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King Abdullah Petroleum Studies and Research Center

World's First Blue Ammonia Shipment Signals Prospective New Low-Carbon Energy Trade for Saudi Arabia

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On September 27, 2020, Saudi Aramco successfully exported the world's first shipment of carbon-neutral ammonia to Japan, helping to fuel the nascent Japanese hydrogen economy. This pilot shipment of 40 tonnes is an important realization of the hydrogen economy for both the Kingdom of Saudi Arabia and Japan. It also signals a potentially important addition to the Kingdom's export commodity portfolio. Hydrogen is experiencing unprecedented momentum as governments worldwide scale up their hydrogen policy ambitions and introduce incentives for investing in hydrogen.

The announcement of the blue ammonia shipments comes almost two months after Neom publicized plans to build the world's largest green ammonia plant in Saudi Arabia's northwestern region by 2025. This plant will be built in partnership with ACWA Power and Air Products. Both announcements signal a strong intent by Saudi Arabia to become a major exporting hub for carbon-neutral hydrogen.

As part of Saudi Arabia's G20 Presidency, the Kingdom has pioneered the concept of the circular carbon economy (CCE), in which hydrogen plays a major role in enabling a low-carbon future. The CCE was showcased in the recently released G20 Energy Ministers Communiqué. It builds on the idea of a circular economy, with a focus on energy and carbon flows (KAPSARC 2020). Under this framework, carbon emissions can be *reduced* by energy efficiency, *recycled* through the natural carbon cycle with bioenergy, *reused* as an input for chemicals and fuels, or *removed* and stored in geologic formations. Today, natural gas and coal are the cheapest way to produce hydrogen, and, if combined with carbon capture, utilization and storage (CCUS), it can close the loop, resulting in net-zero carbon dioxide (CO_2) emission fuels. This is known as blue hydrogen. If renewable energy is used, as in the case of Neom's green ammonia project, it is known as 'green' hydrogen.

Saudi Aramco's pilot shipment was executed as a partnership between the Saudi Basic Industries Corporation (SABIC) and The Institute of Energy Economics, Japan (IEEJ). It also had the support of the Japanese Ministry of Economy, Trade and Industry (METI). The project utilizes existing infrastructure to convert hydrocarbons into hydrogen to make ammonia while capturing CO_2 emissions.

Saudi Arabia adds blue hydrogen exports to its commodity portfolio

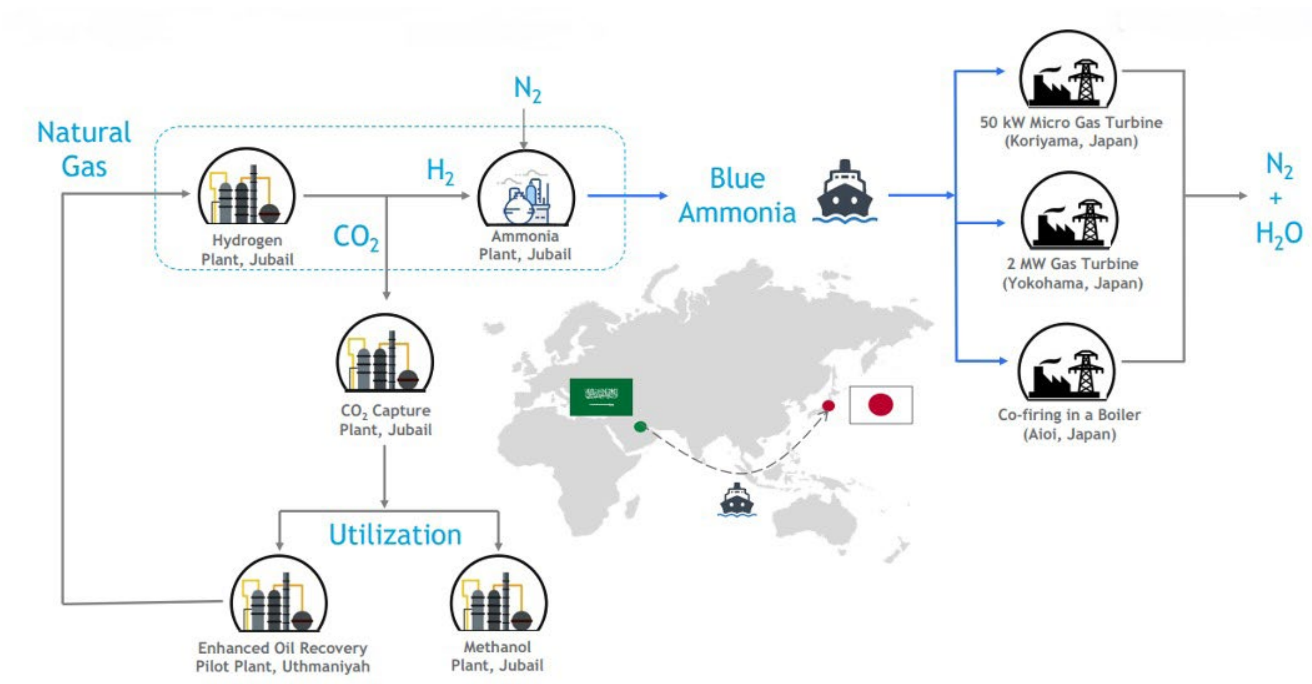
Hydrogen production and its use in industrial applications are not new. Currently, around 75 million tonnes of pure hydrogen is produced globally, and an additional 45 million tonnes is produced as a mixture with other gases (KAPSARC 2020). However, the current process for making hydrogen is responsible for emitting 800 million tonnes of CO_2 per year, or more than 2% of global CO_2 emissions. This is because over 95% of all hydrogen production is sourced from fossil fuels without carbon capture, known as 'grey hydrogen.' Refineries are the largest users of hydrogen, which they use to desulphurize and upgrade fuels, followed by ammonia and methanol plants.

