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The dawn of green hydrogen

Maintaining the GCC's edge in a decarbonized world

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EXECUTIVE SUMMARY

The global energy system stands at the threshold of a new era of abundance that will transform energy economics. Thanks to rapidly declining renewable energy costs and technological advances, hydrogen can become the medium of choice for transporting cheap clean energy across the globe. The COVID-19 pandemic has accelerated the trend toward decarbonization by reducing hydrocarbon demand substantially.

Strategy& estimates that global demand for “green hydrogen,” produced with minimal carbon dioxide (CO_2) emissions, could reach about 530 million tons (Mt) by 2050, displacing roughly 10.4 billion barrels of oil equivalent (around 37 percent of pre-pandemic global oil production). We estimate that the green hydrogen export market could be worth US$300 billion yearly by 2050, creating 400,000 jobs globally in renewable energy and hydrogen production.

Green hydrogen represents a promising opportunity for the Gulf Cooperation Council (GCC)[1] countries. They can produce green hydrogen to boost domestic industries and for export. Although countries such as China and the U.S. are seeking to invest in green hydrogen, their export prospects are limited by large domestic demand that will probably consume most of their production. By contrast, GCC countries can export much of their green hydrogen and still have ample, low-cost renewable energy.

GCC countries need to act boldly to capture this prize with a three-phase plan:

1. Launch a commercial-scale pilot in partnership with a leading electrolysis operating company to build capabilities and identify challenges, and start research and development (R&D). A single unit within an existing government entity should lead this effort.
2. Develop the right policies and regulations to support the domestic market, define the governance and institutional framework, and develop the funding model.
3. Build the export infrastructure and secure supply agreements with key export markets.

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

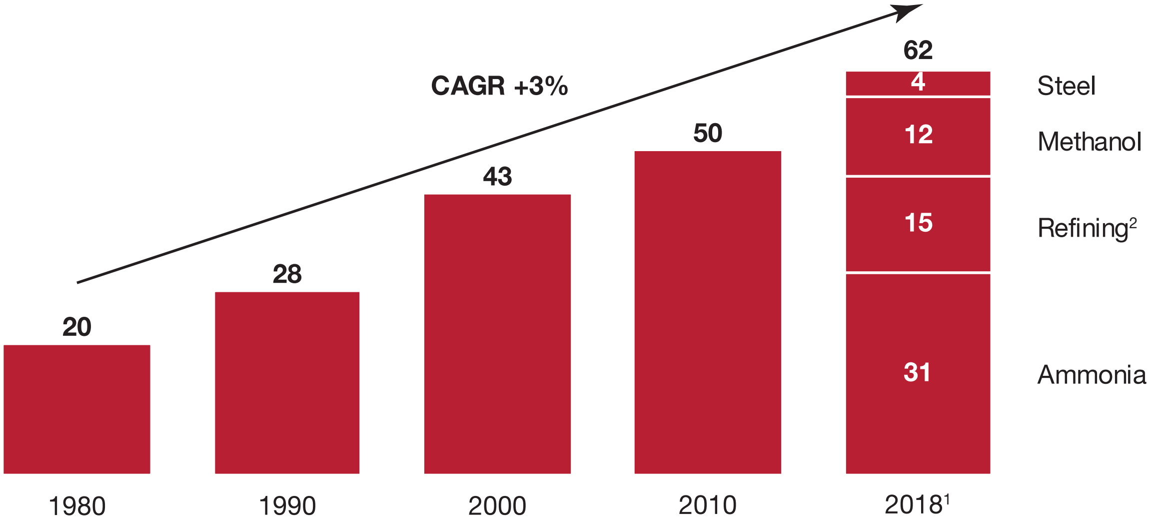
THE GROWING CASE FOR GOING GREEN

Hydrogen, the world's most abundant and lightest element, has a wide range of industrial applications, from refining to petrochemicals to steel manufacturing. It is also a rich source of energy, far more efficient than other fuels. Hydrogen demand has been increasing at a steady pace over the past four decades (*see Exhibit 1*). The problem is that traditional means of producing hydrogen generate large volumes of CO_2. Fortunately, advances in electrolysis technology and the falling cost of renewable energy are enabling the mass production of green hydrogen, which is more environmentally sustainable (*see "Three colors of hydrogen production"*). These developments have altered the calculus for hydrogen and created a significant opportunity for countries to boost economic growth and move away from fossil fuels.

