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Commentary

Fostering Net-Zero Transition Pathways:
The Role of Clean Hydrogen

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> **“Potential hydrogen applications could accelerate renewable energy deployment. They can also help create decarbonization opportunities that require limited low-carbon options.”**

Context

In early 2022, 80 countries (including Saudi Arabia), representing around 74% of global greenhouse gas emissions, pledged to reach net-zero emissions (NZE) in the coming decades (Climate Watch 2022). Achieving these ambitious climate policy objectives requires shifting the energy mix toward existing and emerging low-carbon technologies. Hydrogen can enable renewable electricity integration through storage and load balancing. It can also be used as a feedstock (notably for refining and ammonia) or as energy for fuel cells in transport applications. Potential hydrogen applications could help accelerate renewable energy deployment. They can also help create decarbonization opportunities that require limited low-carbon options, such as in heavy industries (e.g., steel) or heavy-duty vehicles and vessels. The development of clean hydrogen could be a key enabler in national energy plans to reach NZE targets. By June 2021, 13 countries had released a national hydrogen strategy, while 19 were in the process of formulating strategies, including Saudi Arabia (World Energy Council 2021).

Clean Hydrogen has the Potential to Support Global Net-zero Transitions if Conditions of Scale, Cost-Competitiveness and Market Integration are Met

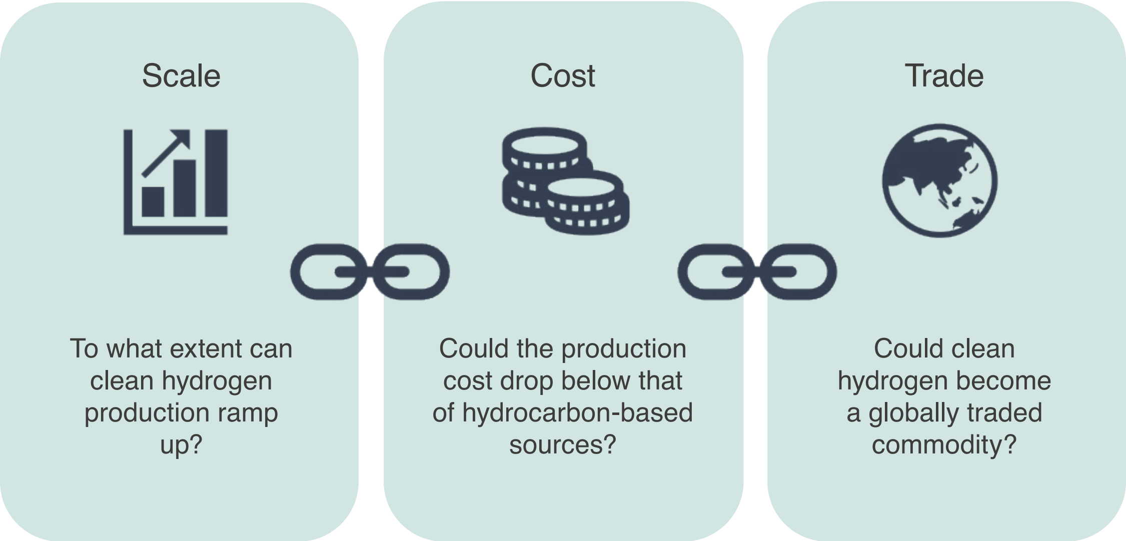
> **“Currently, 96% of hydrogen is supplied from hydrocarbons, generating about 830 Mt of global CO2 emissions per year.”**

In 2020, global demand for hydrogen reached 88.5 million tonnes (Mt) (IEA 2021a). Around 42% of the world’s hydrogen demand comes from the refining industry, where it is mainly used in chemical processes such as separating sulfur. The remaining share is used primarily to produce ammonia for fertilizers. Currently, 96% of hydrogen is supplied from hydrocarbons, that is, gray hydrogen. Gray hydrogen mostly comes from natural gas through steam methane reforming, in which the gas is mixed with high-temperature steam to produce synthetic gas (syngas). The syngas is mixed with water to produce hydrogen and carbon dioxide (CO2), which are separated through selective absorption. This results in CO2 being released into the atmosphere. Gray hydrogen currently generates about 830 Mt of annual global CO2 emissions (Patonia and Poudineh 2022). Although gray hydrogen is the most economical option for hydrogen manufacturing, the process of generating it is highly carbon intensive. For each tonne of hydrogen produced, approximately 9 tonnes of CO2 are emitted (Fattouh 2022). Therefore, as demand for hydrogen grows, the industry faces a challenge to decarbonize its supply and become an energy carrier in net-zero pathways.

