter-fuel competition but also international energy relations, for example, through changes in trading and investment patterns. These changes can affect the region's energy security and decarbonization efforts and raise some important geopolitical implications. As such, understanding government strategies, motivations, and implementation plans is of strategic importance to the United States, which itself is an Indo-Pacific economy.

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To be sure, the clean hydrogen economy is still in its early stages. Much of hydrogen demand today comes from refining and industrial uses, and most of the demand is met mainly from fossil fuels, resulting in close to 900 million metric tons (Mt) of annual carbon dioxide (CO_2) emissions per year.[4] Much technology innovation remains necessary in the production, transportation, and application of clean hydrogen.[5] For example, one of the current research and development (R&D) focuses is on electrolyzer technologies, where each type of technology has its own economic or technical advantage and disadvantage.[6] Also, the production of clean hydrogen requires additional energy infrastructure buildout, such as the carbon capture and storage (CCS) for blue hydrogen production and renewable electricity capacity for green hydrogen production. These capacities are not exclusively being developed to support the hydrogen economy, but how quickly and widely these capacities develop will greatly affect the viability of clean hydrogen production. Furthermore, hydrogen production requires water.[7] In water electrolysis, for example, not only the availability of water but also the cost of electricity become important determinants in the economic viability of individual projects. Insofar as these issues are already being actively discussed in the energy literature and raised to the attention of policymakers, this report focuses on national visions, motivations, and strategies related to the development of clean hydrogen value chains, not the various technological and economic factors that also affect value chain creation.

Specifically, this report outlines hydrogen visions and strategies of major energy importers in the Indo-Pacific (Japan, South Korea, China, India, and Southeast Asia) as well as those of the countries that are traditional energy suppliers to the region (Australia, Russia, Saudi Arabia, and the United Arab Emirates). Detailed discussion of their visions, motivations, strategies, and actions can be found in Appendix. The report also illuminates key motivations behind their hydrogen interests and explores the major implications of such visions and strategies for the region's energy security, decarbonization efforts, and geopolitics. Finally, the report seeks to inform U.S. policymakers about what regional interests in clean hydrogen may mean for U.S. interests in the Indo-Pacific region.

1

Interests, Visions, and Motivations for Clean Hydrogen Development

Interests are rising and visions are starting to solidify for the production and consumption of hydrogen across the five Asian markets and four supplier countries discussed in this report. Their governments have expressed varying interests and visions for the future of hydrogen. Some come in the form of a strategic document, while others come in the form of a verbal statements by senior government officials or national company executives. The visions underline priorities and offer insights into what motivates these countries' exploration or pursuit of hydrogen initiatives. Motivations are largely shaped by a country's resources, geographical characteristics, energy trade ties, economic and industrial structures, and technological competence.

Key Asian Countries

Asia is home to several major global energy importers. Yet, the energy consumption mixes and import profiles of regional economies are diverse, shaped or constrained by geographic characteristics, natural resource endowments, and economic strength. Similarly diverse are hydrogen visions among Asian countries, owing to a high degree of heterogeneity across these characteristics and conditions.

JAPAN AND SOUTH KOREA

To Japan and South Korea, clean hydrogen is about decarbonizing their economies while creating a new, competitive industry as a means for continued economic development. The synergy between consuming hydrogen for decarbonization and advancing hydrogen uses is advanced under Japan's Green Growth Strategy Through Achieving Carbon Neutrality in 2050, which identifies hydrogen as one of the 14 key sectors that will aid the country in achieving the dual objectives of decarbonization and economic development. Through significant public financial support to these sectors, the Green

Growth Strategy is to yield economic benefits in the order of JPY 90 trillion ($880 billion) in 2030 and JPY 190 trillion ($1.8 trillion) in 2050.[8] Likewise, hydrogen is one of the key sectors that underpins South Korea's Green New Deal under the Moon Jae-in administration. The South Korean government sees hydrogen as a potential driver of economic growth worth KRW 43 trillion ($34 billion).[9]

The transportation sector, specifically fuel cell vehicles (FCVs), has been the dominant focus of clean hydrogen in Japan and South Korea. In particular, Japan and South Korea both have a globally competitive automaker which has invested heavily in the development and deployment of FCVs and undertaken technology research and innovation since early on in hydrogen's development. Government promotion of FCVs in these countries may be as much about extending national industrial competitiveness as it is about decarbonizing the transportation sector.

Experiences and expertise in managing significant reliance on maritime transport for energy imports may be an asset that can unlock economic opportunities for Japan and South Korea. Engineering and energy companies from Japan and South Korea have experiences and expertise with processing and shipping LNG that can be leveraged to position themselves as competitive stakeholders in emerging hydrogen supply chains, including in liquefying, storing, and shipping hydrogen (in various forms of carriers, such as ammonia).

Meanwhile, the case for hydrogen use in Japan and South Korea is more nuanced when it comes to energy security. Both are limited in natural resources for domestic natural gas production to support blue hydrogen as well as in available flatland for massive renewable capacity to support green hydrogen. As such, a hydrogen economy alone will not likely solve their energy import reliance. As such, cooperation with resource-rich countries is at the core of the hydrogen visions of Japan and South Korea. Nuclear energy may have a unique role to play. The two countries have experience and expertise in nuclear power generation, which could aid in the pursuit of hydrogen. In fact, the Japanese government has already identified nuclear energy as a potential source of clean hydrogen production. Nuclear energy may become an option in South Korea under the leadership of President Yoon Suk Yeol (in office since May 2022), who has called for nuclear energy to account for 30 percent of South Korea's total energy generation.[10]

CHINA AND INDIA

In contrast to Japan and South Korea, China and India have hydrocarbon resources as well as large landmasses that are relatively conducive to energy infrastructure siting. Clean hydrogen deployment, particularly renewable-based hydrogen production, appeals to their desire to grow renewable energy capacity, which in turn can help strengthen energy security.

Expanding renewable energy capacity is as much about mitigating a steeper rise in fossil fuel import dependence as it is about decarbonization for China and India. For example, despite the availability of domestic hydrocarbon resources, China's import dependence is already high, at 73 percent for oil and 41 percent for natural gas as of 2020.[11] India's combined expenditure for fossil fuel imports is forecast to triple over the next two decades, as the country's net dependence on imported oil rises from 75 percent today to over 90 percent by 2040.[12] In both countries, a key question is whether renewable capacity expansion can keep pace with growing demand from electricity generation and hydrogen production.

China and India's hydrogen pursuits are also driven by economic and industrial interests. China is increasingly interested in advancing technology innovation and expanding manufacturing capacity, not only to meet domestic demand but also to serve overseas markets.[13] For India, green hydrogen could become an export commodity to countries such as Japan and South Korea while also serving the domestic market.[14]

Neither China nor India has articulated detailed pathways, action plans, or timelines for developing a clean hydrogen sector. Existing policies and official statements have a greater focus on the supply side of the equation, providing limited insights into how the domestic market may grow. Also, China and India's visions are much less focused on creating international supply chains or regional markets than the Japan and South Korea's visions. Likewise, China's government does not seem to view hydrogen as a vehicle for an economy-wide transformation. As major energy consumers in the world, the pace and scope of hydrogen development and use in China and India will have important implications for both global hydrogen development and global decarbonization.

SOUTHEAST ASIA

There is a tremendous diversity among the Southeast Asian economies in terms of energy production and consumption profiles. While countries such as Brunei, Indonesia, and Malaysia are traditional natural gas exporters to regional markets, Singapore and Thailand are long-time importers. Such diversity is also evident in Southeast Asian governments' varying levels of interest in and approaches to a hydrogen economy.

As major energy consumers in the world, the pace and scope of hydrogen development and use in China and India will have important implications for both global hydrogen development and global decarbonization.

Generally, interest and progress toward hydrogen development in Southeast Asia is more limited than in the countries discussed above, as energy access (both quantitatively, such as population and geographic coverage, and qualitatively, such as stability and duration of power provision) remains to be an overarching priority for regional policymakers. The production, transportation, and consumption of clean hydrogen commands large initial capital expenditure.[15] As such, political support for launching a major hydrogen industrial strategy or providing significant public funding toward clean hydrogen production and applications remains limited in the region. The fragmented state of electricity networks in the region as well as the lack of affordability and access to technologies make raising the share of renewable energy in the region difficult, which in turn frustrates the development of clean hydrogen.[16]

Singapore stands out as a leading country in the development of clean hydrogen economy not only in Southeast Asia but in the Indo-Pacific region. Singapore's desire to remain key to the regional energy trade is a strong driver for its emerging international engagements, including government-to-government and commercial engagements in hydrogen projects. Elsewhere, several regional economies with natural resources, such as Malaysia, are exploring ways to gain economic opportunities from the hydrogen value chains that are emerging within the Indo-Pacific region.

Traditional Energy Supplier Countries

Interest in hydrogen is rising among countries rich in hydrocarbon resources that are major energy exporters to Asia. Economic diversification tops the list of motivations for clean hydrogen development as the supplier governments increasingly recognize that hydrocarbon resource production and consumption are under growing scrutiny from investors, political leaders, and civil society in advanced industrialized countries for their greenhouse gas-emitting attributes. Hydrogen visions in Australia, Russia, Saudi Arabia, and the United Arab Emirates (UAE) clearly acknowledge this undercurrent. Also, the strategies of all four countries are largely about adapting their economies to the low-carbon preferences of their trading partners in the increasingly carbon-constrained world. For the economies that heavily depend on oil and gas exports for export revenue, clean hydrogen development could help diversify a portfolio of exportable commodities.

By leveraging existing natural gas resources as well as operational expertise and infrastructure, a shift to blue hydrogen would be relatively easier than developing infrastructure and expertise in green hydrogen. Some have also begun exploring the opportunity to capture greater economic value by using low-carbon hydrogen to produce industrial materials for export, in addition to exporting hydrogen itself. Green hydrogen is also gaining attention, as exemplified by interest in supplier countries in accessing electrolysis technology and building out electrolyzer plants. Export seems to be the primary motivation, while decarbonization appears to be a secondary one; for some, decarbonization appears to be a key benefit rather than a driver of developing a clean hydrogen sector.

The strategies of all four countries are largely about adapting their economies to the low-carbon preferences of their trading partners in the increasingly carbon-constrained world.

Meanwhile, some research, such as a 2022 report by the International Renewable Energy Agency (IRENA), has expressed doubt that hydrogen will generate as much export revenue as oil and gas do today.[17] IRENA notes that a key attribute of hydrogen value creation is that it is a conversion business and not an extraction business, thus broadening the pool of potential market participants to include non-hydrocarbon superpowers. The durability of economic diversification as a motivation for clean hydrogen development may not be a foregone conclusion in some of the supplier countries.

Additionally, the current period of high and volatile energy prices, especially for oil and gas, could potentially alter a prospective hydrogen supplier's approach to developing a clean hydrogen sector, at least in the near term. High natural gas prices could dampen supplier interest in investing in blue hydrogen production capabilities, causing them to prefer exporting natural gas to converting natural gas into hydrogen for export. This could limit near-term support for or investment in hydrogen export infrastructure and thereby slow the development of the clean hydrogen sector. Alternatively, this could propel supplier governments to shift support and resources away from blue hydrogen initiatives toward green hydrogen, thereby potentially expediting the timeline for establishing capabilities to produce and export green hydrogen.

AUSTRALIA

As a country in the Indo-Pacific region rich with energy resources, Australia has shown a significant level of interest in developing a clean hydrogen economy and becoming a major supplier of clean hydrogen. Already among the largest exporters of LNG, coal, and uranium today, Australia seeks to become one of the top three hydrogen exporters to Asian markets.[18] Essentially, the path for hydrogen in Australia is about adapting the country's energy export profile to a new reality that is defined by the energy transition and Asian markets' growing interest in low-carbon energy imports.

The country also sees additional economic benefits arising from developing a hydrogen economy. Hydrogen production is seen as an opportunity to diversify the economy, attract investment, provide jobs, and reinvigorate trading relationships, potentially even reaching new markets. In fact, Australia's vision has a highly pragmatic undertone, seeking to proactively capture economic value from the global energy transition and generate national-level synergy from state-level economic development needs and interests.

The Australian government also values the decarbonization benefits of clean hydrogen development. In fact, Australia's climate action is primarily focused on advancing low-emissions technologies such as hydrogen rather than directly on emissions reductions. Moreover, the ongoing effort to develop a "guarantee of origin" system for the hydrogen sector reflects Australia's desire to assume a leadership role in creating an international clean hydrogen market.[19]

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RUSSIA

The Russian government has become increasingly articulate in what the country seeks to gain from an emerging hydrogen economy in Asia and Europe. The overarching drive behind Russia's emerging hydrogen interest is its desire to preserve prominence in the global energy system. Russia has set export ambitions for hydrogen: 0.2 Mt/year by 2024 and 2 Mt/year by 2035, as well as a 20 percent share in the global market by 2030.[20] More recently, the Russian Ministry of Energy expressed even more ambitious goals: an export volume of 2.3 Mt/year by 2030 and 9.4 Mt/year by 2050.[21] All of the Russian strategy documents related to hydrogen acknowledge changing global demand in the face of the energy transition, and its various action items demonstrate a recognition that emissions from future hydrogen fuel production may receive greater scrutiny from foreign buyers.

Russia's official statements are largely focused on the supply side, but they also reveal the country's exploration of domestic demand for hydrogen. The preliminary version of Russia's hydrogen strategy, released in February 2022, suggests a growing interest in using hydrogen for decarbonizing the transportation sector as well as the steel and chemical industry, especially in connection with the upcoming entry into force of the European Union's Carbon Border Adjustment Mechanism.[22]

The Russian invasion of Ukraine (since late February 2022) has cast major uncertainty over the future of hydrogen development in Russia. For example, major international sanctions (including by the United States, the European Union, Japan, and South Korea) on Russian banks are a major blow to planned and potential hydrogen projects in Russia. Moreover, the European Commission's decision to rapidly reduce energy dependence on Russia renders the viability of hydrogen technology cooperation and trade between Russian and European companies highly uncertain or even unlikely.

Europe and Eurasia imported nearly 90 percent of Russian natural gas supplies in 2020. The damaged relationship with Europe could propel Russia to more decisively pivot toward Asia for demand and investment. While the pivot is highly likely, exactly how bilateral energy ties might incorporate hydrogen remains uncertain given the wide-ranging reactions by individual Asian governments to Russian aggression. While Japan and South Korea were quick to join the transatlantic-led sanctions on Russia, China and India have not. Nonetheless, losing access to Western capital could trigger a rethink of Russia's hydrogen vision and strategy to better align its capability with the preferences and priorities of Asian customers. As such, strategic documents that were surveyed for this study are highly subject to change at the time of writing.