EXHIBIT 1

Hydrogen demand is rising steadily

Hydrogen demand (million tons)



[1] Transport fuel, heat, and power were 0.2 million tons in 2018.

[2] Strategy& estimate.

Source: 2018 figures from International Energy Agency, "The Future of Hydrogen: Seizing today's opportunities," June 2019 (https://www.iea.org/reports/the-future-of-hydrogen); Strategy& analysis

Three colors of hydrogen production

There are three main ways to generate hydrogen, represented by the colors gray, blue, and green.

Gray hydrogen. The most common process is to use either natural gas or coal as feedstock that reacts with steam at high temperatures and pressures to produce synthesis gas, which consists primarily of hydrogen and carbon monoxide. The synthesis gas is then reacted with additional water to produce pure hydrogen and CO_2. These are well-established processes, but they generate significant CO_2 emissions, which is why the resulting element is termed “gray hydrogen.”

Blue hydrogen. The second-most-common process, blue hydrogen, relies on the same basic processes as gray hydrogen, but it traps up to 90 percent of the greenhouse gas emissions through carbon-capture technology. In some cases, that carbon is stored underground, which requires considerable capital costs. Or it is reused as a feedstock for industrial applications, in which CO_2 is still ultimately released into the atmosphere.

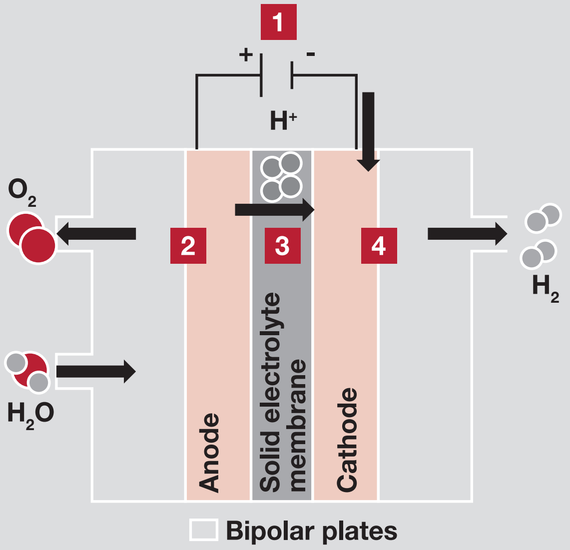
Green hydrogen. The most promising process, green hydrogen, uses renewable energy to power the electrolysis that splits water molecules into hydrogen and oxygen. Electrolysis requires energy. That this energy comes from lower-cost renewable sources is what makes this form of hydrogen “green.”

There are three major electrolysis technologies with different levels of maturity. One technology, alkaline water (ALK), is the most basic and mature technology and has a market share of about 70 percent of the currently very small green hydrogen market. It benefits from low cost, and this process has a long operational life. However ALK processes need to run continuously or the production equipment can get damaged. The intermittent nature of renewable energy, therefore, rules it out as a single source of power for ALK. Another technology is polymer electrolyte membrane (PEM) electrolysis, which has a market share of about 30 percent and is being adopted by most of the leading electrolyzer manufacturers. PEM yields higher-quality hydrogen and can be operated intermittently, but is also expensive and has lower production rates than ALK (*see Exhibit 2, page 4*). A third technology is a solid oxide electrolyzer cell, which is still in the R&D stage. It offers high efficiency at low cost. However, it requires a long startup time and the components of this process have a short operational life.