Hydrogen has been enjoying a resurgence as an energy carrier, with an unprecedented level of support from policymakers worldwide. Its versatility as a fuel source and the fact that it has zero emissions at the point of use has helped it garner momentum as a fuel of choice to replace fossil fuels, particularly in harder-to-abate sectors such as heavy-duty transport, heating, and industry. But for hydrogen to be accepted as a clean fuel, the entire value chain must be decarbonized, particularly the production process. Saudi Arabia could be a key low-cost and large-scale producer of both green and blue hydrogen, given its significant renewable energy resources, massive hydrocarbon reserves, and geological pore space for carbon sequestration.

The production and pilot shipment of 40 tonnes of blue ammonia by Saudi Aramco and SABIC utilizes and connects existing infrastructure and leverages the nearby industrial hubs and ports of Jubail in the Kingdom's Eastern Province. The Saudi Arabian Fertilizer Company (SAFCO), a SABIC affiliate, operates five ammonia plants in Jubail, with a total capacity of about 3.6 million tonnes per year. SABIC also operates the world's largest CO_2 purification and liquefaction plant capable of purifying 500,000 tonnes of raw CO_2 for such uses as methanol and urea production. As shown in Figure 1, natural gas is transported from the oil and gas fields to Jubail after being processed, where it is used as a feedstock to produce hydrogen by steam methane reforming (SMR), which then produces ammonia.

SMR is, to date, the most cost-effective way of making hydrogen. However, the process is energy and carbon intensive. In the case of the blue ammonia project, about 50 tonnes of CO_2 is captured, 30 tonnes of which is utilized in SABIC's Ibn-Sina methanol plant. The remaining 20 tonnes are transported and injected into the Uthmaniyah oil field. The ammonia is then shipped to Japan to generate power at various production sites: the 50 kilowatt (kW) micro gas turbine site in Koriyama, the 2 megawatt (MW) plant in Yokohama, where the ammonia is co-fired with natural gas, and a plant in Aioi where it is co-fired with coal.

Figure 1. Schematic of the blue ammonia project and its value chain.



Source: Aramco.

CCUS is a key enabler of blue hydrogen

These project announcements are a sign of the increasing focus on hydrogen-related investments. For the Kingdom, the yet nascent hydrogen economy represents an opportunity to both diversify its commodity export portfolio and also gain an important foothold in it. Saudi Aramco has been working on carbon management, in the form of CCUS, for decades. It began to inject CO_2 into one of the depleted sections of the Uthamaniyah oilfield in July 2015 as part of an enhanced oil recovery (EOR) pilot project. The EOR plant can receive 800,000 tonnes of piped CO_2 per year from Hawiyah natural gas processing plant, located 85 kilometers away. Once injected into the reservoir, CO_2 becomes miscible under the right conditions, increasing the mobility of trapped oil in the porous media enabling incremental oil gains. The process yields higher oil recoveries when injected into the reservoir and alternated with water, known as water alternating gas (WAG) displacement. The literature suggests that WAG provides incremental recovery in the range of 5% to 10% of oil in-place and may be as high as 20% in some studies (Belazreg and Mahmood 2019).