SAUDI ARABIA

Saudi Arabia's interest in hydrogen is primarily driven by its desire to ensure economic security. Developing a clean hydrogen sector can help the world's top crude oil exporter meet several key mandates of the Saudi Vision 2030, such as diversifying exports, leveraging existing sectors' supply chains to increase local contents, and developing new industrial sectors.[23]

Clean hydrogen could generate a new stream of export revenue that allows Saudi Arabia to become less reliant on oil as the key source of export revenue. This is particularly relevant in the carbon-constrained modern world characterized by a wave of net-zero targets from governments and industries, including Saudi Arabia's own (by 2060). In 2020, oil exports accounted for about 70 percent of the country's total exports in terms of value and about 53 percent of Saudi government revenues.[24] In October 2021, Saudi energy minister Prince Abdulaziz bin Salman al-Saud stated that the country wants to become the top supplier of hydrogen in the world.[25] It has clean hydrogen production targets of 2.9 Mt/yr by 2030 and 4 Mt/yr by 2035.[26]

Clean hydrogen could generate a new stream of export revenue that allows Saudi Arabia to become less reliant on oil as the key source of export revenue.

The current focus is to gain a large market share in blue hydrogen, particularly in the form of blue ammonia in the coming decade (i.e., ammonia produced from the combination of ammonia synthesis using hydrocarbon carbon capture, utilization, and storage).[27] Blue hydrogen and its derivatives can help the country leverage its hydrocarbon resources and existing expertise and infrastructure, such as in carbon capture and storage. In the future, green hydrogen could help the country develop a new industrial sector. Saudi Arabia's green hydrogen-related technological and economic experiments are being incubated in the futuristic city of Neom.

UNITED ARAB EMIRATES

As the first Middle Eastern country to announce a mid-century carbon neutrality commitment, the UAE sees hydrogen as both a potential economic driver and a key tool for climate action. But even before launching the Hydrogen Leadership Roadmap at the United Nations Climate Change Conference in Glasgow (COP26) in November 2021, the UAE identified hydrogen as "a fuel of the future" in its Nationally Determined Contribution under the Paris Agreement, updated in December 2020.[28] The country currently uses hydrogen from unabated natural gas or methane, but the roadmap announcement signals a growing effort to decarbonize its hydrogen supply and consumption profile.[29]

Both blue and green hydrogen are generally seen to aid the UAE's sustainable economic growth through its ability to deliver projects across the clean hydrogen value chain. In particular, blue hydrogen could take advantage of the country's hydrocarbon resources, existing large-scale hydrogen and ammonia production facilities, and large, well-characterized sub-surface formations for CO_2 storage.[30] The UAE can also seize major economic opportunities with the export of low-carbon hydrogen, derivatives, and products to major importing regions, where it targets capturing 25 percent of the global hydrogen market by 2030.[31]

2

Hydrogen Strategies, Actions, and Actors

Some of the national hydrogen strategies are accompanied by technology roadmaps to show the pace and scope of research and development (R&D) underway. Also, some hydrogen strategies are augmented by economic roadmaps and policies that illustrate tools and funding that are already committed or deployed. National governments play a pivotal role in providing such resources, either directly or indirectly, such as through leveraging state-owned companies. In many of the countries studied, leading domestic industrial entities are vital partners to national governments, investing in and executing key hydrogen projects and forming ventures with domestic and international partners.

Key Asian Countries

Asian governments have released various documents that not only provide consumption targets but also show the types of policy instruments and levels of resources they are leveraging to realize their hydrogen visions. Some have a detailed strategy that consists of concrete economic and technology roadmaps as well as budgetary documents. National governments play an indispensable role in the pursuit of a clean hydrogen sector in several countries, although at varying degrees. They not only formulate strategy and set priorities but also provide funding for technology and supply chain development and encourage international engagements.

JAPAN

Since becoming the first country to adopt a national hydrogen framework, called the Basic Hydrogen Strategy (2017), Japan's public sector has actively led the development of a hydrogen economy by formulating several strategic plans and roadmaps and funding key initiatives. Japan's hydrogen development action plans aim to develop basic technologies to reduce hydrogen production costs, enable access to inexpensive energy resources for hydrogen production overseas, and conduct surveys and analytical work on resource and supply chain economics at home and around the world.[32] Efforts to advance production technologies and develop supply chains are a key focus under the government's JPY 2 trillion ($15.3 billion), 10-year grant program, the Green Innovation Fund (GIF), which is under the Green Growth Strategy.

The New Energy and Industrial Technology Development (NEDO), Japan's national R&D agency, is active in hydrogen research and innovation, while the Japan Bank for International Cooperation (JBIC) supports Japan's hydrogen partnerships around the world. The government's political and financial investments are matched by high-level commitments and investments by Japan's leading engineering, manufacturing, and energy companies as well as trading houses that are undertaking several anchoring projects around the world, including in Australia, Saudi Arabia, and the UAE.

Hydrogen will likely remain a priority under the forthcoming Clean Energy Strategy, which is being formulated under the leadership of Prime Minister Fumio Kishida (in office since October 2021) and is targeted for release in summer 2022. Whether this new strategy helps to accelerate the development of a domestic clean hydrogen market and contributes as well as international supply chains is of critical importance to Japan's hydrogen future.

Hydrogen will likely remain a priority under the forthcoming Clean Energy Strategy, which is being formulated under the leadership of Prime Minister Fumio Kishida.

SOUTH KOREA

The national government also plays a pivotal role in South Korea's pursuit of a hydrogen economy. The Hydrogen Economy Roadmap (2019) outlines South Korea's hydrogen vision and strategy, while the Hydrogen Law (2021) serves as the legal foundations for the government's promotion of hydrogen—essentially to realize the roadmap. The Hydrogen Law seeks to promote hydrogen by creating a promotion system, fostering and supporting hydrogen-specialized businesses, installing hydrogen fuel supply facilities, such as hydrogen refueling stations, and designating dedicated agencies responsible for the hydrogen economy.[33]

Plans and actions to realize South Korea's hydrogen vision are carried out by several entities that were designed by the government, including the Hydrogen Convergence Alliance (H2Korea), which provides policy support, infrastructure build-out, technology development, and business coordination.[34] Large government funding underpins South Korea's efforts to develop a hydrogen economy. For example, $702 million in spending is planned for FY 2021, a 40 percent increase from 2020.[35] Moreover, the business community is starting to commit significant resources to help fulfill the government's vision. According to South Korea's economic ministry, five South Korean conglomerates have plans to invest $38 billion in hydrogen technology by 2030.[36] A few South Korean companies are engaged in hydrogen production and supply chain projects overseas, including in Australia, Saudi Arabia, and the UAE.

Whether and how the incoming Yoon administration further facilitates the development of a clean hydrogen sector warrants attention.

CHINA

China's policy framework for hydrogen, especially in comparison to Japan and South Korea, is geared toward executing an industrial policy rather than ushering in an economy-wide transition. Hydrogen is a "frontier" area and one of the six industries for focused advancement under China's 14th Five-Year Plan (2021–2025).[37] Moreover, as exemplified under China's first-ever long-term hydrogen plan (slated for 2021–2035 and released in March 2022), the primary focus is on improving the country's innovation capability and mastering core technologies and manufacturing processes.[38] Innovation and manufacturing competition in this space will warrant close attention as China becomes increasingly focused on advanced electrolysis technologies for hydrogen production, where Europe currently has an edge.

The Chinese government has been a key spender on hydrogen development, including R&D. For example, toward the end of the 13th Five-Year Plan (2016–2020), China's hydrogen technology R&D spending increased sixfold, to a little over $600 million in 2019.[39]

However, the role of the national government in pursuing a clean hydrogen sector is not as pronounced in China as it is in Japan or South Korea. Instead, China's state-owned-enterprises (SOEs) and provincial governments have been playing visible and active roles. For example, over one-third of SOEs have announced plans for hydrogen production, storage, distribution, and utilization, and at least 23 of China's provinces and municipalities have identified hydrogen as a key economic priority or formulated hydrogen development plans, including in their own five-year plans.[40] It is unclear how many of these SOE undertakings have long-term commercial viability or whether many of the subnational plans are aligned with how the national government wants to shape the country's hydrogen economy, particularly as the national government has not yet released a comprehensive national hydrogen strategy. The direction, pace, and scope of China's low-carbon hydrogen endeavors warrant close attention for multiple implications, not only for the Chinese economy but also for the development of the global hydrogen industry.

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INDIA

India has begun encouraging hydrogen technology R&D and market development through public spending as well as the participation of major Indian companies, both state-owned and private. In April 2021, the Indian government announced plans to spend $200 million over the next five to seven years and asked state-owned energy companies to commission seven pilot hydrogen production plants before the end of the 2021 financial year.[41]

Following the official announcement of the National Hydrogen Mission in August 2021, the union (federal) government has been formulating hydrogen policy. The first part of the national hydrogen policy, announced in February 2022, included measures to incentivize hydrogen production, such as setting up manufacturing zones, waiving interstate electricity transmission charges for 25 years, and allowing green hydrogen manufacturers to set up bunkers near ports for storage for exports.[42] Additional incentives, to be announced at a later date, will likely include federal financial support to set up electrolyzer manufacturing as the country seeks to mandate refineries and fertilizer plants to use green hydrogen.[43]

India's plans and actions have been notably focused on the supply side of market activities. Whether and how India incentivizes hydrogen use . . . will invariably affect how much India becomes part of a growing regional supply chain for clean hydrogen.

SOUTHEAST ASIA

Given the diversity of resources and capacity-building requirements across the regional economies, approaches to developing a clean hydrogen economy will likely be incremental and varied. The ASEAN Centre for Energy, which is under the ASEAN Secretariat, has indicated that regional countries rich in hydrocarbons and gas export expertise may consider exporting methane-based unabated hydrogen as a near-term opportunity while they develop capacities to produce and export blue hydrogen during the latter half of this decade.[44]

Although no Southeast Asian government has yet issued any detailed hydrogen strategy, some of the regional economies have begun participating in emerging hydrogen supply chains. For example, Singapore is engaged in several projects to facilitate the use of hydrogen and ammonia in the maritime industry, leveraging investment and technologies by some of its leading companies. Also, traditional gas exporter countries in the region—such as Brunei, Indonesia, and Malaysia—are engaged in emerging endeavors to create regional hydrogen supply chains. Top state energy enterprises, such as Petronas of Malaysia, Pertamina of Indonesia, and PTT of Thailand, seem to be in leading positions to take national hydrogen ambitions to the next stage.

Traditional gas exporter countries in the region—such as Brunei, Indonesia, and Malaysia—are engaged in emerging endeavors to create regional hydrogen supply chains.

Traditional Energy Supplier Countries

Supplier country strategies are largely about leveraging existing assets, capabilities, and experiences to put suppliers in position to capture as much value out of emerging hydrogen value chains. These supplier countries have hydrocarbon resources that can be converted into hydrogen and infrastructure, such as LNG storage and export facilities, that can be repurposed for hydrogen export. Also, some are more eager than others to explore the production of green hydrogen for export, leveraging the ongoing expansion of renewable energy capacity.

The approaches of these supplier governments to fulfilling their hydrogen visions are diverse. Not only are their underlying visions not identical, and thus feature different requirements, but the strategies, tools, and actions in each are shaped by the political-economic makeup of the relevant country, such as the presence of dominant state-owned companies. For example, Russia, Saudi Arabia, and the UAE leverage the resource and business networks of several state companies. Also, several countries seek to create clusters or hubs to support economies of scale in producing and delivering hydrogen to end users at home and abroad. Creating hydrogen hubs is a key feature of the Australian and Russian approaches—though there is a difference in the level of publicly available details.

AUSTRALIA

Australia's hydrogen development is guided by the National Hydrogen Strategy, released in November 2019, which recommends 57 joint actions that cover a host of areas, including exports, transport, industrial use, gas networks, and power systems.[45] Hydrogen initiatives receive support from national, state, and territorial governments. Most of Australia's states and internal territories have a strong interest in developing a hydrogen economy and have put forward some concrete plans and actions.

One of the key government organizations is the Commonwealth Scientific and Industrial Research Organization (CSIRO). CSIRO plays an instrumental role in carrying out hydrogen research and accelerating projects, particularly through the Hydrogen Industry Mission, which has brought together CSIRO and its partners in the research community and industry.[46]

Additionally, the Australian Renewable Energy Agency (ARENA) facilitates clean energy innovation in Australia, particularly to improve the competitiveness of renewable energy technologies, and also supports renewable-based hydrogen projects.[47] Elsewhere, the government has empowered its Clean Energy Finance Corporation, which has a AU$10 billion ($7.2 billion) capitalization, to invest up to AU$ 300 million ($216.2 million) toward demonstrating, commercializing, and deploying hydrogen projects.[48]

The Australian hydrogen strategy focuses heavily on developing regional clusters or hubs of hydrogen development. This serves to minimize the cost of providing infrastructure while supporting economies of scale in producing and delivering hydrogen to end users. The government has allocated AU$464 million ($334.4 million) to support the rollout of hydrogen hubs across seven regional sites. As Australia seeks to become a leading hydrogen exporter, international engagement is a key element of its hydrogen strategy. There is a growing, robust engagement with Japan and South Korea at both the government and commercial levels.

RUSSIA

The Russian hydrogen strategy, which was anticipated to be out as early as by the end of March 2022, should provide detailed insights into how Russia seeks to realize its hydrogen vision.[49] Until then, the Roadmap for Hydrogen Development until 2024 (released in October 2020), the Concept for the Development of Hydrogen Energy in Russia (released in August 2021), and the preliminary version of the hydrogen strategy (February 2022) offer useful insights. The roadmap presents distinct steps and timelines through 2024 for various aspects of the strategy, including strategic planning, state support, production capacity, pilot projects, R&D, regulatory development, workforce development, and international engagement. Meanwhile, the concept document offers areas of emphasis. In the preliminary version of the hydrogen strategy, the Ministry of Energy proposes subsidies for the cost of infrastructure (including terminals, ships, and tank containers), which could require up to $3.7 billion, as well as tax incentives.[50]

While the Ministry of Energy seems to be the most vital actor in fulfilling the country's hydrogen vision, Russia's hydrogen action plans involve a variety of stakeholders from both the public and private sectors. In particular, what role state-owned gas company Gazprom might play in the hydrogen export program warrants close attention. A major producer of high-carbon hydrogen and an exclusive controller of gas pipeline networks, Gazprom seems increasingly engaged in low-carbon hydrogen value creation, although not entirely with enthusiasm.[51] Novatek, Russia's non-state gas company and dominant LNG producer, is another important player. Novatek is starting to commit resources to creating hydrogen value chains. Additionally, state-owned nuclear company Rosatom, the most technologically advanced large Russian company, has plans to act as an investor and developer, with a long-term goal of becoming a hydrogen technology provider.[52]

Developing hydrogen clusters or hubs seems to be at the core of the Russian strategy. Russia seeks to create five clusters: Yamal, Eastern Siberia, Yakutia, Sakhalin, and North-West. Of the five, the Sakhalin is the most developed.[53] Major emphasis is also on international cooperation in areas such as pilot projects, industry standards, and trade regulations.[54] Japan and South Korea are among the prospective international partners identified by the Russian government. However, the pool of partners and markets has likely shrunk following the Russian invasion of Ukraine.