EXHIBIT 2

How polymer electrolyte membrane technology works

Polymer electrolyte membrane electrolysis



Operating Process

1 Voltage applied between electrodes

2 $2H_2O$ gives up electrons at the anode to produce $4H^+$ ions and O_2

3 H^+ ions travel towards the cathode

4 $2H^+$ capture $2e^-$ from the cathode and combine to produce H_2

Source: O. Schmidt, A. Gambhir, I. Staffell, A. Hawkes, J. Nelson, and S. Few, "Future cost and performance of water electrolysis: An expert elicitation study," *International Journal of Hydrogen Energy*, 42 (2017), pp. 30470—30492; International Energy Agency, "The Future of Hydrogen: Seizing today's opportunities," June 2019 (https://www.iea.org/reports/the-future-of-hydrogen); Strategy& analysis

Green hydrogen is formed by using renewable energy to power electrolysis that splits water molecules into their constituent elements: hydrogen and oxygen. The green hydrogen formed through this process is a clean energy source that can be stored for a long time and transported over considerable distances. We expect that the total demand for green hydrogen could reach about 530 Mt by 2050, displacing roughly 10.4 billion barrels of oil equivalent (37 percent of pre-pandemic global oil production) in various sectors such as heating, transportation, power generation, chemicals, and primary steel manufacturing. This is part of a broader move toward decarbonization that has sped up thanks to the COVID-19 pandemic, which has slashed hydrocarbon demand.

At that point, we expect that the yearly global export market for green hydrogen will be worth about $300 billion. Demand for green hydrogen will be greatest among European and East Asian countries, given their considerable energy consumption in the heating, industrial, and transportation sectors, along with the high cost that they pay to import fuel.

For these reasons, green hydrogen holds the potential to ensure an environmentally cleaner and sustainable future for our planet. GCC countries have several advantages, primarily high-yield solar and wind resources that can generate power at a very low levelized cost of energy (LCOE).[2] These will allow the GCC region to produce green hydrogen at scale and at low cost.

However, other countries recognize the opportunity and have already taken steps to seize it. Australia, Canada, China, Germany, and the U.S. have all developed national policies and invested in programs to build their domestic green hydrogen industries. If GCC countries are to catch up, they must act now.

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[2] The levelized cost of energy is a means of comparing the economics of different types of energy technologies. It includes all costs to generate a unit measure of electricity (including the capital expenditure needed to build a facility, the operation of that facility over its lifetime, and the breakdown costs), divided by the amount of energy produced.