Clean hydrogen is produced using low carbon technologies through two main processes, resulting in blue and green hydrogen. Blue hydrogen production uses a process similar to that of gray hydrogen. However, instead of CO2 being released, it is captured or utilized in other industrial processes through carbon capture, utilization and storage (CCUS) facilities. Green hydrogen is produced using electrolysis: splitting the water molecule into hydrogen and oxygen using electricity from renewable sources. Four electrolysis technologies are currently utilized for green hydrogen production: alkaline water (ALK), polymer electrolyte membrane (PEM), anion exchange membrane (AEM) and solid oxide electrolyzers (SOEC). While ALK and PEM are commercially available technologies, AEM and SOEC are limited to the lab scale.

By the end of 2021, 327 clean hydrogen projects were operational worldwide, with a total production capacity of 0.87 Mt (IEA 2021c). Of these 327 plants, 75% produce hydrogen for mobility and power generation end uses (some plants are multipurpose). However, only 10% of the projects have an industrial end use in refineries, methanol production, iron and steel or other industries (IEA 2021c). The pipeline of clean hydrogen projects includes around 4.6 Mt of output by 2030. However, this production level falls far short of meeting industrial clean hydrogen demand (i.e., demand from iron and steel, ammonia, methanol and other activities) to be on track to reach the global NZE scenario. In the NZE scenario, industrial clean hydrogen projects must be ramped up globally to reach 21 Mt by 2030 (IEA 2021a). Clean hydrogen production must be accelerated in many locations to close the 78% supply gap between ongoing projects and potential demand, and to contribute to potential abatement efforts. Clean hydrogen has the potential to contribute 8% of abatement efforts and meet around 19% of the final energy demand required for a net-zero pathway by mid-century (IEA 2021d). To support a global NZE transition, clean hydrogen production must meet three conditions: scale up production, bring down costs and create an integrated market (Figure 1).

Figure 1. Potential enablers to foster clean hydrogen's role in net-zero transitions.



To what extent can clean hydrogen production ramp up?

Could the production cost drop below that of hydrocarbon-based sources?

Could clean hydrogen become a globally traded commodity?

Source: Authors.

First Enabler—*Scale*: Clean Hydrogen Production Could Reach 75-150 Mt by 2030 and Exceed 500 Mt by 2050

Although clean hydrogen's share in global hydrogen supply remains marginal, its production began almost a half-century ago. In one of the early green hydrogen projects in the Cusco region of Peru, hydrogen has been produced using electrolysis for ammonia manufacturing since 1965 (IEA 2021b). The clean hydrogen industry's challenge is to expand the scale of production to unlock its decarbonization potential. Clean hydrogen could play an important role in the net-zero transition pathways as it has the potential to abate 60 gigatonnes (Gt) of CO2 cumulatively by 2050 – the fourth-highest abatement potential after wind and solar, electric vehicles and energy efficiency (IEA 2021d). Some estimates consider the abatement potential of clean hydrogen to reach around 80 Gt of CO2 by 2050. This corresponds to around two years of current global emissions, thus highlighting hydrogen's significant contribution toward reaching NZE by mid-century (Hydrogen Council and McKinsey & Company 2021). If scaled up, clean hydrogen could be almost fully decarbonized by 2050. In the following section, we highlight potential enablers for scaling-up blue and green hydrogen production and targeted output over the coming decades.