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SAUDI ARABIA

Saudi Arabia's official hydrogen strategy is reportedly under development.[55] The Saudi strategy will likely have five areas of focus: hydrogen mobility, hydrogen export infrastructure, a regulatory framework, standards and certifications, and investments of over $36 billion by 2030.[56]

Saudi Arabia has interest in leveraging its natural gas resource wealth, such as the Jafurah field, which is the largest discovered non-associated gas resource in the country.[57] The state-owned Saudi Arabian Oil Company (Aramco) targets first gas production from the $110 billion project in 2024.[58] Saudi Arabia also has experience in industrial-scale production and international sales of chemicals as well as several assets related to carbon capture, utilization, and storage (CCUS), such as the CO_2-to-enhanced oil recovery project at Uthmaniyah and the CO_2-to-chemicals project at Jubail, which will be helpful for developing the blue hydrogen sector.

As the manager of these CCUS capacities and gas resources, Aramco plays a vital role in executing the blue hydrogen plans at home and with international partners. In September 2020, Saudi Aramco shipped 40 tons of blue ammonia from Saudi Arabia to Japan. This was the world's first demonstration of blue ammonia supply chains entailing the production and international maritime transportation of blue ammonia. Also, Aramco has a memorandum of understanding with South Korea's Hyundai OilBank Company, which plans to take liquefied petroleum gas (LPG) cargoes from Saudi Aramco, convert the LPG into hydrogen, and ship the CO_2 that was emitted in the process back to Saudi Arabia.[59]

Meanwhile, renewable-based hydrogen is a key focus of technological and economic experiments in the futuristic city of Neom. Green hydrogen could mean a new industrial sector for Saudi Arabia, which is located in the sun belt and has vast areas of flat, unused land for solar panels.[60] The country has announced plans to install about 27 gigawatts (GW) of mostly solar capacity by 2023 and almost 58 GW by 2030, but *installed* renewable capacity only accounts for 1 percent of its power supply today.[61] Whether and how the Saudis can successfully expand renewable power supply is a key indicator for the success of its green hydrogen endeavors.

UNITED ARAB EMIRATES

The key UAE document is the Hydrogen Leadership Roadmap, which was released at COP26 in November 2021. The roadmap details how the UAE seeks to support the development of low-carbon hydrogen business through a supportive regulatory framework, domestic technology R&D, existing and new government-to-government relationships, land and infrastructure resources, and both domestic and international green financing.[62]

The country's current hydrogen undertakings include at least seven projects, and there are a few state-controlled companies that are engaged in developing a hydrogen sector. In particular, Abu Dhabi National Oil Company (ADNOC) is playing a vital role, particularly with its $122 billion, five-year capital investment program and its political mandate to position "the UAE as a hydrogen leader."[63] Moreover, several national companies, including ADNOC, have taken a strategic step in positioning Masdar (the Abu Dhabi Future Energy Company) to emerge as a "global champion in renewable energy," and in turn green hydrogen.[64]

The UAE's hydrogen relations with Asian economies—most notably with Japan but also with South Korea, China, India, and Thailand—have seen strong private sector participation, including blue ammonia sales to Japan's Itochu, Idemitsu, and Inpex.[65] Meanwhile, Mitsui of Japan and GS Energy of South Korea agreed to participate in a blue ammonia project in Ruwais for supply access.[66]

3

Key Implications

Hydrogen visions, strategies, and actions of Asian governments and their traditional energy supplier countries illustrate growing interests in and commitments to clean hydrogen development in the Indo-Pacific region. They also suggest how government actions may evolve and what types of energy ties and international cooperation may emerge in the future. These actions raise implications for energy security, decarbonization, and geopolitics in the Indo-Pacific region.

Energy Security Implications

Hydrogen development could help alleviate hydrocarbon import dependence in countries with strong renewable resource potential.

The domestic production of clean hydrogen could help China and India alleviate, although not solve, energy security challenges amid their rising energy demand. Insofar as these countries already have a heavy and growing import dependence for hydrocarbons such as natural gas, they appear more partial to pursuing the capability to produce renewable-based hydrogen, so as not to further their hydrocarbon needs. Whether renewable capacity expansion can keep pace with the demand growth from both electricity generation and hydrogen production is an important question. China and India's large and growing energy requirements could mean that much of the clean hydrogen produced in China and India will go to satisfy domestic needs.

Hydrogen is unlikely to materially enhance energy security for countries that currently are highly dependent on energy imports and have a limited renewable resource potential domestically.

The energy security value of hydrogen use is highly uncertain for countries with limited hydrocarbon resources and landmass for large renewable deployment. In terms of energy security, import dependence may not see a material improvement for Japan and South Korea, both of which are heavily resource constrained domestically in satisfying their hydrocarbon needs, including in terms of natural gas supplies. These constraints mean blue hydrogen development is unlikely to become an energy security solution. Also, geographical characteristics make a larger deployment of renewable capacity to support green hydrogen production unlikely, particularly at a level that can materially reduce energy import reliance. Meanwhile, nuclear energy has import substitution potential for Japan and South Korea, both of which have decades of nuclear energy research and innovation expertise as well as operational capacity. How and to what degree these countries link nuclear energy use and hydrogen development is an important energy security question.

However, hydrogen could unlock new energy ties with countries that are outside of the current menu of suppliers, leading to enhance energy security through supplier diversification. For example, Chile seeks to become a leading global exporter of green hydrogen and ammonia by 2040 and sees Asia as a top-level destination.[67] In particular, a clean hydrogen trade that does not rely on prevailing maritime transit routes would improve energy security for importer countries. Insofar as U.S. oil and gas supplies have diversified the pool of energy suppliers to Asian markets, hydrogen supplies from the United States could also provide an energy security benefit to the Indo-Pacific region.

Decarbonization Implications

The hydrogen strategies and actions of Indo-Pacific countries do not suggest a particular preference for renewable-based hydrogen over hydrocarbon-based hydrogen, at least in the near term.

Japan and South Korea's official strategic documents acknowledge the optimal decarbonization benefits from using green hydrogen but also indicate how they view investment in blue hydrogen supply chains as a pragmatic path toward creating clean hydrogen demand and markets, which in turn can help develop green hydrogen production and markets. This approach has been mirrored by the steps being taken by major energy suppliers to Asian markets that are prospective hydrogen exporters. Going forward, however, the declining cost of green hydrogen production is a key factor that could alter the economic and business assumptions that underpin these countries' approaches and investment priorities.

Meanwhile, some Southeast Asian countries appear to see supplying unabated hydrogen (or "gray hydrogen") as an entry way to the budding hydrogen supply chain and an attractive stream of revenue. Aside from the question of whether Southeast Asian countries can mobilize sufficient investment to establish capacities to turn their hydrocarbon resources into hydrogen supplies for exports, the commercial efficacy of exporting gray hydrogen is also uncertain. As a major prospective hydrogen exporter to Asia, Australia is developing a "guarantee of origin" certification mechanism to encourage Australian businesses to sell low-emissions hydrogen domestically and globally. A similar system is well underway within the European Union. Acceptance by trading partners is essential for such a system, and the Australian government appears eager to promote it both bilaterally and multilaterally. Other major prospective hydrogen exporters to Asia may see a commercial rationale to join in promoting such a certification system in the Indo-Pacific region, helping to ensure a return on investment in clean hydrogen production and supply processes that would be expected by European customers.

Hydrogen use in the power sector stirs a decarbonization debate.

Technological research and innovation on ammonia co-combustion is an issue that has elicited varying reactions. Proponents view ammonia co-combustion as a means to reduce carbon emissions from the process of electricity generation from fossil fuels, including coal. According to the IEA's *The Future of Hydrogen*, ammonia co-combustion at a 20 percent share could reduce the annual carbon emissions of coal-fired power plants by one-fifth. Yet, ammonia co-combustion technology has come under scrutiny from those who view it as a means to prolong the life of coal-fired power generation assets, or hydrocarbons as electricity sources more generally. Whether carbon emissions are abated in the process of ammonia production is an important consideration in fully evaluating the decarbonization benefit of ammonia co-combustion. The emissions profile of co-combustion that uses ammonia produced from hydrocarbons with carbon capture is better than that of co-combustion using ammonia without carbon abatement, for example. Countries with a relatively young fleet of coal-fired power plants could find the technology to be attractive once it is commercialized.

Geopolitical Implications

Hydrogen technology innovation and manufacturing capacities may not be immune from the ongoing geo-economic competition.

Hydrogen can be produced from various sources, and the availability of hydrocarbon resources is not the primary determinant of participation in clean hydrogen supply chains. Instead, access to technology to convert resources into various forms of hydrogen is an important license to participate in clean hydrogen value chains. Several major economies, including Europe and China, are investing in hydrogen technology development and equipment manufacturing to ensure stable access to clean hydrogen supply. In fact, Chinese enterprises are expanding the country's domestic capacity to manufacture electrolyzers, and their cheap alkaline electrolyzers have turned China into a major supplier of electrolyzers. However, alkaline electrolyzers are much less compatible with intermittent renewable energy sources than polymer electrolyte membrane (PEM) electrolyzers, which are more technologically advanced. Consequently, PEM and other advanced electrolysis technologies are among the key research and innovation focuses of many countries examined in this report. A critical element of the overall equation is whether China can successfully replicate its commanding position seen in other clean energy supply chains, such as for solar photovoltaic (PV) cells and electric vehicle batteries. While competition may help drive down costs and secure technology access, the uncoupling between China and the West over technology supply chains could hinder rapid cost reduction and a transition to hydrogen.

The clean hydrogen trade could alter some bilateral energy ties.

There is a strong alignment of interests between clean hydrogen importers and suppliers. A few of the surveyed Asian countries look to their existing energy ties as an important vehicle to ensure access to clean hydrogen supplies, while the energy supplier countries surveyed look to clean hydrogen as a key to maintaining market shares in Asia. In particular, clean hydrogen supply chain initiatives that Japan and South Korea have with their traditional energy suppliers in the Middle East are likely to reinforce their respective bilateral energy ties.

Clean hydrogen may also alter existing energy relations in several ways. One such bilateral relationship is between Australia and China. Against the backdrop of rising geopolitical tension with China, the Australian government has explored a number of low-emissions energy partnerships that incorporate hydrogen commitments with traditional partners, such as Japan, South Korea, and Singapore, as part of an effort to minimize Australia's economic exposure to China.[68] Clean hydrogen is emerging as a key vehicle to help Australia rebalance its relations with Asian markets that have become dominated by China.

Also, energy ties between individual Asian importer countries and Russia could undergo a notable change in the coming years. Many advanced industrialized democracies have responded to the Russian invasion of Ukraine with commitments to reduce reliance on Russian energy. The growing isolation of Russia has significantly complicated its ambition and capacity to become a clean hydrogen supplier in the near future.

However, the deepening rift between Russia and Europe will likely propel Russia to seek closer energy trade and technology ties with Asian countries that are outside the bounds of Western democratic norms, such as China and India. If Russia wishes to continue developing the capability to produce and export clean hydrogen, it might seek Chinese or Indian cooperation on hydrogen production technology and infrastructure development. The durability of Russia's relationships with China and India, including the possibility of clean hydrogen cooperation, warrants close attention.

Another potential implication from Russia's war in Ukraine stems from the European desire to reduce reliance on hydrocarbons and accelerate a shift to low-carbon energy sources such as hydrogen. The European shift, if successful, could potentially complicate the emerging synergy between Asian markets and prospective hydrogen supplier countries besides Russia that may now see more near-term export opportunities among European markets.

Policy Considerations for the United States

Actions from the public and business sectors raise a variety of implications for the Indo-Pacific region in terms of regional energy security, decarbonization, and geopolitics. They are also starting to shape the regional landscape at a time when the United States is beginning to make significant investment in creating clean hydrogen supply chains.[69] The United States has a domestic hydrogen market of about 10 Mt, most of which is from fossil fuels through steam methane reforming. U.S. interest in clean hydrogen development is fundamentally about decarbonization, promoting the use of clean hydrogen in the sectors that are difficult to decarbonize through electrification.

Unlike the traditional energy suppliers this report examined, the U.S. clean hydrogen interest is not driven by the need to diversify its economy or export portfolio. In fact, exporting hydrogen is not a prescribed objective of the U.S. endeavor to establish multiple hydrogen hubs. However, domestic assets such as LNG export terminals, carbon capture and storage, hydrocarbon resources for blue hydrogen, and growing renewable energy capacity could be leveraged to make the United States a major hydrogen supplier.

Yet, the U.S. strategy does encompass building manufacturing capacity and ensuring secure supply chains that would complement ongoing technology research and innovation. Building on the U.S. Department of Energy Hydrogen Program Plan (2020), which establishes a framework to encourage hydrogen technology R&D, the Department of Energy announced the Hydrogen Energy Earthshot in June 2021 to reduce the cost of clean hydrogen by 80 percent by 2030 and significantly expand domestic demand for clean hydrogen.[70] Electrolysis technologies are among the focuses of research, development, and deployment for the United States.[71] Moreover, the United States is beginning to focus on manufacturing competition associated with clean hydrogen development. For example, the Biden administration issued an in-depth study on supply chains for fuel cells and electrolyzers in February 2022 to illuminate the state of technology competition as well as the strategic value of being competitive in this sector.[72]

U.S. policymakers have several key considerations in light of the rising clean hydrogen interest in the Indo-Pacific region:

- **Ensure resilience and robustness in clean hydrogen supply chains.** The United States needs to ensure that the emerging clean hydrogen sector is resilient against supply chain disruptions. Hydrogen supply chains entail technologies to produce, transport, and consume hydrogen, as well as the capacity to manufacture related equipment and components. The security of supply chains for clean hydrogen is essential if the United States is to attain the triple benefit of decarbonization, energy security, and industrial competitiveness from creating a clean hydrogen market at home. It is also essential for U.S. regional partners if hydrogen is to meet its decarbonization potential in the Indo-Pacific region. The United States should work with likeminded countries to create regional clean hydrogen supply chains that have diverse participants and are therefore resilient to geopolitical tensions.
- **Recognize the energy security benefit of clean hydrogen exports from the United States.** Some of the Asian importing countries are concerned whether global hydrogen supply capacity will grow quickly enough to meet their anticipated demand. This concern may lead to growing calls for the United States to play a role as a clean hydrogen supplier to help enhance regional energy security, as it has done with LNG. Although clean hydrogen development is at its very early stages in the United States, this concern among some of the key Asian importer countries merits attention if the United States seeks to promote the use of clean hydrogen as a decarbonization tool in the region.
- **Encourage the environmental sustainability in hydrogen value-chain creation.** The U.S. approach to hydrogen development, as per the Infrastructure Investment and Jobs Act, is a technology neutral one with a stringent carbon intensity requirement. The approach is similar to those of advanced industrialized Asian economies as well as most of the prospective hydrogen suppliers to the region that were examined in the report. Because some Southeast Asian countries may seek to emerge as hydrogen suppliers without requisite capacities to abate carbon emissions during the production process, U.S. energy engagement in the Indo-Pacific region should explore ways to speed up capacity development in producing and supplying clean hydrogen.