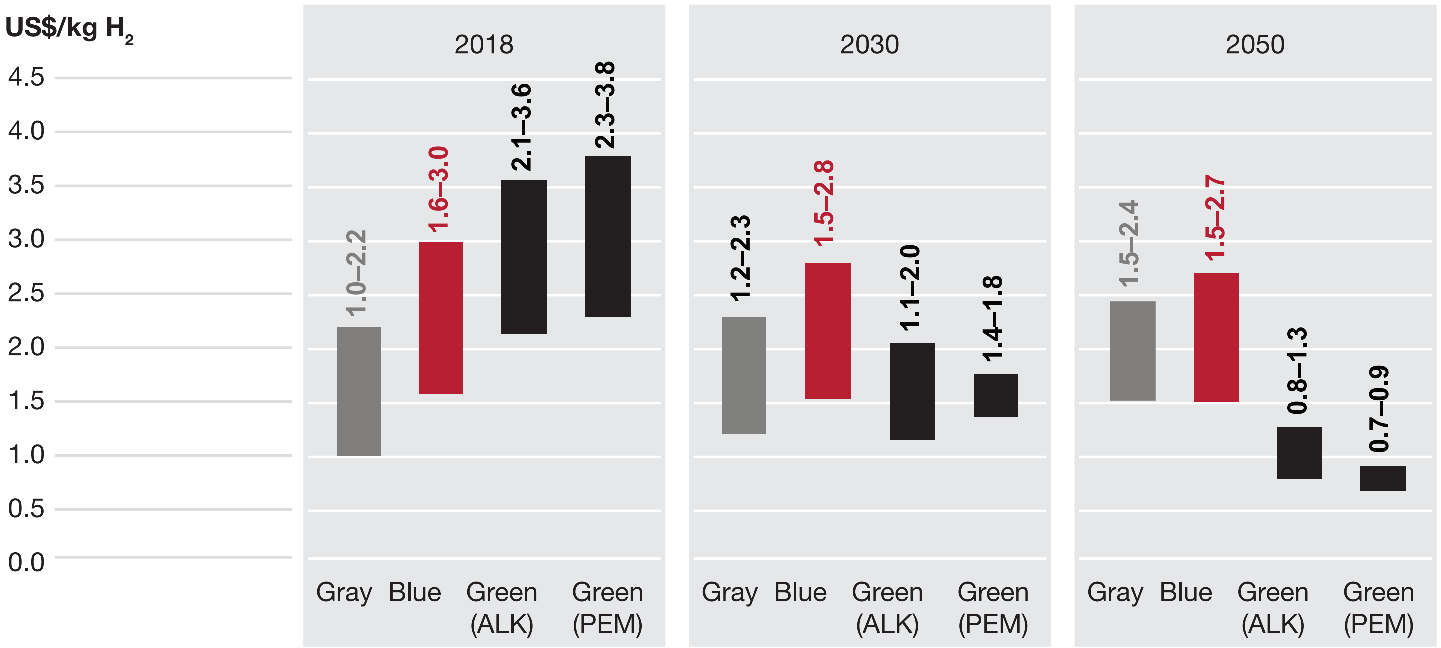
THE ERA OF GREEN HYDROGEN BECKONS

Green hydrogen is currently more expensive than traditional production processes, roughly twice as much as gray hydrogen (*see Exhibit 3*). However, advances in electrolysis technology, decreasing costs of renewables, and increased economies of scale should significantly reduce its production cost and make it an economically viable solution.

EXHIBIT 3

Green hydrogen should become cost competitive compared to gray and blue hydrogen

Hydrogen cost development by production type[1]



	2018	2030	2050
Renewable LCOE (US$/MWh)	**30—45**	**18—26**	**14—18**

Note: ALK = alkaline water, LCOE = levelized cost of energy, MWh = megawatt hour, PEM = polymer electrolyte membrane.

[1] Cost assumptions based on greenfield projects, excluding cost for buildings and cost for building cooling requirements.

Source: International Energy Agency, “The Future of Hydrogen: Seizing today’s opportunities,” June 2019 (https://www.iea.org/reports/the-future-of-hydrogen); Strategy& analysis

Advances in electrolysis technology

Developments in various electrolysis technologies over the past decade, specifically PEM, have increased system efficiencies to nearly 90 percent, and the operational lifetime of the process is approximately 80,000 hours. Also, we estimate that new and cheaper materials will reduce the overall capital cost of PEM equipment, lowering the capital cost per kilowatt (kW), currently between $800 and $1,400, to as little as $200/kW by 2050.

- **Decreasing costs of renewables** Electricity represents a large share in the operating costs of electrolysis processes (roughly 50 percent for PEM electrolysis, assuming electricity prices of 4.5 cents/kilowatt-hour). However, we expect that the installation of more low-cost solar photovoltaic and wind power plants globally over the next decade will produce the required electricity for less than 2 cents/kWh according to the prices of recent tenders.

- **Increased economies of scale** Yearly additions to electrolysis capacity, along with larger average project sizes, are creating larger economies of scale and a reduction in project capital costs.

Based on these factors, Strategy& estimates that the production cost of green hydrogen using the PEM technology will be at par with gray hydrogen by 2030 ($1.40 to $1.80 per kilogram of hydrogen produced) and less than half by 2050 ($0.70 to $0.90 per kilogram).

Lower-cost green hydrogen will lead to benefits in a range of industries and advance the goal of making countries and companies more environmentally sustainable. This will apply to current applications of green hydrogen and new ones. As a result, the demand for green hydrogen is projected to grow significantly by 2050.

Chemicals

Hydrogen is used as a chemical feedstock for the production of ammonia and methanol. We forecast that demand for hydrogen for the chemicals industry should grow from about 43 Mt in 2018 to roughly 120 Mt in 2050, in line with broader growth in the ammonia and methanol markets. As green hydrogen becomes more cost-competitive by 2030, we expect that a large number of new ammonia and methanol production facilities will transition to green hydrogen, leading to demand of up to 55 Mt by 2050.