> **"The clean hydrogen industry's challenge is expanding the scale of production to unlock its decarbonization potential. Clean hydrogen could play an important role in the net-zero transition pathways as it has the potential to abate 60 Gt of CO2 cumulatively by 2050."**

Slow deployment of CCUS projects at scale delayed blue hydrogen's takeoff, but the project pipeline shows an accelerating trend. By September 2021, only around 36.6 Mt of CCUS capacity was operational worldwide, mostly concentrated in the United States due to the country's policies in support of CCUS (Global CCS Institute 2021). Current CCUS projects have comprised less than 15% of planned blue hydrogen projects over the last three decades (Wang, Akimoto, and Nemet 2021). Several factors have caused this delayed uptake in CCUS projects, despite their proven scalability potential. The leading causes of this delay are the absence of a supportive regulatory framework and uncertainties regarding the viability of its business model, and thus the potential for investors to recover their initial investments (Fattouh 2022). Although CCUS remains relatively less mature as an abatement technology than, for instance, electrification, recent pledges to reach NZE targets have spurred CCUS deployment. An additional 111 Mt of CCUS projects are currently in development (of which 28% are in advanced development). These projects, 30% of which will be hydrogen production facilities, are expected to be operational by 2030 (IEA 2021e).

The development of CCUS projects is expected to accelerate over the coming years. However, it still lags the goal of reaching 1.3 Gt of CO2 storage and utilization capacity by 2030 to meet current NZE targets (IEA 2021d). Recent large-scale projects, notably by major oil companies, highlight their willingness to launch blue hydrogen projects and to support their viability. Equinor's blue hydrogen project is located at Saltend Chemicals Park in the United Kingdom (U.K.); it comprises a 600 megawatt (MW) auto thermal reformer, capturing around 0.9 Mt of CO2 emissions per year (Equinor 2020). Shell and Uniper signed an agreement on a 720 MW blue hydrogen plant (from natural gas) that will capture 1.6 Mt of CO2 per year; the plant will be operational in 2027 (Uniper 2022). Alternative methods, for example, auto thermal reforming, could present lower-cost pathways to produce blue hydrogen (Oni et al. 2022). However, it is estimated that around 60% of future large-scale projects will continue to rely on current infrastructure, using conventional steam methane reforming (Clarke and Della Vigna 2022). Such projects can accelerate the process of achieving the economies of scale required to produce blue hydrogen at levels close to those of gray hydrogen. This will improve blue hydrogen's financial viability as CCUS deployment reduces the incremental cost of moving from gray to blue hydrogen.

Green Hydrogen Presents Significant Scalability Potential, Benefitting from the Increase in the Count and Size of Renewable Energy Projects

The current production capacity of green hydrogen is marginal compared to its potential, given the large deployment of renewable energy. By 2020, only around 300 MW of renewables-based electrolysis capacity was operational worldwide (IEA 2021a). While the total current installed capacity remains small, project metrics highlight a significant improvement in size. Most electrolysis projects installed a decade ago were at the kilowatt scale. Many recent projects are now at the megawatt scale, with some reaching a 50 MW capacity, such as the Haiperer project in China, powered by an onshore wind farm (IEA 2021c). The current projects pipeline already reflects the scalability of green hydrogen projects. The average project size could increase by a factor of one hundred (from 2 MW to 200 MW) as early as 2025, before reaching the gigawatt (GW) scale by 2030 (Clarke and Della Vigna 2022). Strong government commitment – through funding, innovation and dedicated policies – to support green hydrogen development will drive up investment (World Energy Council 2021). Countries with large renewable energy potential, mostly solar, have announced multi-gigawatt projects over the past decade. Chile’s national hydrogen strategy targets 25 GW of green hydrogen by 2030 (Government of Chile 2020), while British Petroleum (BP) recently concluded a strategic partnership with Oman to support a multi-gigawatt development in renewable energy and green hydrogen by 2030 (BP 2022). In April 2022, the French utility group EDF launched a plan to develop 3 GW of electrolytic hydrogen worldwide by 2030. The plan involves investments worth between 2 billion euros and 3 billion euros (EDF 2022). Therefore, as part of the efforts to reach NZE by mid-century, green hydrogen will benefit from the large deployment of renewable energy. Electrolysis capacity is estimated to reach 3-4 terawatts, representing between 15% and 25% of the renewable energy additions up to 2050 (Hydrogen Council and McKinsey & Company 2021).

