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How the GCC can become a force in global green hydrogen

The green ammonia supply chain

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EXECUTIVE SUMMARY

The rapid shift to green hydrogen presents Gulf Cooperation Council (GCC)[1] countries with an opportunity to play a leading role in this new industry. Green hydrogen could become a major and versatile power source of the decarbonized future. The GCC holds significant advantages in the production of green hydrogen, due to abundant, low-cost solar energy. However, green hydrogen entails significant transportation costs to supply large export markets in Europe and East Asia. For that reason, the green hydrogen market will be won in the supply chain. The best way for GCC producers to supply large export markets is to use renewable energy to convert green hydrogen to green ammonia (NH_3, an effective hydrogen-carrying compound). GCC producers would then "crack" the ammonia at the export destination to extract the hydrogen for end use.

The green hydrogen economy is challenging, and will entail a new ecosystem with unique requirements and many unsettled elements. Although technically proven, green ammonia production is not yet operating at industrial levels; however, with several large-scale demonstrator projects currently under way, commercialization is imminent. At the other end of the supply chain, ammonia "cracking" technology still requires further development to extract high-purity hydrogen cost effectively at the volumes required.

To succeed, GCC countries must focus on policy imperatives over the next three to five years, in areas such as developing a national strategy; establishing the business case; launching pilot projects; and creating a supportive policy, regulatory, and investment framework. Longer term, GCC producers will have four strategic priorities to achieve scale advantages at all stages of the green ammonia value chain, encompassing production, conversion, transportation, reconversion through cracking, and delivery.

A CRITICAL COMPONENT OF THE DECARBONIZATION AGENDA

The market for green hydrogen is moving swiftly from what seemed like a future hypothetical to an extremely promising reality in which the GCC could play a leading role. Hydrogen is abundant, environmentally sustainable, energy-dense, and when produced through renewable energy is "green" — making it a critical part of the decarbonization agenda. Rapid scale and technology improvements mean that green hydrogen production costs are expected to fall sharply in the next decade, with cheaper renewable energy making an important contribution. Based on these trends, green hydrogen will likely reach a turning point in terms of adoption around 2030. By 2050, global green hydrogen demand is expected to reach over 530 million tons, equivalent to around 7 percent of global primary energy consumption.[2] This would displace 10 billion barrels of oil equivalent per year, around 37 percent of current global oil production.

At the same time, the applications for green hydrogen are growing far beyond existing uses such as feedstock for industrial processes. Over the long term, green hydrogen will become a major and versatile power source of the decarbonized future, whether powering passenger vehicles, industrial processes, or commercial transport. The transition will likely be led initially by transport applications in high-utilization and larger vehicle categories in which the total cost of ownership compared to vehicles running on hydrocarbons looks most compelling (*see "The economics of hydrogen fuel cell electric vehicles")*. Hydrogen-blending solutions in building heat and power also hold potential. Moreover, a full switchover from natural gas would unlock significant demand in areas such as industrial energy, industrial feedstock, and power system applications.

The economics of hydrogen fuel cell electric vehicles

Green hydrogen is triggering a fundamental shake-up in the transportation industry through the emergence of hydrogen fuel cell electric vehicles (FCEVs) — rivalling traditional internal combustion engine vehicles (ICEVs) and battery-powered electric vehicles (BEVs).

Generally speaking, FCEV technology has cost advantages over BEV technology for vehicle categories that have high utilization, require longer daily driving distances, or that are typically larger and heavier in size — such as trucks and buses, taxi fleets, and even forklifts. The combination of limited driving range, lengthy battery recharging time, and the extra weight, size, and complexity of the BEV battery pack for larger, heavier vehicles results in superior FCEV economics in these categories. In Germany, for example, FCEVs in the truck category are already more competitive than BEVs in terms of their total cost of ownership, and will be 30 percent more cost effective by 2030.