CO_2 sequestrated via EOR has been gaining momentum among many oil and gas producers. It helps to bolster oil recovery from their mature oilfields, maximize their returns, and, most importantly, oil operators can leverage their expertise in this area. It also helps producers decarbonize their oil and gas value chain as part of their carbon management programs.

Aramco has stated that the objective of its EOR pilot is to demonstrate the viability of sequestrating CO_2 through EOR and enable future long-term large-scale applications to draw on the lessons learned (Kokal, Sanni and Alhashboul 2016). The company's blue hydrogen is not the first commercial application of its kind in the market. There are currently five active blue hydrogen projects globally, with two more coming on stream by the end of 2020 (Friedmann et al. 2020). Saudi Aramco foresees CCUS playing an important role in a carbon-constrained world and instrumental in enabling a CCE. In fact, the United Nations Intergovernmental Panel on Climate Change has stated that CCS is necessary for emissions reduction to be on target by 2050 (IPCC 2018). Overall, there are 21 CCS projects worldwide and three more under construction (Global CCS Institute 2020). Integrating hydrogen as part of the loop, as noted above, shows the company's determination to further reduce emissions from its operations.

The cost of CCUS has fallen by 50% in the past decade to $50 per metric tonne of CO_2 in 2018/2019, driven by the development and deployment of the technology (Global CCS Institute 2020). Saudi Arabia has a wealth of low-cost hydrocarbons and significant amounts of geologic space for CO_2 storage and nearby industrial hubs. These factors make it perfectly positioned to scale up CCS projects for further cost reductions and extend the lives of existing oilfields due to the increased reserves recovered using CO_2 injection. Saudi Arabia has nearly 500 oil and gas-bearing reservoirs across the Kingdom, concentrated in the Eastern Province (Saudi Aramco 2018). Additionally, King Abdullah University of Science and Technology is leading research to assess the potential of sequestering CO_2 in deep, saline aquifers throughout the Kingdom (Al-Meshari, Muhaish and Aleidan 2014).

The best way to decarbonize the oil and gas sector and offset the high capital costs of new blue hydrogen/ammonia plants may be to retrofit existing SMR plants and other industrial processes with significant CO_2 emissions with CCUS, and expand the sector's existing CO_2 pipeline network. The Kingdom could also offer CCUS as a service in the future, whereby countries with inadequate storage capacity or capabilities could ship CO_2 to Saudi Arabia for utilization and storage. Such innovative approaches to scaling CCS require incentives and regulations to enable the industry to mitigate investment risks and accelerate the development of the technology.

Ammonia as the carrier of choice

The development of technologies to scale up blue and green hydrogen production is essential in reducing costs. Storing and distributing hydrogen poses one of the biggest challenges due to hydrogen's low volumetric energy density. Liquid hydrogen has an energy density of 8 megajoules per liter, and storing hydrogen requires cryogenic temperatures due to its extremely low boiling point of -252.8 degrees Celsius under normal pressure (EERE n.d.). Liquid hydrocarbons, such as gasoline, have four times the energy density of hydrogen under ambient temperatures and pressures, making them less costly to store and transport. These factors are the main reasons why most hydrogen is currently consumed at the point of production. To overcome this challenge and to optimize transportation costs, several hydrogen carriers such as ammonia, methylcyclohexane (MCH), and reversible hydrocarbons are being considered for deep-sea shipment. In December 2019, Kawasaki Heavy Industries unveiled the first marine carrier able to transport liquid hydrogen. The vessel, the Suiso Frontier, was designed as part of a forthcoming demonstration project to transport hydrogen produced from coal in Australia due to begin in March 2021 (Hoshi 2019). It is still unclear what the commercial viability is of transporting liquid hydrogen and how it might fare against future alternative energy carriers.