Combining the factors mentioned above highlights the momentum of clean hydrogen as an enabler of the NZE transition. The output is expected to increase to several million tonnes by 2030, with steeper acceleration after 2050. Depending on the scenario, clean hydrogen production could reach between 75 and 150 Mt by 2030 and between 500 and 660 Mt by 2050 (Clarke and Della Vigna 2022; IEA 2021d; Hydrogen Council and McKinsey & Company 2021). Gray hydrogen will continue to account for a significant output until 2030. However, the output will be almost fully decarbonized by mid-century, with over half (i.e., around 60%) coming from green hydrogen and the remainder from blue hydrogen.

Investment in clean hydrogen should ramp up globally to bring output to levels compatible with the NZE transition. Until 2030, the required investment in the clean hydrogen value chain – production, infrastructure (conversion, transport and storage) and end-use – will be significant. Green hydrogen generation alone would require a cumulative investment of US$250 billion to US$300 billion by 2030 (Clarke and Della Vigna 2022; Hydrogen Council and McKinsey & Company 2021). Accelerating

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the clean hydrogen value chain's contribution to NZE could require up to US$700 billion by 2030, a significant portion (77%) of which remains uncertain. Therefore, funding is a critical enabler of scaling up clean hydrogen and achieving the necessary cost reductions to unlock its decarbonization potential in fostering the NZE transition.

Second Enabler—Cost: Green Hydrogen Costs Could Drop Below US$2 per Kilogram (kg) by 2030 and Below US$1/kg by 2050

A significant cost gap still exists between clean and gray hydrogen. Depending on several factors, including fuel cost and capital and operational expenditures, gray hydrogen's production cost, which ranges between US$0.8 and US$2.0 per kilogram (US$/kg), will remain below that of blue hydrogen (~US$1.6-2.5/kg) and green hydrogen (~US$2.4-6.3/kg) (Clarke and Della Vigna 2022; IRENA 2020). This cost gap represents a major barrier to clean hydrogen adoption worldwide and justifies its current marginal share in global hydrogen production. However, there is significant scope to cut the production cost of clean hydrogen. By 2030, clean hydrogen could provide immediate decarbonization solutions for industry, power generation and transport, as it gains competitiveness in 22 end uses (World Energy Council 2021). The scalability factor discussed above and funding and innovation will enable cost reductions and bring blue and green hydrogen cost levels on a par with or below those of gray hydrogen. This will support hydrogen's competitiveness in the NZE transition. Below, we address the key barriers and enablers to achieving clean hydrogen cost reduction.

Blue hydrogen can only become competitive under a supportive carbon-pricing scheme. In the absence of a cost on carbon emissions, blue hydrogen cannot compete with gray hydrogen. This is because the former faces the incremental costs of capturing, transporting and storing carbon. Currently, the cost of blue hydrogen is around 10%-20% above that of gray hydrogen (Fattouh 2022). The scaling up of CCUS technologies would bring economies of scale, making blue hydrogen more cost competitive. However, its cost gap with gray hydrogen would not close completely. The cost difference remains significant enough to disincentivize an automatic shift toward abating carbon emissions from hydrogen production.

"As carbon-pricing policies begin to take effect in countries that are enforcing their NZE plans, the economic viability of blue hydrogen will improve."

As carbon pricing policies begin to take effect in countries that are enforcing their NZE targets, the economic viability of blue hydrogen will improve. By 2021, 64 carbon pricing initiatives comprising explicit carbon taxation and trading mechanisms are operational worldwide, covering 21.5% of global greenhouse gas emissions (World Bank 2021). In 2021, CO2 prices remained below the range compatible with the Paris Agreement objectives of US$40-80/tonne of CO2 equivalent. Fewer than 4% of global emissions were at prices above that range. However, during the first half of 2022, European carbon prices remained mostly above US$80/tonne, a level sufficient to support blue hydrogen competitiveness.[1] Estimates show that a carbon price of US$55-65/tonne would ensure a breakthrough for blue hydrogen in Europe (Peters et al. 2020).[2]