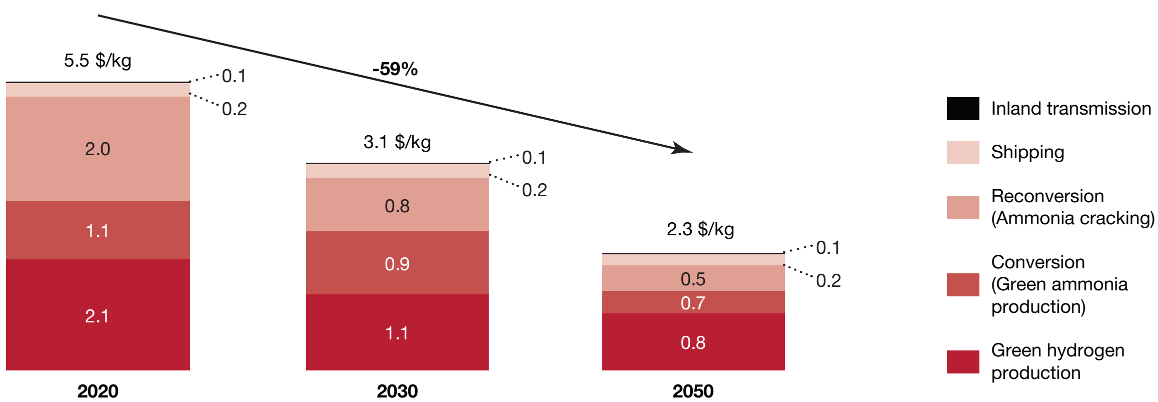
The market for passenger cars is equally promising, with FCEVs forecasted to surpass ICEVs by 2029 in terms of their total cost of ownership. Toyota is planning production of around 200,000 FCEV vehicles per year by 2025 and is targeting in excess of 500,000 units per year by 2030, with Hyundai aiming for 110,000 per year by 2025.[3] These commitments will dramatically reduce FCEV costs, due to mass-market adoption. There are questions as to whether FCEVs or BEVs ultimately will dominate the passenger vehicle market. However, it is already clear that the era of ICEVs is ending.

GREEN AMMONIA AS A TRANSPORTATION SOLUTION AND SUPPLY CHAIN CHALLENGE

The GCC possesses several advantages in producing green hydrogen, such as abundant, low cost, renewable energy resources. However, that is not enough to win in the global market. Green hydrogen transportation can be extremely expensive, costing up to twice as much as the initial production cost. As a result, the main challenge in supplying green hydrogen to large import markets like Europe and East Asia will be cost-effective transportation. GCC producers will need to achieve the lowest possible total landed cost by mastering the supply chain end to end (*see Exhibit 1*).

EXHIBIT 1

The landed cost of supplying green hydrogen to Europe from the GCC will drop by 2050
($/kg)



% of total landed cost	2020	2030	2050
Shipping and transmission	5%	9%	12%
Conversion and reconversion	57%	55%	53%
Green hydrogen production	38%	36%	35%

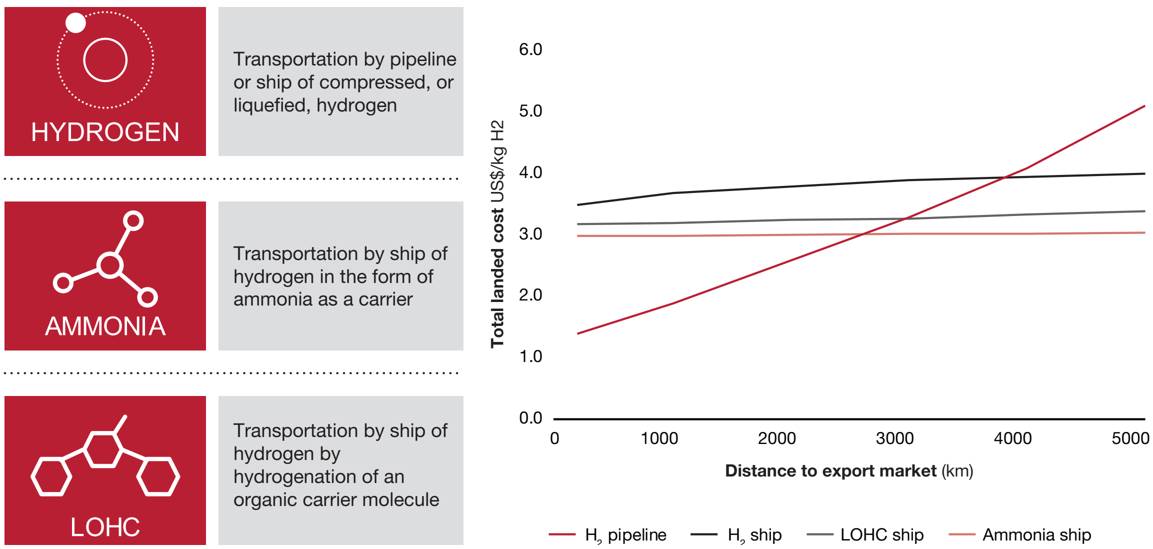
Source: International Energy Agency, "The Future of Hydrogen," 2019 (https://www.iea.org/hydrogen2019/); Strategy& analysis