Both Neom and Saudi Aramco have selected ammonia as their hydrogen carrier of choice for the many advantages that ammonia provides for long-distance shipping. Ammonia plants are the second-largest users of hydrogen after refineries, and ammonia is the precursor for nitrogen-based fertilizers. Ammonia is made by bonding one nitrogen atom with three hydrogen atoms, giving it its chemical formula, NH_3. Ammonia has an extensive and established supply chain, including above-ground storage and shipping options, and 50% higher energy density than liquid hydrogen, making it cost-efficient to transport. Neom plans to produce 650 tonnes of green hydrogen per day, which will feed a 1.2 million tonne per year ammonia plant (Air Products 2020). Air Products, the exclusive off-taker of the green ammonia, plans to ship it to markets in Europe and Asia, where it will be decomposed back to hydrogen (and nitrogen) and distributed to end users in the mobility sector. However, the Japanese partners in Aramco's and SABIC's blue ammonia project plan to use the ammonia directly.

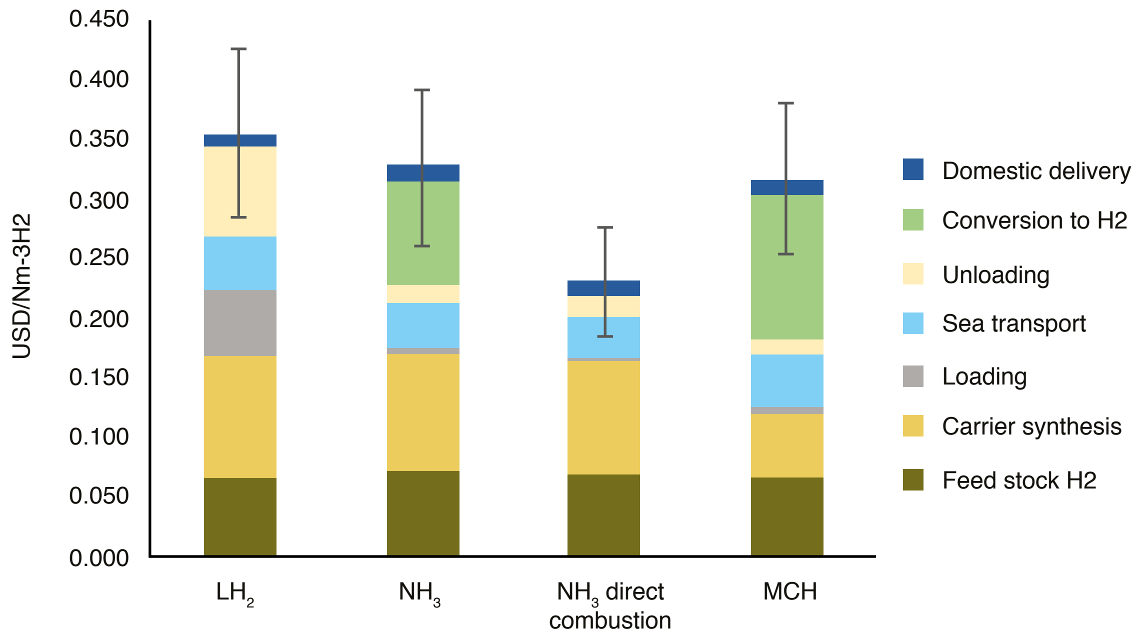
A study conducted by the IEEJ compared the supply costs of producing power in Japan using hydrogen sourced from Saudi Arabia transported in the form of liquid hydrogen (LH_2), ammonia and MCH. It also included the cost of the 'direct combustion' of ammonia for power generation.

As Figure 2 shows, using NH_3 directly in the power plant is the most cost-effective option. The extra step of reconverting ammonia or MCH back into hydrogen contributes a significant extra cost to power generation. Meanwhile, the shipping cost of LH_2 from Saudi Arabia is the least favored option.

Ammonia also has disadvantages. While it does not produce CO_2 at combustion, it is a noxious compound which emits nitrogen oxides (NOx) and increases the concentration of nitrous oxide (N_2O), a significant greenhouse gas. However, NOx emissions can be dealt with using existing technologies such as a selective catalytic reactor. Ammonia is also highly toxic and corrosive, which may require ammonia producers to have stringent safety standards and high capital investments to mitigate these risks.