The future costs of fuel (coal for gasification or natural gas for methane reforming) and the underlying costs of carbon (capturing, transporting and storing carbon) will determine blue hydrogen's competitiveness. Increasing feedstock prices could undermine blue hydrogen's competitiveness. At high natural gas prices (e.g., above 90 euros per megawatthour during extended periods in Q1 2022 and Q2 2022) combined with current carbon prices (e.g., above US$66/tonne), hydrogen production costs exceed US$6/kg (Hieminga and Tillier 2021).[3] At this price level, the cost of blue hydrogen is around three times that of pre-pandemic gas prices at around US$20 per megawatthour (MWh). It is also above the high-end production cost of green hydrogen. Other uncertainty factors facing blue hydrogen lie in the development of CCUS as an immature technology with its high costs, most of which are sunk costs, thus discouraging investment (Yu, Wang, and Vredenburg 2021). Moreover, blue hydrogen is still not carbon free, with a reported leakage rate of around 10%-15%. While carbon capture rates are technically and economically achievable, improving CCUS technology is critical to blue hydrogen's competitiveness. This is because it will allow natural gas to retain its market share beyond 2050 (Fattouh 2022; Budinis et al. 2018).

Reducing green hydrogen costs could make green hydrogen the ultimate decarbonization alternative. While feedstock prices and carbon prices increase the volatility of the cost of blue hydrogen, the competitiveness of green hydrogen mostly depends on capital-driven factors. Two factors are key in driving the cost reduction of green hydrogen: the price of electricity and electrolyzers. The electricity price is the main cost component, accounting for 58% of green hydrogen's costs, followed by electrolyzers' capital costs at 25% (Clarke and Della Vigna 2022). Currently, the cost of green hydrogen is around US$5/kg on average, making it uncompetitive with gray and blue hydrogen (IRENA 2020). Green hydrogen production costs could be reduced through innovation and scale to US$2/kg by 2030 and US$1/kg by 2050 (Clarke and Della Vigna 2022; IRENA 2020).

The first cost factor, renewable electricity, has witnessed a significant reduction over the last decade. The levelized cost of solar photovoltaic (PV) and wind power fell by 85% and 56%, respectively, between 2010 and 2020. Since 2015, renewable energy additions have exceeded that of non-renewable energy, as renewables became competitive with hydrocarbon-based generation in most locations globally. Currently, solar PV and wind's weighted average levelized cost (around US$40/MWh) is below that of fossil generation, which ranges from US$50/MWh to US$150/MWh (IRENA 2022a). In the Gulf region, the prices of solar PV reached record-low levels of below US$16/MWh for bids in Qatar, the United Arab Emirates and Saudi Arabia. Green hydrogen's production cost (US$15/MWh) falls below that of gray and blue hydrogen under current natural gas prices in the European markets, even without a carbon tax (Clarke and Della Vigna 2022). Although wholesale electricity prices remain volatile, improving renewable energy metrics, such as load factors, will further improve the cost-competitiveness of green hydrogen. Wind and solar PV's load factor (i.e., the theoretical number of hours during which the plant generates electricity) could reach 50% for wind or combined wind in some locations. High load factors for renewable energy could permanently reduce generation costs, driving down green hydrogen production costs. Reducing electricity costs, from around US$50/MWh to around US$20/MWh, would reduce green hydrogen's production costs

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by almost US$1.5/kg (IRENA 2020). At electricity prices below US$30/MWh, green hydrogen could already be competitive with blue hydrogen and compete with grey hydrogen at electricity prices below US$20/MWh (Clarke and Della Vigna 2022).

The second cost factor, electrolyzers, could witness a similar learning rate as that observed for renewable energy and batteries.[4] The current average electrolysis system capital cost exceeds US$700/kW and has the potential to drop to around US$500/kW by 2030 (Clarke and Della Vigna 2022). The small size of electrolyzers contributes to their high capital cost, highlighting a need to scale up electrolysis plants. Currently, the capital cost of a typical 5 MW electrolyzer could be reduced by 75% for capacities above 50 MW through scale factors and technological improvements (Böhm et al. 2020). As projects enter the GW scale, costs will drop further. After 2030, the cost of electrolyzers could be reduced by 80% to permanently remain at around US$200-300/kW. This could help reduce the cost of green hydrogen by almost 1.5 US$/kg (IRENA 2020). In fact, electrolyzers are the biggest supporting factor in reaching a production cost of US$1/kg for green hydrogen. Other supporting factors could help reach the US$1/kg benchmark for green hydrogen by mid-century. The International Renewable Energy Agency predicts that the efficiency of electrolyzers could improve by 17%, full load hours could increase by 31% and the installation lifetime could double to 20 years (IRENA 2020). The US$1/kg price level is critical to NZE plans as it enables green hydrogen to compete with gray hydrogen in industrial heat – one of the hardest sectors to abate (Hydrogen Council and McKinsey & Company 2021).