Hydrogen is mostly provided in a gaseous state for end-use applications, which is difficult to transport except over short distances via pipeline. The best way for GCC producers to supply large import markets in Europe and East Asia is to convert green hydrogen to green ammonia. Upon arrival, it is then converted back to gaseous hydrogen for end users through a chemical process known as "cracking." Based on our analysis, delivering hydrogen in the form of green ammonia has the best cost advantages for export markets that are over 2,300 kilometers from production sites (*see Exhibit 2*).

EXHIBIT 2

Shipping hydrogen by ammonia ship is cost competitive for distant markets

Comparison of total landed cost by transportation method (2030)



Note: LOHC = liquid organic hydrogen carrier. Total landed cost = includes cost for conversion/liquification, import/export terminals in case of transportation by ship and reconversion in case of ammonia/LOHC.

Source: International Energy Agency, "The Future of Hydrogen," 2019 (https://www.iea.org/hydrogen2019/); The Royal Society, "Ammonia: zero-carbon fertiliser, fuel and energy store," February 2020 (https://royalsociety.org/-/media/policy/projects/green-ammonia/green-ammonia-policy-briefing.pdf); Strategy& analysis

There are several other reasons why ammonia makes sense as a transportation means for hydrogen. The ammonia value chain is already well established. Ammonia is a globally traded commodity, although production would need to increase substantially to enable large-scale hydrogen transportation. There are also existing international shipping routes that overlap with potential green hydrogen export flows, and a network of ports worldwide that can handle ammonia at industrial scale. Several initiatives are under way to make green ammonia the long-distance hydrogen carrier of choice, including high-profile projects in Australia.

Technological challenges to green ammonia
The green hydrogen economy is challenging, and will entail a new ecosystem with unique requirements and many unsettled elements. Although technically proven, green ammonia production is not yet operating at industrial scale. Ammonia production occurs through a century-old process known as Haber-Bosch, which relies on high temperature and pressure to fuse nitrogen and hydrogen. Green hydrogen and renewable electricity can reduce drastically the emissions involved in producing ammonia, making the process green if there are innovations to the production process (*see "The fundamentals of green ammonia production"*).

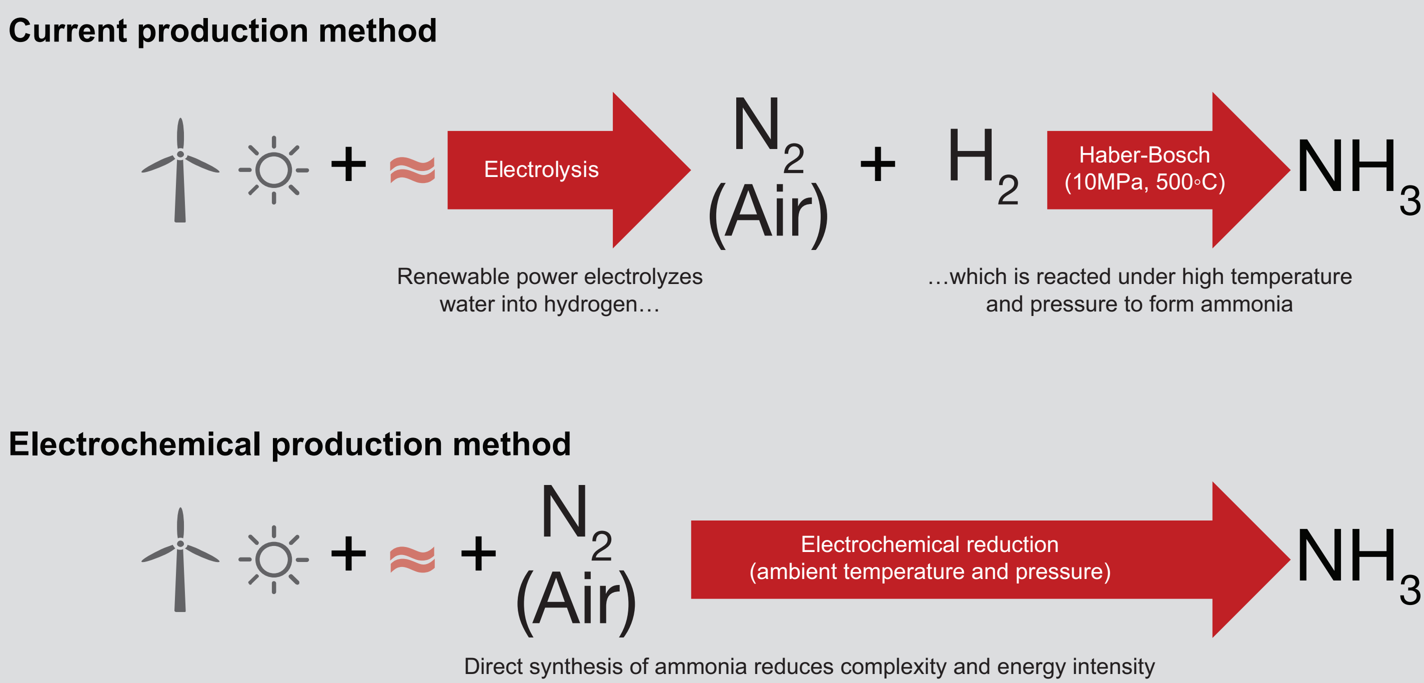
The fundamentals of green ammonia production