Appendix 1

Asian Country Analysis

Japan

Japan sees the development of a hydrogen as a major way to decarbonize its economy while sustaining its industrial competitiveness.[73] By issuing the Basic Hydrogen Strategy in 2017, Japan became the first country to adopt a national hydrogen framework. In December 2020, Japan released the Green Growth Strategy Through Achieving Carbon Neutrality in 2050 (the "Green Growth Strategy"), which features hydrogen among 14 key sectors that will help Japan achieve the dual goals of decarbonization and economic growth.[74] The Green Growth Strategy seeks to yield economic benefits in the order of $1.4 trillion in 2030 and $2.9 trillion in 2050 ($1=JPY 100). The Japanese government doubled down on hydrogen with a June 2021 update to the Green Growth Strategy that adds specific action plans to priority sectors.[75]

The country's refining industry accounts for about 90 percent of Japan's hydrogen consumption of 2 Mt/yr in 2020; about half the supply is met with natural gas-based hydrogen, 45 percent is by-product hydrogen from refineries and the petrochemical industry, and the rest comes from coal-based production.[76] Japan is focused on expanding its hydrogen market from 2 Mt/yr today to 3 Mt/yr by 2030 and 20 Mt/yr by 2050; through scale, the country seeks to drive down the cost of hydrogen from about $1 per cubic meter in 2017 to $0.30 by 2030 and about or below $0.20 by 2050.[77]

While Japan sees reliance on hydrocarbons as inevitable for hydrogen production in the near term, the country seeks in the long term to shift the source of hydrogen and fuel cells from fossil fuels such as natural gas to renewable energy. Domestic renewables are notably among the potential hydrogen sources of interest to the Japanese government, but this may largely be aspirational since Japan has comparatively limited potential for renewable energy production. With a commercial nuclear power fleet of over 30 reactors, as well as multi-decadal experiences in operating them, nuclear energy is a viable option for hydrogen production for Japan. Nuclear energy can be used to make hydrogen electrolytically, and in the future, high-temperature nuclear reactors could be used to make hydrogen thermochemically. Some research and commercial initiatives are underway. In Fukui prefecture, the local utility and the city of Fukui are cooperating to demonstrate the use of surplus nuclear power supply for electrolysis to produce and supply hydrogen to local hydrogen refueling stations (HRSs).[78] Also, there is a plan to use the heat from the Japan Atomic Energy Agency's high-temperature test reactor to produce hydrogen from 2030.[79]

Per the sixth Strategic Energy Plan, adopted in the fall of 2021, hydrogen and ammonia will need to make up 1 percent of both the primary energy mix and the electricity supply mix in 2030 to achieve the country's Nationally Determined Contribution of a 46 percent reduction in greenhouse gas emissions against 2013 levels.[80] As the national government under the leadership of Prime Minister Kishida Fumio (in office since October 2021) formulates the Clean Energy Strategy, targeted for summer 2022 release, hydrogen will likely remain a priority. The Clean Energy Strategy seeks to "lay down viable paths for various types of suppliers and consumers to pursue carbon neutrality" while generating business opportunities and minimizing additional economic burden on Japanese society.[81]

Japan is the forerunner in promoting hydrogen applications in passenger vehicles. As a major investor in the development and deployment of fuel cell vehicles (FCVs), Japan seeks to gain industrial competitiveness from expanding FCV adoption at home and around the world. For example, Japan leads the world in fuel cell research, holding 36 percent of all patents, positioning the country to be an attractive partner technologically even though it is unlikely to become a hydrogen supplier or the biggest FCV market.[82] The mobility targets under the revised Strategic Roadmap for Hydrogen and Fuel Cells (March 2019) are 200,000 FCVs by 2025 and 800,000 by 2030, as well as 320 HRSs by 2025 and 1,000 by 2030. The government has identified fuel cell trucks as an area of export interest.[83]

Another application for hydrogen is its use in the form of ammonia for electricity generation. Japan is investing in the development and commercialization of technology to co-combust ammonia with fossil fuels. The Japanese government views ammonia co-combustion as a means to reduce carbon emissions from the electricity sector as well as an area where the country's leading manufacturers of equipment such as boilers could emerge as major global exporters, particularly to regional markets in Asia whose coal-fired power plants are relatively young.[84]

Another venue where Japan sees a potential synergy between decarbonization and industrial competitiveness is the maritime transport of hydrogen. Experiences and technologies such as liquefaction, storage and shipping that Japanese companies have gained from the LNG business could be leveraged to advance technologies for the hydrogen trade.[85]

Additionally, Japan is beginning to focus on hydrogen use in industrial sectors where emission reductions are more difficult than in the transportation or power generation sectors. The Kishida government, with input from private sector experts and advisers, has begun examining how best to help the nation's industrial sector stay competitive and create greater economic value out of hydrogen applications in the harder-to-abate steel, chemical, pulp and paper, and cement industries.

The national government has also issued several strategic documents covering technological and economic aspects, such as the Strategic Roadmap for Hydrogen and Fuel Cells (2014, 2016, and 2019), the Green Growth Strategy, and the Clean Energy Strategy, which is under development. Japan's hydrogen development action plans are organized around the development of basic technologies to reduce hydrogen production costs, improve access to inexpensive energy resources for hydrogen production overseas, and conduct surveys and analytical work on resource and supply chain economics at home and around the world.[86]

These strategies and plans are executed through a combination of strong public financial support, active resource diplomacy by the national government, and effective public-private partnerships.

The Japanese government provides robust funding for research development, demonstration, and deployment. Most notably, hydrogen is one of the 14 areas that qualify for the government's JPY 2 trillion ($18 billion), 10-year grant program, the Green Innovation Fund (GIF), which is one of the key tools for implementing the Green Growth Strategy. Japan's national R&D agency, New Energy and Industrial Technology Development (NEDO), administers GIF grant-making. A few of the projects for GIF grant consideration concern the production, transportation, or application of hydrogen. Most notably, the first award under the GIF in August 2021 went to 11 recipients involved in two categories of hydrogen projects, one of which focuses on large-scale hydrogen supply chain development (worth $2.3 billion) and another of which focuses on an electrolysis demonstration ($535 million).

NEDO is also active in hydrogen research and innovation. While Japan is currently focused on fossil fuel-based hydrogen supply chains, the country is also aiming to establish a manufacturing technology base by 2030 to produce hydrogen from domestic renewable sources. As such, NEDO seems to be instrumental in advancing electrolysis research and innovation, an area where the Japanese government believes national expertise is particularly lagging.[87] For example, NEDO is leading projects to demonstrate alkaline electrolysis technology in the Fukushima prefecture and proton exchange membrane electrolysis technology in the Yamanashi prefecture. The project in Fukushima is part of the Fukushima Hydrogen Energy Research Field (FH2R), which opened in March 2020. The FH2R uses solar power generation (20 MW capacity) and electricity from the grid to electrolyze water in a 10 MW-class hydrogen production unit and hosts various tests to identify the optimal operation control technologies that combine power grid demand response with hydrogen supply and demand response.

Another key public sector player is the Japan Bank for International Cooperation (JBIC). The country's official export credit agency has been carrying out Japan's hydrogen industrial strategy, especially in developing hydrogen supply chains with international partners. For example, the JBIC has signed a $2.1 billion facility agreement as well as a cooperation agreement with the UAE to strengthen bilateral energy ties, including to promote projects that can lead to hydrogen and ammonia supply chains. The JBIC announcement stresses Abu Dhabi's track record of being "a stable and important supply source of crude oil to Japan for more than 40 years" and its importance for Japan's energy resource strategy, illuminating Japan's desire that this tie extends to the emerging bilateral trade in hydrogen.[88]

Russia is another partner to the JBIC's strategic energy cooperation involving hydrogen and ammonia. Specifically, the JBIC and Novatek of Russia signed an agreement in September 2021 to promote decarbonization in Russia while also helping to strengthen Japan's access to energy resources through the "exchange of information and opinions" on hydrogen; ammonia; carbon capture, utilization, and storage (CCUS); and renewable energy.[89] The deterioration of Japan-Russia ties following Russia's invasion of Ukraine is a major variable affecting the future of Japan's hydrogen engagement with Russia.

The government's political and financial investments are matched by private sector commitments. Toyota has been instrumental in the development and deployment of FCVs as well as the rollout of HRSs in Japan. Japan has the largest fleet of HRSs in the world, having finished over 150 stations across the nation since rollout began in 2013.[90] The Japanese government provides financial support for their construction and operation, but costs remain high. In order to facilitate HRS expansion and to ensure their effective operation, eleven companies, including automakers, infrastructure developers, and investors, joined forces under Japan H2 Mobility, led by the Toyota Motor Company.

As for applications for hydrogen in the power sector, Japan's leading electricity generators and industrial equipment manufacturers—such as JERA, J-Power, Mitsubishi Heavy Industries, and IHI Corporation—are working to advance ammonia blending and combustion to reduce the carbon footprint of the power sector.

The development of international hydrogen supply chains is a major agenda, and Japan's leading engineering, manufacturing, and energy companies as well as trading houses are undertaking several anchoring projects around the world, including in Australia, Brunei, Saudi Arabia, Singapore, and the UAE.

Australia to date is the most active ground for Japanese corporate participation, with over a dozen Japanese companies engaged in hydrogen projects, especially in clean hydrogen production and storage. For example, the CO_2-free Hydrogen Energy Supply-chain Technology Research Association (HySTRA; comprised of Iwatani, Shell Japan, J-Power, Marubeni, ENEOS, Kawasaki Heavy Industries, and K Line) has run a $364 million demonstration project at the Latrobe Valley in Victoria to gasify brown coal, capture and store emitted carbon, liquefy and store hydrogen, and ship it to Japan. Kawasaki Heavy Industries Ltd. has played a pivotal role in this endeavor and in the future of maritime hydrogen trading by launching the world's first liquefied hydrogen vessel in 2019 and completing the world's first liquefied hydrogen shipment from Australia to Japan in February 2022.[91]

In Brunei, the Advanced Hydrogen Energy Chain Association for Technology Development (AHEAD; comprised of Chiyoda, Mitsubishi, Mitsui, and NYK Line) has undertaken a project to supply hydrogen from Brunei to Japan, while Inpex, JERA, Idemitsu, Itochu, and Mitsui have entered into a variety of hydrogen-related business relationships in the UAE.

South Korea

South Korea is pursuing hydrogen for economic growth and industrial competitiveness as well as for decarbonization.[92] The national government sees hydrogen as a potential driver of economic growth worth KRW 43 trillion ($34 billion).[93] Hydrogen is one of the key sectors that underpin the Korean Green New Deal, announced in 2020, which plans to invest KRW 73 trillion ($58 billion) to create almost 660,000 jobs by 2025.[94]

Hydrogen consumption in South Korea was about 1.8 Mt in 2020, and almost all demand came from the refining and petrochemical sectors, leaving demand from other hydrogen applications (e.g., FCVs) at 130,000 tons annually.[95] South Korea has a robust goal of increasing the annual consumption of such non-refinery applications to 1.94 Mt in 2030 and 5.26 Mt in 2040.[96] Moreover, the national government aims to power 10 percent of the country's cities, counties, and towns with hydrogen by 2030.[97]

As South Korea seeks to build out supply bases to meet its anticipated demand growth, the development of hydrogen-receiving infrastructure is set to begin in 2022. South Korea's efforts also include R&D on liquefied hydrogen storage technology and the reduction of transportation costs. Additionally, the roadmap notes the government's long-term aim of building a specialized hydrogen pipeline network across the country.

The government is also focusing on non-hydrocarbon-based hydrogen supplies. In fact, while about one-third of the country's hydrogen consumption in 2040 is estimated to be based on LNG, Kogas plans to invest $37 billion overseas by 2040 to establish renewable power generation facilities that produce hydrogen.[98]

Also, large-scale electrolysis R&D and demonstration of renewable-based hydrogen production are due to begin by 2022.[99] Additionally, the administration of Yoon Suk Yeol (in office since May 2022) could add nuclear energy to a menu of sources for clean hydrogen production in South Korea. Then-candidate Yoon called for nuclear energy to account for 30 percent of South Korea's total energy generation, seeking to reverse his predecessor's nuclear phase-out plans.[100]

South Korea has emerged as a leading force in the global FCV market. In 2020, the country led the world in FCV installation, with over 10,000 FCVs on the road, doubling the national stock from 2019.[101] The South Korean government set a 2025 FCV target of 200,000 units and a 2040 FCV target of nearly 3 million units, including 30,000 fuel cell trucks and 40,000 fuel cell buses.[102]

FCV rollout and South Korea's 2040 vision necessitate HRS buildout. The Hydrogen Energy Network was established in 2019 with an initial investment of $119 million to expand the fleet from about two dozen HRSs in 2019 to 310 by 2022 and 1,200 by 2040.[103]

South Korea's hydrogen vision is outlined in the Hydrogen Economy Roadmap, released in 2019.[104] The roadmap provides guidelines and key deployment targets for the development of hydrogen at home. The most significant step, however, was the passage by the Korean National Assembly of the Hydrogen Economy Promotion and Hydrogen Safety Management Law ("Hydrogen Law") in January 2020. The Hydrogen Law, which went into effect in 2021, laid the legal foundations for the implementation of safety standards for facilities as well as the government's promotion of hydrogen—essentially to realize the roadmap. The Hydrogen Law seeks to promote hydrogen by fostering and supporting hydrogen-specialized businesses, installing hydrogen fuel supply facilities (e.g., HRSs), and designating dedicated agencies for a hydrogen economy.[105]

The plans to realize South Korea's hydrogen vision are carried out by several entities that were designed by the South Korean government in accordance with the Hydrogen Law. The Hydrogen Convergence Alliance (H2Korea) plays an instrumental role in promoting and developing the hydrogen industry in South Korea. Established by the South Korean government in 2017, H2Korea has four categories of remit: policy support, infrastructure build-out, technology development, and business coordination.[106] Meanwhile, the Korea Gas Corporation (Kogas), a state-run utility, is tasked with hydrogen distribution, and the Korea Gas Safety Corporation is in charge of hydrogen safety issues.[107]

Large government funding underpins South Korea's effort to develop a hydrogen economy. Public spending for FY 2021 was $702 million, a 40 percent increase from FY 2020.[108] Also, the government has committed $2.3 billion to establish a public-private hydrogen vehicle industry by 2022.[109] At present, about half the cost of installing HRSs is subsidized by the government. Moreover, the national and local governments provided subsidies for an FCV purchase ranging from $27,300 to $30,300 in 2019.