Third Enabler—Trade: Around One-Third of Clean Hydrogen to be Traded Through a Cross-Border Exchange

Currently, cross-border hydrogen trade is almost non-existent. Nearly all hydrogen is consumed close to the point of production. This is mostly due to hydrogen’s low volumetric energy density compared to traditional gaseous and liquid fuels. This makes it challenging to transport large volumes of hydrogen cost-effectively. However, as policymakers have included hydrogen as part of their NZE decarbonization plans, demand for hydrogen as an energy carrier is likely to grow. Many countries have recognized, through their national hydrogen strategies, the need for hydrogen imports to meet their targets. It is estimated that around one-third of green hydrogen produced by 2050 will be traded across borders (IRENA 2022b). The European Union (EU) bloc and countries such as Germany, the Netherlands, Japan and South Korea consider imports important to close the supply-demand energy gap in the energy transition.

There are various ways to transport hydrogen, with each presenting advantages and disadvantages according to the travel distance, the available infrastructure and the end-use. Similar to natural gas, transporting hydrogen via pipelines, where possible, is the most cost-effective way to supply it to end-users. There are only about 4,600 kilometers (km) of hydrogen pipelines in the United States and Europe, compared with around 1.4 million km of natural gas transmission pipelines worldwide (IRENA 2022b). Several natural gas transmission system operators are considering blending hydrogen with natural gas in existing natural gas pipeline networks. Snam, one of Europe’s largest gas system operators, has been experimenting with a 10% hydrogen blend, by volume, in its pipeline networks (Jewkes 2021). High exposure of hydrogen to certain steels can be problematic as hydrogen can cause embrittlement, which increases the risk of cracking. Thresholds beyond which hydrogen causes the embrittlement of specific steel grades are rarely explored in the literature, and the long-term impacts of hydrogen blending need to be assessed (Trautmann et al. 2020). Snam states that 70% of its natural gas pipelines are made from hydrogen compatible material (Snam 2022). However, end-use appliances, such as boilers and power plants, and industrial processes will also have to be upgraded to accommodate hydrogen, if possible.

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The European Hydrogen Backbone (EHB), an initiative by a group of European energy infrastructure operators, is one of the most ambitious cross-border hydrogen pipeline projects. It connects 25 EU countries in addition to Norway, the U.K. and Switzerland (EHB 2022). Two-thirds of the EHB convert existing natural gas pipelines, and newly constructed hydrogen pipelines make up the remaining third. This network will cover regionally produced and imported hydrogen. However, in the absence of pipelines, transporting hydrogen from distant regions, where favorable conditions allow for low-cost and low-carbon hydrogen, to end-users around the world will require shipping it in liquid form or using a carrier such as ammonia or a liquid organic hydrogen carrier (LOHC). Shipping hydrogen in the form of ammonia is popular as it takes advantage of the existing and robust global ammonia supply chain, including ships, ports and storage tanks. Ammonia’s energy density per unit of volume is also superior to that of liquid hydrogen, making it easier and less costly to store and transport. Additionally, less energy is needed to liquefy ammonia compared to liquid hydrogen (-33 degrees Celsius [°C] for ammonia versus -253°C for liquid hydrogen) and to maintain it in liquid form throughout its journey. The biggest downside to ammonia is the high energy required for its reconversion to hydrogen, which corresponds to energy losses of 15%-33% (IRENA 2022b). Therefore, Japan opted to use ammonia in power generation directly, as part of a Saudi-Japan demonstration project to explore low-carbon ammonia’s production and delivery from Saudi Arabia to Japan (Shabaneh, Al Suwailem, and Roychoudhury 2020).