Directly burning ammonia may be more favorable than power generation and other applications for providing heat as it requires minimal adjustment to existing infrastructure. However, transport and steel making require pure hydrogen. Thus, ammonia and other carriers can be a good transitionary solution until the infrastructure for and the adoption of pure hydrogen are scaled up.

Figure 2. Supply cost of producing power in Japan from Saudi Arabian hydrogen.



Source: METI (2018).

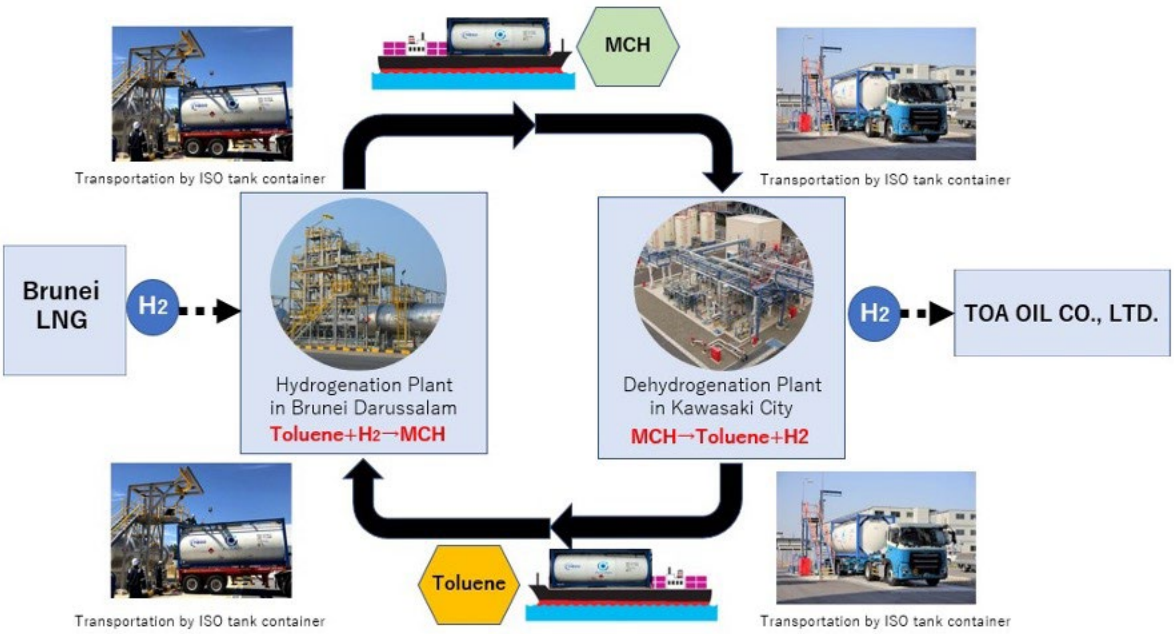
Japan spearheading hydrogen-based demonstration projects

On July 10, 2019, Saudi Aramco signed a memorandum of understanding with the IEEJ to conduct a pre-feasibility study for carbon-free ammonia production in Saudi Arabia (Saudi Aramco 2019). Japan has been at the forefront of promoting a 'hydrogen society' and is one of the first countries to roll out a hydrogen strategy. Its strategy sets a goal to make hydrogen competitive with imported liquefied natural gas (LNG) for power generation and promote fuel-cell vehicle penetration and hydrogen refuelling stations (METI 2017).

As the hydrogen economy gathers momentum, increasing commercial announcements of hydrogen projects signal an increasing interest by organizations seeking to gain a first-mover advantage. Japanese companies have been extremely proactive in this space, developing pilot projects to identify and scale-up commercial projects.

A consortium of Japanese companies, Advanced Hydrogen Energy Chain Association for Technology Development (AHEAD), comprising Mitsubishi, Nippon Yusen Kabushiki Kaisha (NYK), Mitsui & Co. and Chiyoda Corporation, developed the world's first international hydrogen supply chain. It falls under the Global Hydrogen Supply Chain Demonstration Project, connecting Brunei Darussalam and Japan, and showcased its hydrogen import project in November 2019. A hydrogenation plant, operated by AHEAD, at Sungai Liang Industrial Park (SPARK), produced liquefied hydrogen from natural gas sourced from Brunei LNG Sendirian Berhad (The Star 2020). The liquefied hydrogen was then converted into methylcyclohexane (MCH) to be used as a hydrogen carrier, enabling shipping by commercial vessels at ambient temperatures and pressures.