Public support has also taken the form of regulatory measures. Since 2012, South Korea's renewable portfolio standard (RPS) has supported the deployment of large-scale stationary fuel cell power generation. Under the RPS, large power producers are mandated to meet a minimum portion of their power generation from new and renewable technologies, including fuel cell power generation. Additionally, the government has reduced the price of natural gas from the grid if it is used to produce fuel cells.[110]

Large South Korean business entities are key partners to the South Korean government. According to South Korea's economic ministry, five South Korean conglomerates have plans to invest $38 billion in hydrogen technology by 2030.[111] For example, Hyundai Motors Group alone has investment plans of $6.7 billion to meet its FCV vision for 2030.[112] Beyond Hyundai Motor's pivotal leadership in hydrogen applications in the passenger vehicle market, other Hyundai Group companies, POSCO Group, SK Group, and Hanwha Group are some major South Korean industrial participants in the emerging industry space for hydrogen and fuel cells.

As it aims to power 10 percent of its cities with hydrogen, the national government chose the cities Ansan, Ulsan, and Wanju as pilot cities in 2019 to test the application of hydrogen in transportation, industry, and space heating.[113] The city of Ansan is a leading industrial city, while the city of Ulsan is home to a large petrochemical complex. When completed, the 4.7-square-kilometer Ulsan hydrogen hub will consist of three main areas: a hydrogen industry base district focused on producing hydrogen fuel cells; an electrogene auto factory for manufacturing FCEV parts and supplies; and an R&D business center.[114]

In terms of developing supply chains beyond its national borders, South Korea is reportedly exploring various projects with prospective hydrogen resource suppliers. For example, the Hyundai OilBank Company plans to take liquefied petroleum gas (LPG) cargoes from Saudi Aramco, convert the LPG into hydrogen, and ship the CO_2 that was emitted in the process back to Saudi Arabia.[115]

Also, several of South Korea's major shipbuilding companies, such as Hyundai Heavy Industries, have begun developing hydrogen-powered vessels to ship hydrogen.[116] These endeavors seem to speak to South Korea's existing strength in shipbuilding and its interest in decarbonization while helping to develop the country's future maritime hydrogen import capability. Additionally, POSCO—South Korea's largest steel-maker—is pursuing the development of green steel and steel component manufacturing with a few Australian companies, including BHP and the Fortescue Metals Group.[117]

China

China is increasingly cultivating the production and consumption of lower-emission hydrogen to help meet its energy needs and spur industrial development while also decarbonizing its economy.[118] In particular, China's 2060 carbon neutrality commitment in 2020 is a major policy-oriented development that could aid the shift in hydrogen production away from fossil fuels to renewables, greater deployment of FCVs, and the use of hydrogen in harder-to-abate sectors.

China is the largest global producer of hydrogen today, at about 33 Mt/yr.[119] Most of the volume is produced from fossil fuels (60 percent from coal and 25 percent from natural gas) as feedstocks in refineries or chemical facilities.[120] Hydrogen demand outlooks suggest strong growth. The China

Hydrogen Alliance, a government-supported industry group launched in 2018, forecasts China's hydrogen demand to reach 60 Mt/yr in 2050.[121]

China's interest in hydrogen began with its use in the transportation sector in the early 2000s as policymakers saw the growing auto sector and the attendant rise in fuel imports as a source of strategic vulnerability and an aggravator to air pollution in cities.[122] Made in China 2025—a 10-year industrial plan released in 2015 to upgrade China's manufacturing industry—included hydrogen as a key technology in the new energy vehicle (NEVs) sector.[123] At the end of 2020, there were 8,400 FCVs deployed in China, making the country the third-largest FCV market and the largest for fuel cell trucks and buses in the world.[124]

China's FCV sector may lack the track record or momentum that has been present in its battery electric vehicle market, but it still is on a growth trajectory.[125] The country's FCV fleet is set to reach 50,000 units in 2025 and 1 million units in 2035.[126] Also, over the next decade and a half, the number of HRSs is expected to grow from 72 units as of mid-2020 to 2,000 units by 2035, according to the New Energy Vehicle Industrial Development Plan for 2021 to 2035, released in 2020.[127]

Additionally, hydrogen use in harder-to-abate sectors is on the horizon. China's key steel producers, including Baowu subsidiary Baosteel, Hebei Iron and Steel, and Xingtai Iron and Steel, are set to begin building their first hydrogen furnaces (which heat a steel blast furnace using hydrogen, instead of methane), which are expected to come online between 2022 and 2024.[128] For China's Baowu, the world's largest steel producer by tonnage, hydrogen is a key tool for its plans to reduce the carbon intensity of its operation by 30 percent by 2035 and achieve carbon neutrality by 2050.[129] In the chemical sector, the Ningxia Baofeng Energy Group, which makes coal-based chemical products, started building a pilot project on solar power-based hydrogen production in Ningxia Province.[130]

The cost of hydrogen production from coal remains very low in China: producing coal-based hydrogen costs roughly half as much as renewable-based hydrogen.[131] The cost disadvantage has hampered green hydrogen development, which currently accounts for 1.5 percent of the total national hydrogen supply.[132] The central government appears increasingly focused on the prospect for green hydrogen development, however, illuminating a potential combination of energy storage and hydrogen technologies in the context of expanding renewable energy supplies.[133]

Home to the largest installed renewable power generation capacity in the world today, China plans to double its solar and wind generation capacity from nearly 600 GW in 2020 to 1,200 GW by 2030.[134] Strong expansion of renewable capacity would be a major enabler for growth in green hydrogen production. The China Hydrogen Alliance has forecast the country's green hydrogen production to reach 100 Mt/yr by 2060, or 20 percent of the country's final energy consumption.[135]

Chinese companies have begun investing in and manufacturing electrolyzers. As of 2020, China accounted for 8 percent of the global stock of 290 MW electrolyzers and 35 percent of the global manufacturing capacity of electrolyzer equipment and components.[136] China is fast emerging as a major home to installed electrolysis capacity. In 2022, Chinese capacity is expected to be five times greater than 2021, accounting for more than 60 percent of the global total.[137] Chinese companies are seeking to build out electrolyzer manufacturing capacity to 1.5–2.5 GW in 2022 in order to meet growing orders from both domestic and overseas customers.[138] The China Hydrogen Alliance is calling for 100 GW electrolyzer capacity by 2030 to produce green hydrogen.[139]

However, according to the Chinese government's hydrogen plan through 2035, annual green hydrogen production is expected to reach 100,000 to 200,000 tons by 2025.[140] The 2025 target is notably modest against the backdrop of the strong industry outlook.

The modest green hydrogen "target" for 2025 could reflect the uncertainty about whether renewables expansion will keep pace with the demand growth for both electricity generation and hydrogen production, at least in the near term. More importantly, the modest target may reveal how China's existing expertise, technologies, and infrastructure in hydrogen production has limited relevance to clean hydrogen production.[141] For example, China's current competitiveness lies with alkaline electrolysis technology, which is well established and cheap but much less compatible with intermittent renewable energy sources than polymer electrolyte membrane (PEM) electrolyzers. PEM electrolyzers account for less than 10 percent of the Chinese market, which is otherwise dominated by alkaline electrolyzers.[142] PEM electrolyzers are more expensive and technologically advanced, and Europe is leading the world in PEM innovation and manufacturing today. As China becomes increasingly focused on PEM electrolyzers, how global innovation and manufacturing competition shape up over green hydrogen technologies warrants close attention.

Hydrogen emerged in prominence following its mention in China's 14th Five-Year Plan (2021–2025) as a "frontier" area and one of the six industries for focused advancement.[143] In March, the Chinese government released China's first-ever long-term hydrogen plan (2021–2035), which emphasizes the country's desire to improve its innovation capability and master core technologies and manufacturing processes by 2025.[144] A more comprehensive strategy to develop a hydrogen industry may take a few more years.[145]

Nevertheless, many subnational governments and central government authorities—such as the National Energy Administration, Ministry of Industry and Information Technology, Ministry of Finance, and Ministry of Science and Technology—have published policies to support the development of the hydrogen economy, including hydrogen production, storage, and transportation and standards development for FCVs.[146]

The Chinese government has been a key spender on hydrogen development, including R&D. Toward the end of the 13th Five-Year Plan (2016–2020), China's hydrogen technology R&D spending increased sixfold, to a little over $600 million in 2019.[147] Also, the statewide subsidy program is available to support the development of fuel cell batteries.[148]

Moreover, a number of investment funds have been set up for the development and application of hydrogen, including the Shanxi Hydrogen Energy Industrial Fund, set up in 2021.[149] Participants in these funds have included state-owned enterprises (SOEs), research institutions, universities, local governments, and commercial entities. While less common, hydrogen projects have also received bank loans, bonds, and equity investments.[150] Lastly, while Europe leads in hydrogen start-ups, China is emerging as a source of hydrogen technology start-ups and venture capital for scale-up.[151]

Public spending support has focused on NEVs. For example, the national government has provided tax reduction and subsidies for FCVs, ranging from RMB 20,000 to RMB 50,000 (about $3,200 to $7,900), depending on the type of vehicle and the capacity of fuel cells.[152] Notably, NEV support is beginning to shift away from direct subsidies, which are being phased out between 2020 and 2022 at an annual rate of 10 percent and are scheduled to be withdrawn altogether by the end of 2022.[153] Instead of direct subsidies, public financial support will take the form of tax exemptions (e.g., no vehicle purchase tax), charging subsidies, parking incentives, and incentives for R&D investment from SOEs.[154] Additionally, under the Accelerating the Development and Commercialization of Fuel Cell Vehicles in China program, administered by the United Nations Development Programme (in close collaboration with China's Ministry of Science and Technology and with funding from the Global Environment Facility), seven Chinese cities have invested $365 million since 2017, far exceeding the initial budget of $62 million.[155]

SOEs are emerging as a key driving force. According to China's State-Owned Assets Supervision and Administration Commission, over one-third of SOEs are making plans for hydrogen production, storage, distribution, and utilization.[156] For example, Sinopec—one of China's top national oil companies—has built 31 HRSs in 17 provinces and cities.[157] It is also active in green hydrogen development. Sinopec is pursuing a goal of becoming the largest national hydrogen producer, with initial planned investments of about $4.6 billion in the next five years, covering projects such as a photovoltaic hydrogen production project in Xinjiang, a wind and optical power hydrogen plant in Inner Mongolia, and offshore wind power hydrogen production in Fujian Province.[158] Also, the State Power Investment Corporation—the largest renewable asset owner in the world—is not only involved in the HRS business but is also aiming to build 10 GW of electrolyzer manufacturing capacity by 2027.[159] While non-SOEs are present in the hydrogen sector, they appear to be limiting their activities to electrolyzer development for now.[160]

Subnational governments have been another set of active players in China's hydrogen development. Notwithstanding the absence of a comprehensive national hydrogen strategy, by April 2021, 23 of China's provinces and municipalities had identified hydrogen as a key economic priority or formulated hydrogen development plans, including in their own five-year plans.[161] Plans by Beijing and Jiangsu Province include accelerating the planning and construction of HRSs, while Zhejiang Province aims to use hydrogen in combined power and heating, use FCVs in public and port logistics transportation, and combine hydrogen production with offshore wind capacity.[162]

The growing number of hydrogen projects span the geography of the country. For example, in the coastal province of Shandong, which is among the richest provinces, hydrogen is expected to play a key role in energy supply and economic development. Sinopec has built a large fuel cell supply demonstration project in the province, with a total investment of $7.4 million.[163] Another example is Inner Mongolia, where the provincial energy planning ministry intends to develop seven wind and solar power projects in the cities of Ordos and Baotou that could produce nearly 67,000 tons of low-carbon hydrogen a year. As the second-largest coal producing province in China, Inner Mongolia has also become the leading province in renewable power.

Inner Mongolia targets 100,000 tons a year of green hydrogen capacity by 2023, including 60 HRSs and over 3,800 FCVs operating in the mining, logistics, and public transportation sectors.[164] Furthermore, under the four-year program to advance hydrogen technology research and supply chain development, the national government has selected the Beijing-Tianjin-Hebei cluster, Guangdong and Henan Provinces, and Shanghai for demonstration projects where local governments that satisfy specific targets will be awarded up to RMB 1.7 billion ($269 million) as a fiscal bonus.[165] How these numerous, un-coordinated subnational undertakings could evolve under a more decisive national leadership would warrant close attention.

India

India is another Asian country with significant potential for clean hydrogen production and use. The sixth-largest economy in the world, India currently consumes about 7 Mt/yr of hydrogen, and its demand might see a four-fold rise to 28 Mt/yr by 2050.[166] India's hydrogen demand comes mostly from refining (45 percent) and chemicals (35 percent).[167] At present, most hydrogen consumption is met through the domestic production of fossil fuels, especially natural gas (about 75 percent) and coal (over 15 percent) in 2020.[168]

Hydrogen seems to have a strong appeal to India from an energy security perspective. During his speech commemorating India's independence day in 2021, Prime Minister Narendra Modi announced the National Hydrogen Mission (NHM):

> The National Hydrogen Mission and the green hydrogen sector will give us a quantum jump in meeting our climate targets. We have to make India a green hydrogen hub, and this will also lead to a clean energy transition . . . India is not energy independent. It spends over Rs 12 lakh crore on importing energy. We need to become energy independent before 100 years of independence is completed (i.e., by 2047).[169]

First suggested by Prime Minister Modi at a renewable investment conference in the winter of 2020, the NHM is closely tied to the country's ambition to expand the role of renewables in the country's energy supply. While decarbonization is a key benefit of green hydrogen use, India's pursuit of hydrogen is another means to expand renewable energy that could help alleviate India's heavy projected dependence on energy imports. According to the IEA's baseline scenario, India's combined expenditure for fossil fuel imports will triple over the next two decades as the country's net dependence on imported oil rises from 75 percent today to over 90 percent by 2040.[170] Modi's emphasis on hydrogen as a valuable avenue for becoming "self-reliant" in energy reflects how energy security is at the core of the country's interest in hydrogen.[171]

India has 89.6 GW of installed renewable energy capacity (not including hydropower), with another 49.6 GW being installed and an additional 27.4 GW tendered as of today.[172] At COP26 in November 2021, Prime Minister Modi announced India's goals of meeting half of its energy requirement from non-fossil fuel sources and building 500 GW of installed clean electricity capacity by 2030.[173] The government sees expanding renewable capacity as underpinning its green hydrogen production capacity. By 2050, India aims to meet about 75 to 80 percent of its hydrogen needs from domestic renewable resources.[174] Whether and how India achieves its highly ambitious renewable goals is an important question, not only for the pace of its decarbonization but also for the development of its clean hydrogen sector.