Steel

Policies to counter climate change are expected to force primary steel producers to make the transition from conventional techniques to more environmentally friendly processes. These include the direct reduced iron (DRI) method, which uses hydrogen as a reducing agent. By 2050, we estimate that global annual primary steel production should be about 1.5 billion tons, of which nearly a third will be generated from the DRI method. This shift in manufacturing processes will potentially increase green hydrogen demand to about 10 Mt by 2050 according to our estimates.

Heat

Commercial and residential heat is typically generated by burning natural gas in boilers. Injecting up to 10 percent hydrogen (by volume) into the natural gas distribution network, representing about 115 Mt by 2050 according to our estimates, would not require any major alterations to equipment and would significantly reduce carbon emissions.

Power generation

Conventional power, from the burning of liquid and gas hydrocarbons, currently represents the largest share of electricity generation around the world. Countries with limited renewable energy and hydrocarbon resources (such as Japan and South Korea) rely significantly on expensive imported and polluting fuels. Importing electricity through transmission lines is problematic due to high costs, system losses, and geographical barriers. However, green hydrogen presents an alternative. Countries that today rely on importing hydrocarbons could instead import low-cost green hydrogen and convert it into electricity through large-scale fuel cells in domestic power plants.

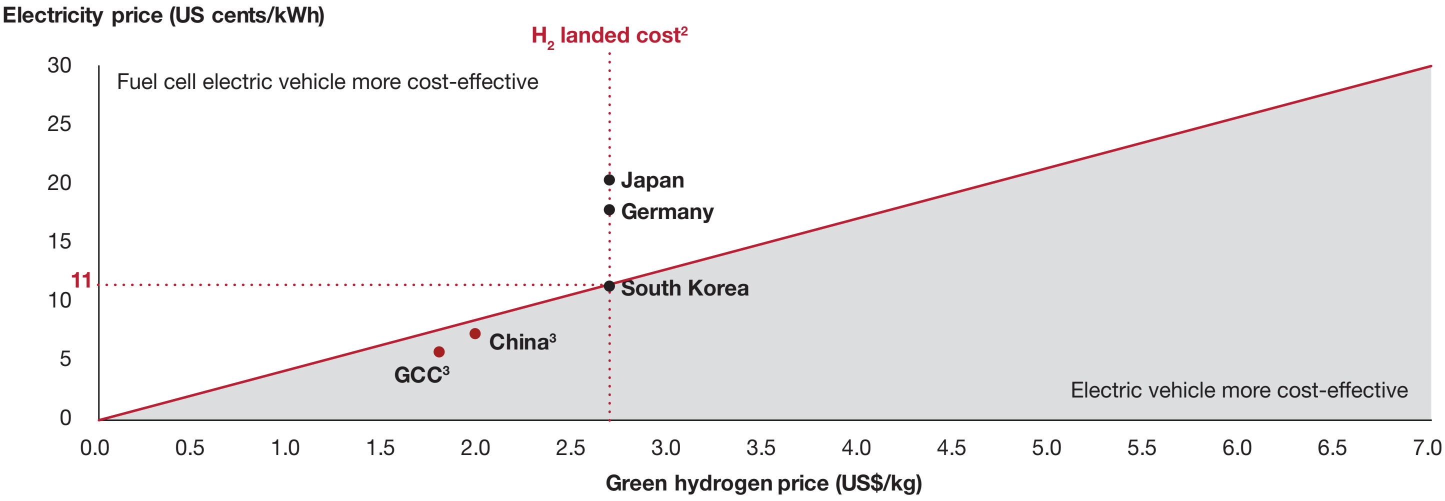
Transport fuel

Vehicles powered by internal combustion engines face growing competition from electric vehicles (EVs) that are more environmentally sustainable. Power for EVs can be provided by plugging the vehicle into the electricity network to charge a battery or by filling the vehicle's tank with hydrogen and converting it to electricity through fuel cells (*see "The advantages of fuel cells"*). Our analysis indicates that fuel-cell EVs could be a more cost-effective alternative to hydrocarbons, and to battery-powered EVs in countries with high electricity prices (*see Exhibit 4*). Also, many studies have shown that for long-haul heavy duty transportation, fuel-cell EVs are more cost-effective than battery-powered EVs.