Ammonia is also highly toxic, and safety standards currently observed in the chemical sector must be transferred and tailored to new end uses. Nevertheless, ammonia has been chosen as the carrier in many projects. Almost 85% of the proposed, export-oriented hydrogen projects intend to use ammonia as the carrier (Tomnay 2022). To date, there is no commercial vessel that can ship liquid hydrogen. The Suiso Frontier was the first ship to test the transport of liquid hydrogen on a deep sea route from Japan to Australia as part of the Hydrogen Energy Supply Chain Pilot Project (HESC 2022). It is unclear how the cost of liquid hydrogen transport would fare against other carriers in the future. However, the evolution of hydrogen transport technologies and costs will play an important role in shaping future trade flows and determining the hydrogen market’s growth.

Another essential aspect for facilitating commercialization and accelerating the cross-border trade of low-carbon hydrogen is the establishment of international standards. Cleaner pathways for hydrogen production are typically more expensive than traditionally produced hydrogen from hydrocarbons without carbon management. Thus, buyers of low-carbon hydrogen require a certificate that verifies the carbon content of the product they are buying.

Currently, there are various certification schemes in different stages of development. However, a globally recognized certification scheme could accelerate the development of hydrogen projects and trade.

What Opportunities Exist for a Clean Hydrogen Economy in Saudi Arabia?

Saudi Arabia views hydrogen as one of the main drivers in achieving its emissions reduction goals. In October 2021, during the Saudi Green Initiative (SGI), Saudi Arabia announced an NZE target to be achieved by 2060. It also upgraded its nationally determined contribution under the Paris Agreement to avoid generating 278 Mt of CO2 equivalent by 2030 (UNFCCC 2022). To meet its emissions reduction targets, the Kingdom identified various approaches and initiatives, such as enhancing its energy efficiency standards, increasing its renewable energy capacity and developing carbon capture technologies (SGI 2021). Low-carbon hydrogen production and exports are also among the initiatives it announced at the SGI.

The Kingdom plans to produce 4 Mt of low-carbon hydrogen by 2030 to avoid generating 27 Mt per annum of CO2 (SGI 2021). Thus far, however, only the Helios green hydrogen project in Neom, with a capacity of about 240,000 tonnes per annum, is under development. While these targets are ambitious, the potential costs and resources needed to produce large volumes of low-carbon hydrogen are quite significant. The Kingdom enjoys one of the lowest costs of renewable energy in the world. It also has vast and low-cost natural gas reserves and space for geologic carbon sequestration – key components of green and blue hydrogen production. The cost of producing green hydrogen is expected to fall by around 30% by the end of the decade (Hasan and Shabaneh 2022). This is driven by further cost declines in renewable electricity and electrolyzers, and high-capacity factors for electrolyzers in Saudi Arabia for hybrid PV-wind applications. Blue hydrogen's potential in Saudi Arabia is also significant as the Kingdom is home to the eighth-largest natural gas reserves in the world and has ample geologic space for CO2 sequestration. It currently operates one of the largest carbon capture and storage units in the region, capturing 800,000 tonnes of CO2 annually to enhance oil recovery (Braun and Shabaneh 2021). SABIC, Saudi Arabia's largest petrochemical company, operates the largest CO2 purification plants in the world. It captures 500,000 tonnes of CO2 per year, purifies it and distributes it to nearby urea and methanol plants and the food and beverage industry (SABIC 2022).

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In addition to exports, domestic hydrogen use has garnered interest. This is particularly apparent in the transport sector: The government signed eight memorandums of understanding (MoUs) with various entities to explore hydrogen use in fuel-cell vehicles, rail and the production of sustainable jet fuel (Saudi Gazette 2022). Saudi Arabia is also home to large carbon-intensive sectors, such as chemicals, cement and steel, where hydrogen can play an important role in decarbonizing some applications. However, the plans for domestic uses of hydrogen are limited to transportation use. As for exports, the Kingdom has a geographic advantage, situated in proximity to the potentially large hydrogen-consuming regions of Europe and Asia. Saudi Aramco has also signed an MoU with South Korea's Hyundai

Heavy Industries to explore research and development opportunities regarding blue hydrogen and ammonia, and the Public Investment Fund signed an MoU with Samsung and the Korean steel-making company POSCO to develop an export-oriented green hydrogen project (Arab News 2022; Aramco 2021). Saudi Arabia signed an MoU with Germany, a potential export market, to collaborate on issues pertaining to technology, business and regulation (BMWK 2021).