Initial areas of focus under the National Hydrogen Energy Roadmap of 2006, launched by the Ministry of New and Renewable Energy, included the use of hydrogen in the domestic transport and electricity generation sectors.[175] The focus has since expanded to include production and export. Today, India seeks to leverage its landmass, as well as low solar and wind tariffs, to produce low-cost green hydrogen and ammonia for export to Japan, South Korea, and Europe.[176] According to the National Hydrogen Policy, released on February 17, 2022, India plans to produce a cumulative 5 Mt/yr of green hydrogen by 2030 in an effort to become a production and export hub for green hydrogen.[177]

Commercial investments are underway. The Indian government has begun encouraging R&D on hydrogen-related technologies as well as the creation of a hydrogen market through public spending and the participation of state-owned energy companies. In April 2021, the Indian government announced plans to spend $200 million over the next five to seven years and asked state-owned energy companies to commission seven pilot hydrogen production plants before the end of FY 2021.[178]

In an effort to realize the country's hydrogen vision, state-owned Indian Oil Corporation announced plans in July 2021 to construct a green hydrogen production facility at its Mathura refinery, expanding its ongoing hydrogen projects beyond R&D of hydrogen production, storage, and applications.[179] Also, GAIL Limited, a government-owned natural gas corporation, has floated a tender to procure electrolyzer, while state-run NTPC has begun exploring green hydrogen production on a commercial scale in Gujarat.[180]

India's effort to develop a clean hydrogen industry is not limited to the state-owned segment of the industry. Low-carbon hydrogen production may gain additional momentum from the private sector, such as Reliance Industries Ltd., which has begun investing in clean energy projects as the company seeks to meet its net-zero commitment by 2035. In January 2022, Reliance Industries Ltd. announced its plans to invest $79 billion for clean energy projects, including a 100 GW renewable energy power plant, and to produce blue hydrogen at about $1.2–1.5 per kilogram, likely at its Jamnagar complex in Gujarat.[181]

There are a few other Indian and non-Indian companies that are involved in hydrogen production, storage, and delivery in India. For example, in March 2021, Indian engineering services company BGR Systems and Ireland-based green hydrogen technology company Fusion Fuel Green announced a partnership for the development of green hydrogen production projects in India.[182] American companies that are looking to become part of India's hydrogen value chains include Praxair, Inox, Air Products, Fuel Cell Energy, and H2Scan.[183]

In the latest development, the first part of the national hydrogen policy was announced on February 17, 2022. According to the policy, the Indian government will incentivize clean hydrogen production by setting up manufacturing zones, waiving interstate electricity transmission charges for 25 years, providing green hydrogen and ammonia producers with priority connectivity to electric grids, and allowing green hydrogen manufacturers to set up bunkers near ports for storage for exports.[184] Additional incentives, to be announced at a later date, will likely include federal financial support to set up electrolyzer manufacturing, as the country wants to mandate refineries and fertilizer plants to use green hydrogen.[185] The initial thinking by India's power ministry is to require the use of 10 percent hydrogen and raise the share to 20 to 25 percent in three to four years.[186]

Southeast Asia

Generally, hydrogen development in Southeast Asia has been more limited than in the other countries in Asia discussed in this report. Energy access (both quantitatively, such as population and geographic coverage, and qualitatively, such as stability and duration of power provision) remains a key priority for regional policymakers. The production, transportation, and consumption of clean hydrogen requires substantial initial capital expenditure.[187] As such, political support for launching major hydrogen industrial strategies or providing significant public funding toward clean hydrogen production and applications remains limited in the region.

The regional approach to developing a clean hydrogen economy will likely be incremental and vary based on the diversity of resources and capacity-building requirements across regional economies. The ASEAN Centre for Energy, under the ASEAN Secretariat, has detailed how the roadmap for hydrogen development may look:[188]

> **2020–2025:** Countries with advantages in fossil fuel resources and existing infrastructure, such as gas pipelines and LNG liquefaction plants, could consider developing capacities in producing and exporting hydrogen generated from natural gas or methane through steam reforming (called "gray hydrogen," the most common form today).
>
> **2026–2030:** After the capacity and infrastructure are built for gray hydrogen production, shift to blue hydrogen production and exports with the help of carbon capture and storage (CCS), or CCS-plus utilization (CCUS) if enhanced oil recovery (EOR) opportunities exist.
>
> **After 2030:** After the cost of renewable-based electricity significantly declines and the share of renewable power generation has reached high levels in the ASEAN member states, hydrogen from electrolysis could be deployed as energy storage for intermittent renewables and also provide auxiliary grid services such as balancing loads and peak generation. Green hydrogen begins to dominate the scene and be used both for domestic downstream energy applications and for export to overseas markets.

Hydrogen production from renewable energy sources will remain challenging due to the fragmented state of electricity networks in the region as well as the limited affordability of and access to such technologies.[189] Under the second phase of the ASEAN Plan of Action for Energy Cooperation 2021–2025, ASEAN governments have announced goals of increasing the share of renewables in terms of primary energy from about 14 percent in 2019 to 23 percent of in 2025 and in terms of installed power capacity from about 28.7 percent in 2019 to 35 percent by 2025.[190] The region's 72 GW renewable capacity might require an additional 35 to 40 GW to meet the 2025 goals.[191]

Tough some regional governments lack major strategic documents, there is emerging interest and inquiries in hydrogen.

SINGAPORE

The government of Singapore seems to be carefully exploring opportunities for the country to emerge as a future hub for the regional and global hydrogen trade. This includes preserving its current preeminence as an oil and gas trading hub while expanding its share in the evolving value chains associated with the energy transition. Also, the city-state government is very interested in and supportive of hydrogen development in Southeast Asia, as such development supports its plan for Singapore's businesses to tap into sustainability opportunities in the region.[192]

A few developments warrant attention. In October 2019, the government announced that the country will harness "4 Switches" to guide and transform Singapore's energy supply, consisting of emerging low-carbon alternatives—namely hydrogen and CCUS—alongside natural gas, solar, and regional power grids.[193] This was followed by the launch of its Green Plan 2030 in February 2021, which further elevated low-carbon energy, including hydrogen. [194] The Green Plan 2030 is a "whole-of-nation movement" to transform the country into a "glowing global city of sustainability." The plan stipulates various near- and long-term sustainability targets that include energy targets, such as a five-fold increase in solar power deployment to at least 2 GW in 2030 (equivalent of 3 percent of projected power demand), deployment of 200 MW of energy storage systems beyond 2025, and clean electricity imports to diversify the power supply mix.

As a urban city-state with a dense population, Singapore does not have the land to generate large volumes of renewable energy or renewable-based hydrogen. Instead, Singapore seems increasingly focused on the role that the country may play in hydrogen-related technical innovation value chains. The Research, Innovation and Enterprise 2025 Plan, announced by the Prime Minister's Office in December 2020, noted the government's decision to sustain investments in research and innovation activities at about 1 percent of GDP, or SGD $25 billion ($191 million) for 2021 to 2025.[195] Explaining the importance of using low-carbon hydrogen as part of the country's efforts to prepare for climate change, the plan also identified hydrogen and CCUS as key areas of R&D for government funding, with an eye toward developing capabilities and solutions to decarbonize the power system.[196] Moreover, the Singaporean government announced in June 2021 that it had undertaken a detailed feasibility study on hydrogen in 2020 and that its findings would inform its low-carbon research, development, and deployment efforts as well as guide private sector work to deploy low-carbon solutions and develop the hydrogen supply chain.[197]

Companies seem increasingly engaged in several projects to facilitate the use of hydrogen and ammonia in the maritime industry. For example, Singapore-based Keppel Offshore & Marine is working with several global companies to facilitate the use of renewable-based ammonia in bunkering.[198] The joint feasibility of green ammonia bunkering at the Port of Singapore entails the development of a cost-effective green ammonia supply chain and design of ammonia bunkering vessels and related infrastructure. Keppel O&M is also undertaking a floating energy project, Floating Living Lab, that is scheduled to feature engines that can run on hydrogen-blended natural gas.[199] Also, in July 2021, the country's sovereign wealth fund Temasek and Singapore-based Nanofilm Technologies announced a $140 million joint venture known as Sydrogen Energy, which leverages Nanofilm's core technologies to "develop new components and solutions to overcome existing limitations in enabling the use of hydrogen as an energy source."[200]

MALAYSIA

Malaysia is a hydrocarbon supplier in the region that is beginning to explore hydrogen production and use. Malaysia is starting to articulate its vision for a hydrogen economy, though it remains less detailed. The country's hydrogen interest stems from its concern over the future of oil and gas markets. Petronas, Malaysia's state-owned oil and gas company, sees "great potential" in hydrogen as an emerging alternative to oil and gas and targets its domestic hydrogen projects to begin operations from 2024, starting with blue hydrogen and followed by green hydrogen.[201]

Malaysia's Ministry of Environment and Water is reportedly in the process of preparing a Low Carbon Mobility Blueprint, which includes a long-term strategy for hydrogen development. The Malaysian Investment Development Authority has also proposed a three-phase plan to develop a hydrogen economy that prioritizes decarbonization of its chemical industry, followed by application in the transportation sector and in energy storage.[202]

Several clean hydrogen projects in Malaysia involve regional economies, such as Japan and South Korea. In October 2020, state-owned agency Sarawak Economic Development Corporation (SEDC), through its subsidiary, signed a memorandum of understanding with Japan's Sumitomo and ENEOS to develop green hydrogen supply networks. Petronas also seeks to partner with ENEOS to develop a clean hydrogen supply chain that includes hydrogen production and transportation between Malaysia and Japan.[203] Meanwhile, the SEDC subsidiary plans to work with South Korea's Samsung Engineering, POSCO, and Lotte Chemical to develop a green hydrogen and ammonia-focused Sarawak H2biscus Project in the town of Bintulu.[204] Indeed, Malaysia's clean hydrogen efforts seem to be centered in the state of Sarawak, which has significant hydropower resources as well as energy infrastructure, including a Pertronas LNG complex.

BRUNEI

Brunei is a regional supplier of natural gas and has taken part in a demonstration project with a group of Japanese companies to produce hydrogen from steam methane reform and convert it into methylcyclohexane at the Brunei Sungai Liang Industrial Park plant.[205] Having shipped the first batch to Japan in 2020, the project aims to supply 210 tons of hydrogen annually once completed.[206]

INDONESIA

Another hydrocarbon resource holder, Indonesia's government has begun exploring the economic and environmental value of a hydrogen economy. For example, Indonesia's state-owned Pertamina is considering using hydrogen to expand the role of renewables in the country's energy supply mix. It has a 2026 target of adding 10 GW of lower-emissions power sources, including 5 GW from renewable energy and 1 GW from other non-fossil fuel sources such as hydrogen.[207] Pertamina is also piloting a hydrogen plant with an annual capacity of 37 tons that is integrated with its geothermal plant in Lampung in Sumatra.[208] Internationally, the country recently announced a public-private bilateral agreement with Japan on hydrogen cooperation, ranging from the development and deployment of hydrogen and ammonia technologies to investment and joint projects to facilitate the creation of low-carbon hydrogen supply chains, including feasibility studies and demonstration projects.[209]

THAILAND

In Thailand's case, state-owned energy company PTT has established the Hydrogen Thailand Group in October 2020 to jump-start hydrogen development in Thailand as a means to reduce greenhouse gas emissions.[210] The county's regional partnerships include the March 2022 agreement between its Ministry of Energy and Japan's METI, which includes cooperation on "decarbonization technologies such as hydrogen" under the newly established Japan-Thailand Energy Policy Dialogue.[211]

Appendix 2

Prospective Supplier Country Analysis

Australia

As a country rich in energy resources in the Indo-Pacific region, Australia has shown a significant level of interest in developing a clean hydrogen economy and becoming a major supplier of clean hydrogen. Already among the largest exporters of LNG, coal, and uranium, primarily to Asian markets, Australia seeks to become one of the top three hydrogen exporters to Asia.[212] Essentially, the country's approach to hydrogen is about adapting its energy export profile to a new reality that is defined by the energy transition and growing interest in low-carbon energy imports in Asian markets.

The country sees additional economic benefits arising from developing a hydrogen economy. Hydrogen production is seen as an opportunity to diversify the economy, attract investment, provide jobs, and reinvigorate trading relationships, potentially reaching new markets. Nationally, the hydrogen sector is projected to add between AU$11–26 billion ($7.76–$18.3 billion) to GDP by 2050 and create between 7,600 and 17,000 jobs.[213]

The Australian government also seeks decarbonization benefits from clean hydrogen development. In fact, advancement in technologies such as hydrogen is at the core of Australia's climate action. Hydrogen is one of five priority low-emissions technologies that the government focuses on under the Technology Investment Roadmap, which is a broader industrial strategy document that also served as the basis for Australia's Long-term Emissions Reduction Plan.[214] Priority goals under the roadmap include reducing the cost of clean hydrogen below $2 per kilogram—referred to as "H2 under 2." Instead of announcing a more ambitious emissions reduction pledge for 2030 in the form of a revised Nationally Determined Contribution, Australia presented the Long-term Emissions Reduction Plan at COP26 in October 2021.[215] Additionally, the ongoing effort to develop a "guarantee of origin" system for the hydrogen sector reflects

Australia's desire to pursue a leadership role in creating an international clean hydrogen market.[216] The proposed international certification system would allow hydrogen suppliers to certify that hydrogen and its derivatives are produced from sustainable sources, by measuring and tracking emissions from the production process as well as the types of technology used in the process.

The Australian vision notably lacks the volumetric targets for production or export seen in visions by some other prospective exporter countries. Instead, Australia has adopted an "adaptative approach" to put themselves in a position to successfully scale up hydrogen initiatives as large-scale markets emerge.[217] Under the hydrogen strategy, the government undertakes various activities in two phases. The first phase, through 2025, focuses on creating, testing, and proving Australia's clean hydrogen supply chains (the "foundations and demonstration phase"). The subsequent phase, beyond 2025, focuses on actions to scale up the industry and activate markets (the "large-scale market activation phase"). This phase contains fewer concrete actions, such as the use of clean hydrogen for industrial feedstocks and long-distance heavy-duty transport and the blending of hydrogen into gas networks.