The processes required to manufacture ammonia sustainably are developing rapidly. At present, the main industrial means of producing ammonia is the Haber-Bosch process. It entails the catalytic reaction of nitrogen and hydrogen at high temperature (greater than 400 degrees Celsius) and pressure (more than 100 bars, or 100 times the atmospheric pressure on the surface of the earth).

To produce green ammonia, a manufacturer uses renewable energy to electrolyze water, breaking it down into hydrogen and oxygen. Simultaneously, an air separation unit generates nitrogen. The system then uses renewable energy to power the Haber-Bosch process (*see Exhibit 3*).

An electrochemical reduction alternative
In the future, electrochemical reduction could produce green ammonia directly from water and nitrogen using renewable electricity. This would cut costs significantly because it would eliminate the need for either a separate hydrogen production step or the energy-intensive Haber-Bosch process. Electrochemical reduction technology is in early and promising stages of scientific research. It will require breakthroughs in catalysts and production processes to achieve commercial viability. If it works, this production technique could substantially improve green ammonia supply chain economics, especially for exporters such as the GCC countries.

EXHIBIT 3
Green ammonia production can become simpler and more efficient



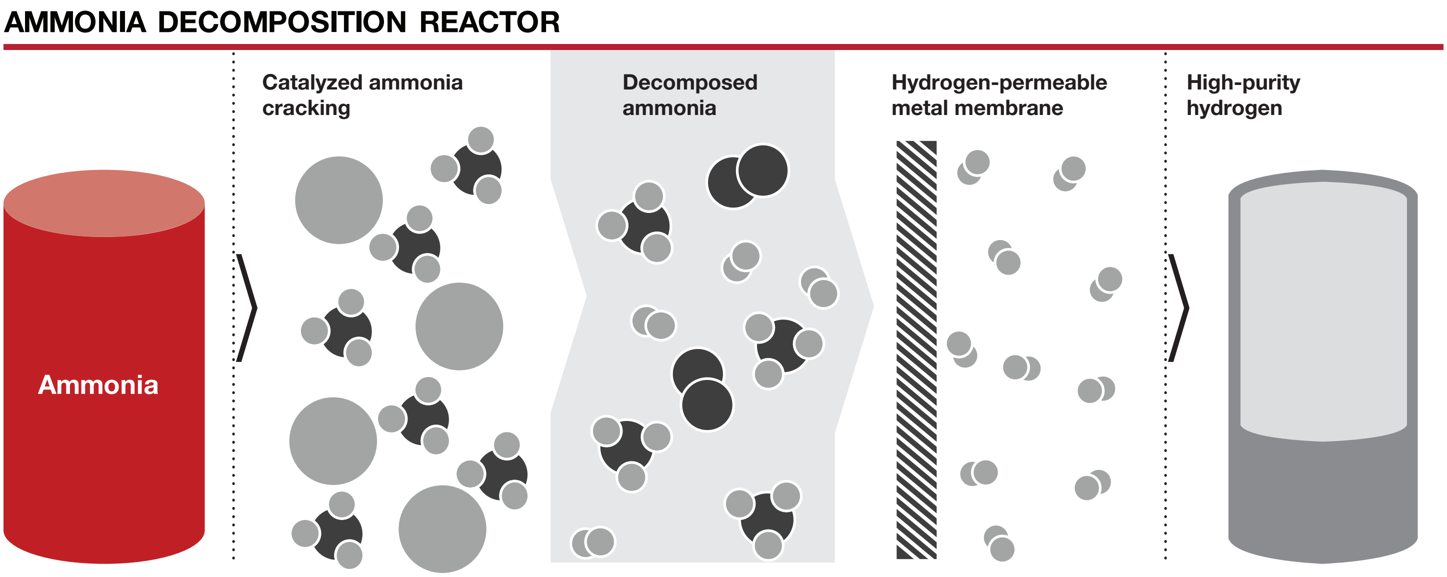
Source: Strategy&

At the other end of the supply chain, ammonia must be decomposed, or cracked, to extract high-purity hydrogen cost effectively and at large scale. This technology is still at an early stage of development, making it the least mature component of the green ammonia supply chain. At present there are no established processes to decompose ammonia into hydrogen at large scale and at fuel cell–grade purity. The best options available rely on an electric-powered furnace to apply heat and pressure to ammonia with the aid of a catalyst to produce a forming gas (a mixture of hydrogen and nitrogen). These processes rarely include any additional steps to purify the hydrogen thereafter.