Currently, there is a large focus in Saudi Arabia on utilizing renewable electricity and natural gas to displace liquid fuels from the power sector, where they occupy a large share of the power mix. The Kingdom has set a target for equal shares of power generation from renewable electricity and natural gas by 2030 (Alshammari 2021). The renewable electricity and natural gas capacity required to reach those targets, however, will be quite significant, and increasing those capacities for future hydrogen projects could be challenging. To put this in perspective, producing 1 Mt of green hydrogen would require over 10 GW of electrolyzer capacity, assuming a load factor of 50%. It would also require around 20 GW of renewable energy capacity, which could power approximately 3 million homes. The production of hydrogen from steam methane reformation is more efficient than that of green hydrogen via electrolysis. Thus, blue and green hydrogen are important and complementary technologies for achieving the Kingdom’s hydrogen goals.

To achieve carbon neutrality, a regulatory framework conducive to low-carbon investment is needed. The Circular Carbon Economy (CCE) framework, which was pioneered in Saudi Arabia during its presidency of the G20, is expected to support such investment through incentives and regulations while maintaining socioeconomic development. To ensure a smooth transition, the CCE National Program has been introduced to bring together stakeholders from industry, research institutions and the government. This program is currently being implemented to promote the CCE and achieve its climate neutrality goals.

Conclusion

The current momentum for the NZE transition is strong, with countries committing to reach that target in the coming decades. Clean hydrogen can constitute a key pillar in achieving the NZE transition by supplying fuel for sectors that are hard to abate. Currently, clean hydrogen represents a marginal fraction of the global hydrogen supply, demand for which is still met by hydrocarbons, mainly natural gas, without abated emissions. Several countries have issued a national hydrogen strategy with the aim of scaling up clean hydrogen production. Supporting policies focus on enhancing funding, innovation and international collaboration. Experts anticipate a leap in clean hydrogen projects. However, although the outlook for clean hydrogen looks promising, it is conditional on meeting three conditions: scale, cost and trade. First, projects for both blue and green hydrogen will benefit from an increase in the project size for CCUS facilities and renewable energy projects. Second, large-scale projects can help achieve significant cost reductions through technological learning regarding carbon storage and transportation and renewable energy deployment. However, policies and innovation remain critical to cost reduction. An effective carbon pricing policy is fundamental to blue hydrogen’s cost competitiveness, while innovation in electrolyzers will help achieve most of the cost reductions needed to make green hydrogen cost competitive. Third, the deployment of clean hydrogen projects will be geographically unbalanced. Setting reliable and effective transportation means and policies between importing and exporting regions is an important factor for clean hydrogen's success as an energy carrier in the NZE transition. However, the commoditization of clean hydrogen raises issues regarding end-use tracking, data availability and certification of origin. We leave these aspects to be tackled in future research.

Entnotes

[1] Up-to-date European Trading System carbon prices are available at https://ember-climate.org/data/data-tools/carbon-price-viewer/

[2] We use an exchange rate of 1 euro = US$1.1.

[3] Natural gas reference prices for Europe are available at https://www.theice.com/products/27996665/Dutch-TTF-Gas-Futures/data?marketId=5387641.

[4] The learning rate of technology captures the cost evolution as the cumulative output doubles.

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About the Project

Hydrogen is emerging as an important energy vector that can accelerate the path toward net-zero emissions. Given its diverse applications and its potential to abate carbon emissions, it is ideally suited to be an enabler of the circular carbon economy. This project aims to investigate the different pathways toward a hydrogen economy and the role of resource-rich countries in offering low-cost clean hydrogen solutions.

About KAPSARC

KAPSARC is an advisory think tank within global energy economics and sustainability providing advisory services to entities and authorities in the Saudi energy sector to advance Saudi Arabia's energy sector and inform global policies through evidence-based advice and applied research.

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