EXHIBIT 4

Fuel cell electric vehicles can be more cost-effective than those dependent on hydrocarbons

Cost-effectiveness[1] 2050



[1] Excluding infrastructure cost for electric vehicles and fuel cell electric vehicles. [2] Including cost for hydrogen conversion into ammonia, transmission, distribution, and reconversion (conservative case). [3] Including cost for domestic hydrogen distribution in a pipeline (100 tons per day) over 500 kilometers.

Source: "Global EV Outlook 2019: Scaling-up the transition to electric mobility," International Energy Agency 2019; Energy Information Administration, Annual Energy Outlook, 2020; Strategy& analysis

The advantages of fuel cells

A fuel cell uses an electrochemical reaction to combine oxygen and hydrogen to generate electricity and heat (along with water as a by-product). Because oxygen is readily available in the atmosphere, a fuel cell needs only to be supplied with hydrogen. Fuel cells offer many advantages when compared to other power generation sources:

Higher efficiency: Internal combustion engines operate at about 25 percent efficiency. Combined cycle gas turbines operate at a thermal efficiency of about 65 percent. By contrast, fuel cells are generally held to run at efficiency levels of 80 to 90 percent.[3]

Cleaner fuel: Fuel cells powered by green hydrogen do not need conventional fuels such as oil or gas. They can therefore reduce a country's dependence on hydrocarbon imports.

Quieter operation: Fuel cells have no moving parts, which allows them to operate with almost no noise.

Faster refills: The hydrogen tank of a fuel cell can be filled in less than five minutes, compared to batteries that require 30 minutes to several or more hours for a full charge.

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3 International Energy Agency, "The Future of Hydrogen: Seizing today's opportunities," June 2019 (https://www.iea.org/reports/the-future-of-hydrogen).

THE RIGHT TO WIN THE GREEN HYDROGEN PRIZE

Barriers to entry in the green hydrogen production business are relatively low, given that the technology is easily accessible. However, only a handful of countries have the comparative advantages to become market leaders, with GCC countries at the top of the list. These requirements include:

High-yield renewable resources
Green hydrogen production demands a streamlined supply of low-cost, sustainable energy throughout the year. GCC countries have some of the highest solar exposures in the world. Solar power plants in the region can expect 1,750 to 1,930 hours of full-load operation per year, almost double the exposure of solar power plants in Central Europe. In addition, certain regions in the GCC have wind speeds above seven meters per second, ideal for utility-scale wind power plants. Countries in the region have already established ambitious renewable energy programs, enabling project developers to build large scale renewable power plants that deliver the world's lowest LCOEs of under 2 cents/kWh.

Large areas of barren, flat land
Countries will need to build large-scale renewable capacity to meet part of the 2050 global demand for green hydrogen. We estimate that 4,700 gigawatts of new capacity will be needed, nearly five times existing installed capacity worldwide. GCC countries have ample land that can be used to construct large-scale capacity of renewable energy and electrolysis plants. Indeed, all the renewable energy and electrolysis infrastructure that will be needed to meet 2050 global export demand for green hydrogen could be built on just one-fifth of Saudi Arabia's barren land area.