Since 2019, membrane reactor technology has emerged as a potential solution to the challenge of cracking ammonia. Membrane reactor technology allows for both the chemical reaction to produce hydrogen, and the separation of hydrogen from the nitrogen in ammonia, to occur simultaneously inside the same reactor at much lower temperatures (*see Exhibit 4*). The technological process is potentially simpler, more efficient, and produces higher purity hydrogen. To date, research on membrane reactor technology has focused primarily on testing the feasibility of smaller scale cracking to support an accelerated deployment of hydrogen refueling stations. However, membranes are modular in design and so should serve both in small-scale applications and at large-scale ammonia import terminals.

EXHIBIT 4

How membrane reactor technology works



Source: The Royal Society, "Ammonia: zero-carbon fertiliser, fuel and energy store," February 2020 (https://royalsociety.org/-/media/policy/projects/green-ammonia/green-ammonia-policy-briefing.pdf); Strategy& analysis

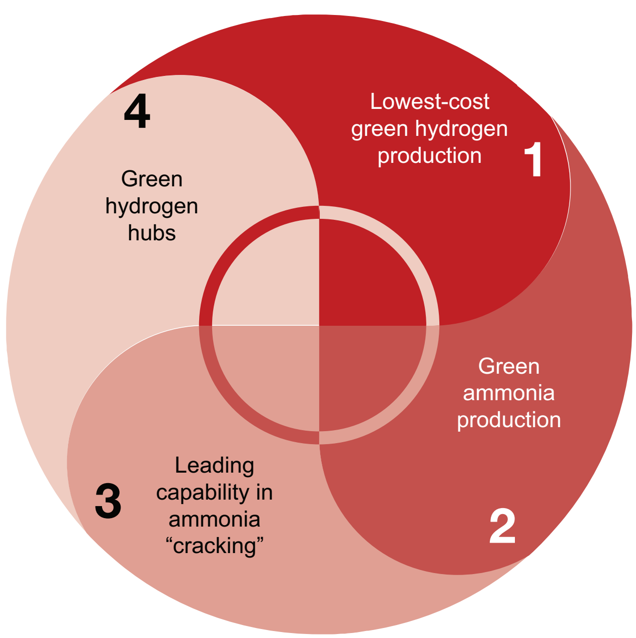
THE GREEN HYDROGEN EXPORT MARKET WILL BE WON IN THE SUPPLY CHAIN

There is an immediate imperative for GCC countries over the next three to five years to lay the groundwork for a well-functioning green hydrogen economy for domestic use and export. This requires policymakers to define a national strategy for a green hydrogen ecosystem; establish the policy, regulatory, and investment environment that will instill confidence among participants and lead to faster progress; and initiate pilot projects to develop and demonstrate green hydrogen technologies and to establish the formula for commercial success.

From an export perspective, GCC countries should raise their profile on the international stage, to help shape the standards and direction of a green hydrogen supply chain. They should also focus on international pilot projects that can improve supply chain economics for the supply of hydrogen to their target green hydrogen export markets.

Long-term strategic priorities
GCC countries need to focus on four long-term strategic priorities to successfully supply export markets with green hydrogen (*see Exhibit 5*).