This approach would allow for some practical and needed adjustments to the Australian plans and measures in light of the uncertainty associated with the scale and pace of industry developments from new technology and changing market dynamics.[218] In particular, limited domestic energy demand and reliance on foreign direct investment to finance export projects require Australia to be adaptive to the needs of foreign consumers and capital.[219] Estimates of the country's ability to supply hydrogen vary widely. According to ACIL Allen Analysis, Australia's annual export capacity would be between 0.24 and 1.09 Mt/yr in 2030 and between 0.62 and3.18 Mt/yr in 2040.[220] Meanwhile, Deloitte's estimate for 2050 is between 2 and 20 Mt/yr.[221]

Australia's vision has a highly pragmatic undertone, seeking to proactively capture economic value from the global energy transition and generate national-level synergy from state-level economic development needs and interests. Most state governments have their own hydrogen strategies, and many of the strategies and visions are about expanding renewable energy capacity to diversify local economies. Even if high-carbon resources remain prominent in their current energy and electricity systems, many states are exploring renewable-based hydrogen development and seeking investment to support regional economic growth. One such state project is in the Pilbara region of Western Australia, which is best known for its large iron ore industry. In Pilbara, the Asian Renewable Energy Hub proposes a massive 26 GW renewable power capacity to underpin green hydrogen production.[222] Much of the planned renewable power will be converted into hydrogen and ammonia for export, while some will be consumed locally to electrify and decarbonize economic and industrial operations.

Australia's hydrogen development is guided by the National Hydrogen Strategy, released in November 2019, which recommends 57 joint actions that cover a host of areas, including exports, transport, industrial use, gas networks, and power systems.[223] Specifically, the actions include seven thematic areas: national coordination, production capacity, responsive regulation, international engagement, innovation, skills and workforce, and community confidence. Hydrogen initiatives receive support from the national, state, and territorial government levels. Most of Australia's states and internal territories have a strong interest in developing a hydrogen economy, with some concrete plans and actions.

Several public entities play an important role in carrying out Australia's hydrogen industrial strategy. The Commonwealth Scientific and Industrial Research Organization (CSIRO) plays an instrumental role, not only in carrying out hydrogen research but also in accelerating projects, particularly through the Hydrogen Industry Mission since its May 2021 inception. The Hydrogen Industry Mission has brought together CSIRO and its partners in the research community and the industry sector, who are investing over AU$68 million ($49 million) to help build a hydrogen industry.[224]

Also, the Australian Renewable Energy Agency (ARENA), launched in 2012, facilitates clean energy innovation in Australia, particularly to improve the competitiveness of renewable energy technologies. In coordination with the National Hydrogen Strategy, ARENA announced a funding round of AU$70 million ($50.5 million), subsequently raised to AU$103.3 million ($74.5 million), in 2019 to support renewable-based hydrogen projects in Australia.[225] In May 2021, ARENA announced three efforts to jumpstart large-scale production of renewable hydrogen.[226] Additionally, the government has empowered its Clean Energy Finance Corporation, which has a capitalization of AU$10 billion ($7.2 billion), to invest up to AU$300 million ($216.2 million) toward demonstrating, commercializing, and deploying hydrogen projects under its Advanced Hydrogen Fund.[227]

The domestic hydrogen industry is short of dominant players, but there is a range of new entrants from both the green energy space and fossil fuel sectors.[228] For example, LNG exporter Woodside Energy is looking at both green and blue hydrogen. Another notable Australian player is Fortescue Future Industries, a renewable subsidiary of the Fortescue Metals Group. In the fall of 2021, the company announced plans to build a 2 GW electrolyzer factory in Queensland—about double the capacity of the world's largest electrolyzer plant today—with an initial investment of $83 million and a completion target of early 2023.[229] Additionally, the Australian Hydrogen Council provides a platform for stakeholder collaboration to facilitate the commercialization of technologies for hydrogen and fuel cell applications within Australia.[230]

Originally named Hydrogen Mobility Australia, the council's key founding members were Toyota and Hyundai, illuminating how the Australian path for a hydrogen economy has been linked to Japanese and South Korean interests in Australia as both a market for FCVs that their leading automakers produce and a supplier of hydrogen molecules to their markets.

The Australian hydrogen strategy focuses heavily on developing regional clusters or hubs of hydrogen development in order to minimize the cost of providing infrastructure while supporting economies of scale in producing and delivering hydrogen to end users. The government has allocated AU$464 million ($334.4 million) to support the rollout of hydrogen hubs across seven regional sites. The funding supports multiple hub development activities, including AU$54 million ($38.9 million) toward the creation of a regional hydrogen export hub, AU$20 million ($14.4 million) toward hub feasibility studies, and AU$150 million ($108.1 million) toward hub design and implementation work.[231] In April and May 2022, the industrial hub selections were announced, including seven program recipients for implementation grants, and nine program recipients for development and design grants.[232]

As Australia seeks to become a leading hydrogen exporter, international engagement is a key element of its hydrogen strategy. For example, in January 2020, two months after the launch of the National Hydrogen Strategy, Australia's Ministry for Industry, Innovation and Science (predecessor to the Department of Industry, Science, Energy and Resources) held the Japan-Australia Ministerial Economic Dialogue with Japan's Ministry of Economy, Trade and Industry. They released a joint statement regarding cooperation on hydrogen and fuel cells that recognizes the synergy between Japanese and Australian interests and capacities in creating a regional hydrogen supply chain.[233] In addition to reaffirming interest in exchanging technology and safety-related information, the two governments expressed a clear desire to cooperate in shaping global hydrogen regulations, codes, and standards to expand domestic and international markets. A number of Japanese companies are involved in projects along the hydrogen supply chains in Australia. The most notable Japanese commercial engagement may be the pilot project at the Latrobe Valley in Victoria, which is part of the Hydrogen Energy Supply Chain project. It is a signature hydrogen project by the Australian government, which has already committed AU$58 million ($41.8 million) toward its success.[234] The Latrobe Valley project, undertaken alongside HySTRA (comprised of Iwatani, Shell Japan, J-Power, Marubeni, ENEOS, Kawasaki Heavy Industries, and K Line) resulted in the world's first shipment of liquified hydrogen from Australia to Japan in late February.[235]

South Korea is another important regional destination for Australia's future hydrogen supply, and the two countries are becoming closely engaged in hydrogen supply chain and application work. For example, in November 2021, the governments of Australia and South Korea announced the bilateral Low and Zero Emissions Technology Partnership, with a focus on clean hydrogen and ammonia supply, low emissions iron ore and steel making, and CCS, with an initial commitment of AU$100 million ($72.1 million).[236] Besides the government-to-government cooperation commitment, Australia's Woodside Petroleum has been working with Hyundai and Kogas to expand the HRS buildout in Australia, while Fortescue Metals Group—together with CSIRO—has begun cooperation with Hyundai to accelerate the development of green hydrogen technology, including the future commercialization of CSIRO-developed technology.[237] Australia's additional hydrogen engagement with Asian economies includes the 2021 agreement with Singapore to collaborate on a AU$30 million ($21.6 million) project to support hydrogen use in the maritime sector. This entails industry-led pilot and demonstration projects that will be supported with AU$10 million ($7.2 million) from each government, with further investment coming from industry.[238]

Russia

The Russian invasion of Ukraine (since late February 2022) has cast major uncertainty over the future of hydrogen development in Russia.[239] For example, international sanctions (including by the United States, the European Union, Japan, and South Korea) on Russian banks have been a major blow to planned and potential hydrogen projects in Russia. Moreover, the European Commission's decision to rapidly reduce energy dependence on Russia renders the viability of hydrogen technology cooperation and trade between Russia and European companies highly uncertain, if not unlikely.

Europe and Eurasia consumed nearly 90 percent of Russian natural gas supplies in 2020. The damaged relationship with Europe could propel Russia to pivot decisively toward Asia for demand and investment. While the pivot is highly likely, exactly how bilateral energy ties might incorporate hydrogen remains uncertain given the wide-ranging reactions by individual Asian governments to Russian aggression. While Japan and South Korea were quick to join the transatlantic-led sanctions on Russia, China and India have not. Nonetheless, losing access to Western capital could trigger a revision of Russia's hydrogen vision and strategy to better align its capability with the preferences and priorities of Asian customers. As such, strategic documents that were surveyed for this study are highly subject to change at the time of writing.

Russia's advantage as a potential hydrogen supplier comes from its relative proximity to Asian markets dependent on energy imports. The Russian government has become increasingly articulate in what the country expects from an emerging hydrogen economy in Asia. The overarching drive behind Russia's emerging hydrogen interest is its desire to preserve its own prominence in the global energy system.

Russia seems acutely aware of changing global energy markets under a carbon-constrained world, including how foreign countries are developing plans and programs to develop and consume hydrogen energy as part of United Nations-led climate mitigation efforts, for example. In fact, all Russian strategy documents related to hydrogen acknowledge changing global demand in the face of the energy transition, and the country's various action items demonstrate a recognition that emissions from future hydrogen fuel production may receive greater scrutiny from foreign buyers.

Russia's first known public expression of interest came in June 2020 when it released its Energy Strategy to 2035, which outlines Russia's overarching, medium-term plans for its energy sector.[240] The document includes a broad overview of its plan for hydrogen, including its interest in using natural gas, renewables, and nuclear energy to produce hydrogen, as well as its intention to stimulate demand for fuel cells in the domestic market.[241] The document also noted the country's desire to enter into "the ranks of the world leaders in [hydrogen] production and export."[242]

The Russian hydrogen strategy, anticipated to be out as early as by the end of March 2022, should provide more detailed insights into how Russia seeks to realize its hydrogen vision.[243] Until the document is actually released, key insights can be drawn from several official documents related to hydrogen that followed the Energy Strategy to 2035. The Roadmap for Hydrogen Development until 2024, released in October 2020, presents distinct steps and timelines through 2024 for various aspects of the strategy, including strategic planning, state support, production capacity, pilot projects, R&D, regulatory development, workforce development, and international engagement. Meanwhile, the Concept for the Development of Hydrogen Energy in Russia, released in August 2021, offers areas of emphasis.

Hydrogen export was a key theme in both the roadmap and the concept documents.[244] For example, the roadmap, which provides multiyear action plans, aims to prioritize work necessary to develop a "highly productive export-oriented sector."[245] Russia believes that its vast fossil fuel resource endowment and mature oil and gas industry give the country a competitive advantage as a hydrogen producer, and that its proximity to European and Indo-Pacific markets offers an advantage as a hydrogen exporter.

The scope of Russia's export ambition is 0.2 Mt/yr by 2024 and 2 Mt/yr by 2035, as well as a 20 percent share in the global market by 2030.[246] More recently, the Russian Ministry of Energy reportedly expects an export volume of 2.3 Mt/yr by 2030 and 9.4 Mt/yr by 2050, as presented in a preliminary version of Russia's long-awaited hydrogen strategy, which was released (but not yet formalized or finalized) a week before the Russian war.[247] A pre-war market analysis suggested that exports by 2050 might generate as much as $100 billion annually for the Russian economy, compared to about $120 billion annually in total economic value from the export of 5 million barrels per day, which was the running average for Russia's oil export level in recent years.[248]

Meanwhile, the Russia's concept document acknowledges that the current level of domestic technological expertise requires some type of reliance on foreign technologies, such as electrolysis, large-scale storage and transportation, and carbon capture and transportation, and indicates that the government is contemplating providing support for domestic R&D.[249] Russia may have a solid scientific background in hydrogen research that dates back to the Soviet era, but much of the country's R&D capability is "narrowly specialized and compartmentalized, the technology readiness level is low, and commercialization remains a challenge."[250] While the official documents mention green hydrogen numerous times as a likely priority, it is uncertain whether Russia has the resolve or means to emerge as a competitive producer of green hydrogen and, therefore, as a successful exporter.

Russia's official statements are largely focused on the supply side, but they also reveal the country's exploration of facilitating domestic demand for hydrogen. The preliminary version of the hydrogen strategy, released in February 2022, suggests a growing interest in using hydrogen for decarbonizing the transportation sector as well as the steel and chemical industry, especially in connection with the upcoming entry into force of the European Union's Carbon Border Adjustment Mechanism and the need to reduce the carbon footprint of Russian exports.[251]

The Ministry of Energy seems to be the most vital actor in fulfilling the country's hydrogen vision. In the preliminary version of the hydrogen strategy, the ministry proposes subsidies for the cost of infrastructure (including terminals, ships, and tank containers) that could require up to $3.7 billion as well as tax incentives.[252] A variety of stakeholders from both the public and private sectors are working closely with the energy ministry. The working group on hydrogen, set up in July 2021 and chaired by Russia's deputy prime minister, is joined by multiple ministries, scientific institutes, banks and investment companies, and industry companies (e.g., metallurgical, chemical, energy, equipment manufacturing, engineering companies). Such companies include state-owned enterprises, such as oil and gas producer Rosneft, gas company Gazprom, nuclear corporation Rosatom, and heavy-duty truck manufacturer Kamaz, and private companies, such as gas company Novatek and petrochemical producer Sibur.[253]

In particular, Gazprom's potential role in hydrogen exports warrants close attention. A major producer of high-carbon hydrogen and an exclusive controller of gas pipeline networks, Gazprom seems increasingly engaged in hydrogen value creation, especially related to natural gas, although not entirely with enthusiasm.[254] In December 2020, Gazprom announced the creation of Gazprom Hydrogen, which aims to implement innovative pilot projects.[255] Importantly, the construction of a blue hydrogen plant at the German end of the Nord Stream pipeline was among the potential projects hinted at the time of announcement, but the prospect for the project has changed dramatically since the Russian invasion of Ukraine in February 2022.

Novatek, a private Russian gas company and the dominant producer of LNG, is starting to commit resources to creating hydrogen value chains. In the summer of 2021, Novatek announced a decision to switch technology at its Obsky LNG project on the Yamal Peninsula to produce blue hydrogen and ammonia instead.[256] In the first phase of the operation, Novatek is aiming to produce about 2 Mt of ammonia and about 120,000 tons of hydrogen from natural gas per year.[257] The target ammonia production volume for Novatek is equivalent of the volume of hydrogen that Russia hopes to export annually by 2035.