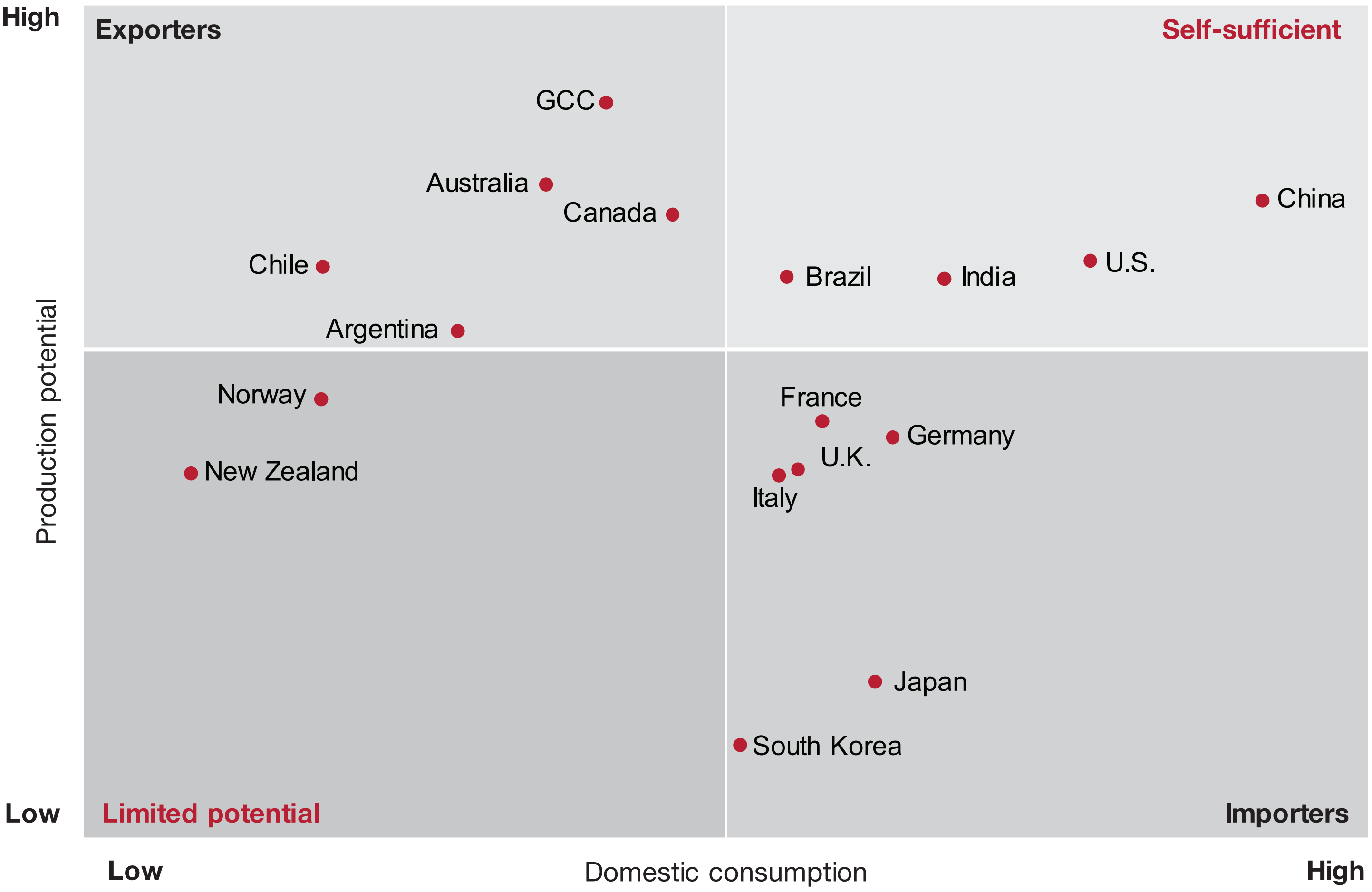
Water
We estimate that meeting green hydrogen demand in 2050 will require around 5.6 trillion liters of deionized water. For this, the GCC countries have ready access to sea water.

Low domestic consumption
Countries such as Brazil, China, India, and the U.S. meet the criteria for large-scale and relatively low-cost green hydrogen production. However, their export potential is limited as domestic demand will absorb most of their own production. By contrast, Argentina, Australia, Canada, and Saudi Arabia can export most of their green hydrogen production, because electricity and gas are cheaper than hydrogen for these countries' domestic energy requirements (*see Exhibit 5*).

EXHIBIT 5

GCC countries have great export potential

Green hydrogen production, domestic consumption, and export potential



Source: Strategy&

THE SIZE OF THE PRIZE

Producers can adopt various transport modes, such as compressed or liquefied hydrogen, hydrogen in the form of ammonia, or through an organic carrier molecule. For distances that fall below about 1,800 kilometers, transporting hydrogen through pipelines is the lowest-cost option. For longer distances, ammonia ships are the most economic solution.