EXHIBIT 5
Long-term strategic priorities for GCC producers to lead the green hydrogen export market



Source: Strategy&

1. **Establish lowest-cost, large-scale green hydrogen production capability**
   GCC countries should continue to invest in utility-scale solar farms to achieve low-cost renewable electricity input prices for hydrogen production. Simultaneously, GCC countries should deploy the electrolyzer technology most suited to large-scale green hydrogen production and capitalize on economies of scale.

2. **Focus on green ammonia production as a hydrogen carrier and storage medium**
   GCC countries should build state-of-the-art green ammonia production plants that are closely integrated with hydrogen generation. They can reduce costs and create scale advantages through technological innovation in green ammonia production, such as by adapting established processes in the short term, and dramatically improving them in the long term to rely exclusively on renewable energy. This must be a key focus area for research and development (R&D) spending and an opportunity to localize world-leading capabilities in the GCC that will underpin the new global hydrogen economy.

3. **Master ammonia cracking in key export destinations**
   Ammonia will need to be cracked back into hydrogen for use as an energy source in major green hydrogen export destinations. This process needs to occur near large end-use centers and should be integrated within port terminal infrastructure. GCC producers should establish vertically integrated cracking operations in key export markets to improve economies of scale. Such vertical integration of cracking capacity could reduce costs by 15 to 20 percent through scale advantages. Improving this cracking technology is another place where R&D investment could yield a substantial return on the landed cost of hydrogen in target markets and provide high-purity hydrogen to end users.

   The choice of export markets is critical. GCC exporters should adopt a long-term view and focus on a relatively small number of markets with sustainable demand due to high consumption and low production potential. For example, the EU, Japan, South Korea, and the U.K. all plan to become major net importers of green hydrogen. Based on current energy importing patterns, these markets could import 40 percent to 90 percent of their hydrogen demand. Cost efficiencies in the value chain will help GCC countries in these export markets. The GCC will face competition from domestic producers in the EU, which will become more important as production costs fall, and Australian producers in Japan. The Japanese market in particular will be extremely attractive. Japan is unlikely to produce much of its own green hydrogen because it lacks the space for large renewable-energy operations, which will force it to rely on imports. Australia is already targeting the Japanese market and has a well-developed national hydrogen strategy. Critically, the right export market will also be one that can partner on R&D with green hydrogen producers in the GCC, generating benefits for both sides.

4. **Create green hydrogen hubs**
   To achieve maximum cost efficiency, GCC exporters should establish integrated green hydrogen–ammonia infrastructure hubs focused on domestic production and centralized reconversion activities in export destinations. In the GCC these hubs could be co-located with, or near, renewable electricity generation. They should take advantage of current GCC port and industrial infrastructure and build on existing shipping capabilities, particularly in liquefied natural gas. These hubs will attract investment in related industries that will further and accelerate mastery of the hydrogen supply chain, helping to achieve the lowest unit cost throughout.

CONCLUSION

Although many countries have ambitious plans for green hydrogen, the GCC states have unique advantages that could allow them to lead the hydrogen economy. They also have an incentive to move away from fossil fuels. By seizing the green hydrogen opportunity, GCC countries can lay the foundation for economic growth in a decarbonized world and ensure their continued influence in the energy market.

ENDNOTES

1. The GCC countries are Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and the United Arab Emirates.

2. Dr. Yahya Anouti, Dr. Shihab Elborai, Dr. Raed Kombargi, and Ramzi Hage, “The dawn of green hydrogen: Maintaining the GCC’s edge in a decarbonized world,” Strategy&, 2020 (https://www.strategyand.pwc.com/m1/en/reports/2020/the-dawn-of-green-hydrogen/the-dawn-of-green-hydrogen.pdf).

3. Sichao Kan, “South Korea’s Hydrogen Strategy and Industrial Perspectives,” Éditio Énergie, Ifri (https://www.ifri.org/sites/default/files/atoms/files/sichao_kan_hydrogen_korea_2020_1.pdf); Kyunghee Park, “Hyundai Hydrogen Chief on why the company bet on fuel cells,” Bloomberg, June 9, 2020 (https://www.bloomberg.com/news/articles/2020-06-09/hyundai-s-hydrogen-chief-on-why-the-auto-giant-bet-on-fuel-cells); Mark Kane, “Hyundai Strategy 2025: 670,000 BEVs/FCEVs Annually By 2025,” insideevs, December 5, 2019 (https://insideevs.com/news/386308/hyundai-strategy-2025/).

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