Additionally, Russia's state nuclear company Rosatom has plans to act as an investor and developer, with a long-term goal of becoming a hydrogen technology provider over the next few years.[258] Rosatom is the most technologically advanced large Russian company and is interested in the entire hydrogen supply chain as well as a host of production methods, including but not limited to electrolysis, steam-methane reform with carbon capture, and high-temperature gas-cooled nuclear reactors.[259]

Developing hydrogen clusters seems to be at the core of the Russian strategy. The concept paper outlined Russia's plan to create three hydrogen clusters or hubs: a northwest cluster, an eastern cluster, and an Arctic cluster. The document also leaves the possibility for a fourth, southern cluster, whose viability seems highly contingent of demand growth, among other factors. The northwest cluster is designed to serve European markets, in recognition of growing regional interest in hydrogen use, particularly of hydrogen fuels emitting low to zero carbon. The eastern cluster is for export to Asian markets, also in recognition of growing regional interest in hydrogen use, especially in the transportation sector. The Arctic cluster has a particular geopolitical undertone in that it fits clearly within Russia's broader strategic interest in maintaining a strong economic (and military) presence in the Arctic, and it also corresponds with new gas resource development.[260] Following the concept document's discussion of hubs, the Ministry of Energy proposes five clusters: Yamal, Eastern Siberia, Yakutia, Sakhalin, and North-West. Of the five, the Sakhalin cluster is the most developed.[261]

The success of Russia's hydrogen sector is heavily reliant on foreign capital and technology. The Russian government places a key emphasis on international cooperation in areas such as pilot projects, industry standards, and trade regulations.[262] The roadmap lists Asian countries such as Japan and South Korea among potential international partners for Russia. Engaging Asian economies is a key means for Russia to help realize its hydrogen export interests. For example, on the margin of the annual Eastern Economic Forum in September 2021, Russian president Vladimir Putin suggested Japanese and Chinese participation in a green hydrogen and ammonia production base in the Russian Far East, where plans for hydrogen production are under development in the Kamchatka Peninsula and on Sakhalin Island.[263] Rosatom is already engaged in a feasibility study with Japan's economic ministry and Kawasaki Heavy Industries for a pilot project on shipping hydrogen from Russia to Japan.[264] Meanwhile, Gazprom and the Sakhalin government have agreed to cooperate on hydrogen production with Japanese companies Mitsui and Mitsubishi, respectively.[265] South Korea has also begun pursuing cooperation with Russia, including in commercializing hydrogen and developing its global supply chains.[266] As noted earlier, the Russian invasion of Ukraine has likely reduced the pool of potential partners significantly. How the war affects Russia's hydrogen cooperation with Japan and South Korea warrants close attention.

Interestingly, Russia's hydrogen cooperation is not limited to its potential customers and instead extends to its potential rivals as a hydrogen exporter. For example, there is an agreement between Russia and the UAE, signed in November 2021. Under this agreement, the two countries are seeking to collaborate on hydrogen production, storage, and transport, particularly in the manufacturing of equipment for production, liquefaction, and use of raw hydrogen.[267]

Saudi Arabia

Saudi Arabia's interest in hydrogen is primarily driven by its desire to ensure economic security.[268] Developing a clean hydrogen sector can help the world's top crude oil exporter meet several key mandates of the Saudi Vision 2030, including diversifying its exports, leveraging existing sectors' supply chains to increase local contents, and developing new industrial sectors.[269]

Hydrogen production and export could allow Saudi Arabia to become less reliant on domestic oil as a key source of export revenue from global markets. In 2020, oil exports accounted for about 70 percent of the country's total exports in terms of value and about 53 percent of Saudi government revenues.[270]

Asia is the top source of the country's oil export revenue; in 2020, Asia was the destination for an estimated 77 percent of Saudi crude exports and one-third of Saudi refined petroleum products.[271] A new stream of exports with a lower carbon profile may be of particular value in a carbon-constrained world characterized by a wave of net-zero targets from governments and industries, including Saudi Arabia's own (by 2060). In October 2021, Saudi energy minister Prince Abdulaziz bin Salman al-Saud stated that the country wants to become the top supplier of hydrogen in the world.[272]

As Saudi Arabia explores ways to become the top supplier of hydrogen in the world, it has clean hydrogen production targets of 2.9 Mt/yr by 2030 and 4 Mt/yr by 2035.[273] The current focus is to gain a large market share in blue hydrogen, particularly in the form of blue ammonia in the coming decade (i.e., ammonia produced from the combination of ammonia synthesis using hydrocarbon CCUS).[274]

The development of a clean hydrogen industry, particularly the use of hydrogen from carbon-abated natural gas, would also echo the country's growing pursuit of a circular carbon economy, which is a framework for managing and reducing emissions through carbon reduction, reuse, recycle, and removal.[275] The domestic consumption of clean hydrogen, such as in transportation, would help reduce the carbon profile of Saudi economic activities.

As of early April 2022, the Saudi government is reportedly finalizing an official hydrogen strategy that outlines five areas of focus: hydrogen mobility, hydrogen export infrastructure, a regulatory framework, standards and certifications, and investments of over $36 billion by 2030.[276] Even in the absence of a national hydrogen strategy, various statements and actions by political leaders and corporate executives have provided some insight into how Saudi Arabia may pursue hydrogen deployment.

Saudi Arabia has an interest in leveraging its natural gas resource wealth. For example, the country is planning to use a significant portion of natural gas from the unconventional Jafurah field to produce blue hydrogen.[277] Located roughly equidistant between Riyadh and the Saudi-Qatari border in the east, the Jafurah field is the largest discovered non-associated gas resource in Saudi Arabia, holding 200 trillion cubic feet of gas; Aramco targets first gas production from the $110 billion project in 2024.[278] Also, Saudi Arabia has experience in industrial-scale production and international sales of chemicals, as well as several CCUS-related assets, such as the CO_2-to-EOR project at Uthmaniyah and the CO_2-to-chemicals project at Jubail, to develop the blue hydrogen sector. As such, the pace of developing a clean hydrogen sector will be closely linked to the country's CCUS strategy, including the pursuit of CO_2 use beyond EOR.

As the manager of these CCUS capacities and gas resources, the state-owned Saudi Arabian Oil Company (Aramco) plays a vital role in executing the blue hydrogen plans at home and with international partners. In September 2020, Aramco shipped 40 tons of blue ammonia from Saudi Arabia to Japan. This was the world's first demonstration of blue ammonia supply chains entailing the production and international maritime transportation of blue ammonia. This project reaffirmed Aramco's view that existing technology solutions (i.e., the extraction, processing, and conversion of natural gas into hydrogen and ammonia) can help provide cost-effective and scalable low-emission solutions.[279] Also, Aramco has a memorandum of understanding with South Korea's Hyundai OilBank Company, which plans to take LPG cargoes from Saudi Aramco, convert the LPG into hydrogen, and ship the CO_2 emitted in the process back to Saudi Arabia.[280]

Renewable-based hydrogen is a key focus of technological and economic experiments in the futuristic city of Neom. The kingdom's pursuit of green hydrogen is led by Riyadh-based private firm ACWA

Power. Neom features a $5 billion green hydrogen project that is a joint venture between Neom, ACWA Power, and Pennsylvania-based Air Products. Expected onstream in 2026, the project's 4 GW renewable capacity—including wind power—would make it the world's largest renewable hydrogen-to-ammonia facility. It would produce 240,000 tons per year of hydrogen to create 1.2 million tons per year of green ammonia—roughly equivalent to *3.85 million barrels of ammonia, or* 5 million barrels of oil or hydrogen *per year.*[281] (In comparison, the Saudi annual crude oil production volume is about 12 million barrels *per day*.) Another major stakeholder in green hydrogen, especially in export, is the Public Investment Fund (PIF), a $500 billion sovereign wealth fund. As a primary source of green initiatives, including green hydrogen, the PIF signed a memorandum of understanding with South Korean firms Samsung and POSCO in January 2022 to study a hydrogen export project.[282]

Hydrogen from renewable energy sources could mean a new industrial sector for Saudi Arabia, which is located in the sun belt and has vast areas of flat, unused land for solar panels.[283] The country has announced plans to install about 27 GW of mostly solar capacity by 2023 and almost 58 GW by 2030.[284] However, *installed* renewables capacity in Saudi Arabia remains limited, at 413 MW (including 409 MW of solar), accounting for 1 percent of its power supply.[285] A late comer to renewable energy development, Saudi Arabia only saw its first PV power plant open in April 2021 and its first wind farm produce electricity in August 2021. This raises questions about the timeline in which the Saudi hydrogen vision may materialize with renewable-based supplies.

United Arab Emirates

As the first Middle Eastern country to announce a mid-century carbon neutrality commitment, the UAE sees hydrogen as a potential economic driver as well as a key tool in its climate action. The country sees itself "well positioned to be a leader in low carbon hydrogen," with competitive advantages for hydrogen from both carbon-abated natural gas and renewable energy sources.[286] The country's vision and actions are largely led by Abu Dhabi, one of the seven emirates that constitute the UAE.[287]

Even before launching the Hydrogen Leadership Roadmap at COP26 in November 2021, the UAE identified hydrogen as "a fuel of the future" in its Nationally Determined Contribution under the Paris Agreement, updated in December 2020.[288] The country currently uses hydrogen from unabated natural gas or methane, but the roadmap announcement signals the country's growing effort to decarbonize its hydrogen supply and consumption profile.[289]

Both blue and green hydrogen are expected to aid the UAE's sustainable economic growth through projects across the clean hydrogen value chain. In particular, blue hydrogen could take advantage of the country's hydrocarbon resources, existing large-scale hydrogen and ammonia production facilities, and large, well-characterized sub-surface formations for CO_2 storage.[290] The UAE has particular economic opportunity in the export of low-carbon hydrogen and derivatives and products to major importing regions, aiming to capture 25 percent of the global hydrogen market by 2030.[291] The country's export ambition is underpinned by seven hydrogen projects already underway.[292] The stated markets of particular interest, at least initially, are Japan, South Korea, Germany, and India.

Meanwhile, green hydrogen could also help the country meet its net-zero goals. The UAE's installed renewable energy capacity—mostly from solar PV projects—is on a trajectory for strong expansion, from about 2.3 GW in 2020 to 9 GW in 2025.[293] When nuclear energy is included, the country's non-fossil fuel power capacity could reach 20 GW by 2030.[294]

According to its Hydrogen Leadership Roadmap, the UAE seeks to support the development of a low-carbon hydrogen industry through a supportive regulatory framework, domestic technology R&D, existing and new government-to-government relationships, land and infrastructure resources, and both domestic and international green financing.[295]

The country's current undertakings include at least seven projects, such as a solar PV and green hydrogen production facility, blue ammonia production plant, green hydrogen demonstration plant for road transport, green ammonia project using electrolysis, and a green hydrogen project enabling green steel production. These projects count UAE state companies such as the Abu Dhabi National Oil Company (ADNOC), Mubadala Investment Company, Abu Dhabi Development Holding Company (ADQ), and Dubai Electricity and Water Authority (DEWA) as active players. For example, the Abu Dhabi Hydrogen Alliance was formed between ADNOC, Mubadala, ADQ, and the Ministry of Energy and Infrastructure to coordinate their efforts and combine their skills and assets.[296]

Moreover, with the support of Crown Prince Mohamed bin Zayed, ADNOC and the government-controlled Abu Dhabi National Energy Company announced a decision to become shareholders in the Abu Dhabi Future Energy Company (Masdar), alongside Mubadala, in December 2021. This is a strategic step by these Abu Dhabi stakeholders to combine individual efforts and portfolios to turn Masdar into a "global champion in renewable energy," and in turn green hydrogen.[297]

In particular, ADNOC is playing a vital role. In announcing its approval of ADNOC's $122 billion, five-year capital investment program in November 2020, the country's Supreme Council for Financial and Economic Affairs also instructed ADNOC to position "the UAE as a hydrogen leader."[298] ADNOC has since proposed a major blue ammonia project in Ruwais that entails a 1 Mt/yr ammonia plant as part of the Ta'ziz industrial hub, with a start-up target of 2025.[299] Also, ADNOC is expected to take a 43 percent share in Masdar's green hydrogen business upon completion of the transaction.[300]

The UAE's pursuit of cultivating a hydrogen supply chain has resulted in several international partnerships, both in the upstream and midstream segments. In January 2022, Masdar signed a collaboration agreement with French multinational utility company Engie to study a 200 MW green hydrogen facility that could come onstream in 2025.[301] The facility would supply ammonia production plants, also at the Ta'ziz industrial hub in Ruwais, owned by Fertiglobe, which is a joint venture between ADNOC and the Netherlands-based chemical producer OCI. In the same month, Masdar also signed a collaboration agreement with TotalEnergies and Siemens Energy to co-develop a demonstration plant at Masdar City that aims to turn green hydrogen into sustainable aviation fuel.[302]

As the UAE looks to emerge as a hydrogen exporter, the government and ADNOC have signed cooperation agreements with the Japanese government, as Japan considers developing blue ammonia supply chains in the Middle East by the late 2020s. In July 2021, ADNOC agreed to a joint study with the Japan Oil, Gas and Metals National Corporation—as well as a few Japanese private companies—to explore the possibility of producing 1 Mt/yr of blue ammonia in Abu Dhabi and transporting it to Japan.[303] In November 2021, ADNOC also signed a facility agreement worth $3 billion with JBIC that included $0.9 billion in co-financing by four Japanese private banks as well as a memorandum of understanding with JBIC that aims to further bilateral energy ties, with a particular focus on hydrogen and fuel ammonia supply chain projects. Indeed, the UAE's relations with Asian economies—albeit most notably with Japan but also with South Korea, China, India, and Thailand—have seen strong private sector participation, including blue ammonia sales to Japan's Itochu, Idemitsu, and INPEX.[304]

Meanwhile, Mitsui of Japan and GS Energy of South Korea agreed to participate in the blue ammonia project in Ruwais for supply access.[305]

About the Author

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Endnotes

1 **Liquid hydrogen:** The hydrogen molecules must be cooled to -253 degrees Celsius at port terminals before being loaded onto highly insulated tanker ships. As a result, the liquefaction process consumes 25 to 35 percent of the initial quantity of hydrogen. **Liquid organic hydrogen carriers (LOHCs):** A slate of different organic compounds can absorb and release hydrogen through a chemical reaction. LOHCs can serve as a storage and transportation medium for hydrogen and can be transported as liquids without cooling. LOHCs are very similar to crude oil and oil products. **Ammonia:** Hydrogen can be turned into ammonia by reacting with nitrogen from the air, using nothing but electricity, water, and air. Ammonia has a much higher energy density. Ammonia is currently used a feedstock, notably to make fertilizers. The downside is that ammonia is toxic if leakages occur and is a potential source of nitrogen oxide emissions.

2 In this report, hydrogen produced from fossil fuels where carbon emissions are captured is interchangeably referred as "blue hydrogen," while renewable-based hydrogen is interchangeably referred to as "green hydrogen."

3 International Energy Agency (IEA), *Global Hydrogen Review 2021: Executive Summary* (Paris: IEA, November 2021), https://www.iea.org/reports/global-hydrogen-review-2021/executive-summary.

4 IEA, *Hydrogen Tracking Report* (Paris: IEA, November 2021), https://www.iea.org/reports/hydrogen.

5 IEA, *Global Hydrogen Review 2021* (Paris: IEA, November 2021), 172, https://iea.blob.core.windows.net/assets/5bd46d7b-906a-4429-abda-e9c507a62341/GlobalHydrogenReview2021.pdf.

6 International Renewable Energy Agency (IRENA), *Geopolitics of the Energy Transition: The Hydrogen Factor* (Abu Dhabi: IRENA, January 2022), 36, https://irena.org/-/media/Files/IRENA/Agency/Publication/2022/Jan/IRENA_Geopolitics_Hydrogen_2022.pdf.

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