We estimate that the investments required to meet green hydrogen export demand in 2050 are around $2.1 trillion. Of this total, $1 trillion is needed to build the dedicated renewable energy capacity, $900 billion to set up the hydrogen conversion and export facilities, and $200 billion to develop the water electrolysis facilities.

Other countries already have plans for their hydrogen economies and could leave GCC countries behind. Australia is planning to increase hydrogen production sharply to supply its domestic heating, transportation, electricity, and industrial sectors. Under a high hydrogen scenario, Australia could potentially export more than 3 Mt each year starting in 2040. The export effort could earn about $9 billion per year.[4] The province of British Columbia in Canada is developing plans to produce approximately 1.5 Mt of blue and green hydrogen by 2050 and generate export revenues of $15 billion.[5] China aims to establish hydrogen clusters that would increase local demand to 60 Mt by 2050 in the transportation, alternative feedstocks, building heat and power, and industrial sectors.[6]

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[4] “Opportunities for Australia from Hydrogen Exports,” ACIL Allen Consulting for ARENA, August 2018 (https://arena.gov.au/assets/2018/08/opportunities-for-australia-from-hydrogen-exports.pdf).

[5] Zen and the Art of Clean Energy Solutions, the Institute for Breakthrough Energy and Emission Technologies, and G&S Budd Consulting Services, “The British Columbia Hydrogen Study,” 2019 (https://www2.gov.bc.ca/assets/gov/government/ministries-organizations/zen-bcbn-hydrogen-study-final-v6.pdf).

[6] Louis Brasington, “Hydrogen in China,” CleanTech, September 24, 2019 (https://www.cleantech.com/hydrogen-in-china/).

HOW TO CAPTURE THE PRIZE

Given the dual shock of the global COVID-19 pandemic and steep decline in oil prices, GCC countries need to act boldly now to catch up and overtake these countries. GCC governments must act fast to implement a three-phase green hydrogen plan.

1. Piloting (2 to 4 years)
To kick-off the green hydrogen program, GCC governments should partner with a leading electrolysis operating company to develop a commercial-scale pilot project. This should incorporate a renewable energy plant, an electrolysis facility, and a single domestic source of demand such as an ammonia plant. The pilot project will help policymakers develop domestic technical capabilities, identify local environmental challenges, and initiate R&D activities to develop potential mitigation measures — all in the context of real-world applications rather than theoretical scenarios.

In addition to establishing technical aspects, the project can help governments begin to craft policies and regulations. A single unit should lead these activities. That unit should be hosted within an existing entity, taking advantage of existing infrastructure where possible, and in coordination with the relevant ministry.

2. Developing national policies to support domestic consumption (5 to 15 years)
Once the pilot has resolved all its critical challenges and has proven that its technology is commercially viable, the government should develop a comprehensive green hydrogen policy. This should:

- set ambitious and realistic capacity targets that take into account domestic and global market trends

- define the sector’s governance and institutional framework

- identify key regulations that the government should develop (e.g., technical codes and safety standards) to properly integrate hydrogen into the energy system

- outline the funding model and requirements

Implementing this policy will enable governments to scale up renewable and electrolysis capacity to serve a larger domestic demand base, while taking into account key design and infrastructure modifications required for the domestic environment. As capacity grows and applications increase, GCC governments can consider setting up a green hydrogen company. This enterprise would house all the key capabilities acquired over the years.

3. Export competition (16-plus years)

Once the domestic green hydrogen industry is fully operational, economies of scale and technological advances will further reduce production costs — a critical step to unlock global export opportunities. Initially exports of green hydrogen will be in the form of green finished industrial products (e.g., green steel, green polymers) and energy-intensive intermediate products (e.g., green methanol, green direct reduced iron). Over time, exporting countries can shift to direct energy exports. Eventually, the green hydrogen company should take the lead in signing supply agreements with key green hydrogen export markets. These should be based on an understanding of regional imbalances in hydrogen and which export markets are most accessible from the GCC compared to other exporters. With the right markets established, governments can then build the export terminal and infrastructure for shipping and pipeline channels.

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.

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