Figure 3. Brunei – Japan's hydrogen supply chain demonstration project flow.



Source: Nippon Yusen Kabushiki Kaisha (NYK).

The Global Hydrogen Supply Chain Demonstration Project, funded by Japan's New Energy and Industrial Technology Development Organisation (NEDO), plans to supply a total of 210 metric tonnes to Japan (one shipment every week), completing the final shipment by the end of 2020. The shipped MCH, separated into hydrogen and toluene at the dehydrogenation plant in Keihn Refinery, Kawasaki, is used in a gas turbine at the Mizue Thermal Power Plant of Toa Oil Co. for power generation (The Star 2020). The separated toluene is transported back to Brunei Darussalam for binding again with hydrogen. The criticality of this supply chain for hydrogen is focused on shipping, and this is where NYK's role as a shipper comes to the fore. AHEAD has plans to transport 0.35 million tonnes of hydrogen annually by 2030, which could be used to power a 1-gigawatt plant, and is seeking to resolve issues regarding the scale and logistics of this operation (Reuters 2020).

This pilot project and the pilot shipment by Saudi Aramco clearly indicate that the Japanese government is maintaining pace with its 2014 Strategic Road Map for Hydrogen and Fuel Cells. The road map stated that the demonstration of the storage and transportation of imported hydrogen should be completed by 2020. The road map sets out the introduction of hydrogen power generation by 2030 in Japan and the use of zero-emission hydrogen in manufacturing, transportation and storage by 2040 (Chiyoda Corporation n.d.).

Japan is involved in several hydrogen export projects similar to those in Brunei and Saudi Arabia. They include the construction of a liquefaction, storage and loading terminal, using lignite as a feedstock, in Victoria, Australia, and a renewables-based green hydrogen project in Norway. The latter is a partnership between Kawasaki Heavy Industries, Nel Hydrogen, Mitsubishi and Statoil (Karagiannopoulos 2017).

Japan has not been alone in pursuing a hydrogen-based economy. European nations like Germany, the Netherlands, and Portugal have started to roll out domestic hydrogen strategies and have sought to secure hydrogen imports for their future needs. Germany has been talking to nations as diverse as Nigeria, the Democratic Republic of Congo and Australia to secure hydrogen imports.

Hydrogen has great potential, but policy support is vital

In BP's Energy Outlook 2020, the role of carbon-neutral hydrogen is negligible under its base-case scenario. However, it will constitute 7% and 16% of the total primary energy consumption by 2050 in their carbon-constrained scenarios *Rapid* and *Net-Zero*, respectively (BP 2020). BP estimates that blue and green hydrogen will have an even split in the share of the primary energy. Saudi Arabia is one of the few countries fortunate enough to have the vast resources needed to produce blue and green hydrogen at low cost, meaning that it would play a vital role in scaling-up hydrogen production. Policymakers in Asia and Europe have been supportive of hydrogen, and national hydrogen roadmaps illustrate the significant role hydrogen imports could play in helping countries in these regions meet their respective targets. Saudi Arabia could be extremely competitive in the hydrogen market, located between large and growing hydrogen demand centers in Europe and Asia.

Neom and Saudi Aramco's announcements indicate that policy in the Kingdom is headed toward supporting both blue and green hydrogen. Saudi Arabia can leverage its shipping and trading expertise, as well as its existing relationships with its energy partners to offer hydrogen as an additional product within its export portfolio. As one of the first movers, it can gain an advantage in securing exclusive contracts with key buyers and service contractors. This would enable the country to get a competitive edge and establish a large presence in the hydrogen markets. However, the cost of carbon-neutral hydrogen production and storage remains prohibitive. Large investments are required to scale-up hydrogen production to make a meaningful contribution to mitigating carbon emissions. According to BloombergNEF, $11 trillion of investments in supply and infrastructure are required for hydrogen to meet a quarter of final energy demand by 2050 (BloombergNEF 2020).

COVID-19 has had a large negative impact on the global economy, which has affected the abilities of governments to invest in new projects. The hydrogen economy continues to hold promise for a cleaner and greener world. However, it will require increasing investments and policy focus to come to fruition.

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