

# The Economics and Resource Potential of Hydrogen Production in Saudi Arabia

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## **Key Points**

lobally, hydrogen has historically been used narrowly in the refining and chemical sectors and for other non-energy end-use industrial applications. Increasingly, however, its potential as a clean and flexible fuel is being investigated. It is emerging as a possible front-runner solution for decarbonizing hard-to-abate sectors. Its role as a potential energy carrier in future energy systems is also receiving considerable attention. Hydrogen can provide much-needed flexibility to support the increased deployment of renewables and help achieve decarbonization objectives.

Saudi Arabia has catalyzed the expansion of hydrogen with a novel demonstration shipment of blue ammonia to Japan. The Kingdom will also host the world's largest green hydrogen plant, which is scheduled to come online in 2025. This study therefore assesses the economics and potential competitiveness of hydrogen energy production in Saudi Arabia. Our main findings are as follows.

The cost of producing green hydrogen is estimated to be \$2.41 per kilogram (kg) at a reference price of \$23.4 per megawatthour (MWh). This reference price reflects the first utility-scale solar-based project, Sakaka, which was commissioned in 2020. However, the average auction price of the seven new solar projects awarded in 2020 was \$18.3/MWh. Using this price as the current benchmark for solar energy in the Kingdom, green hydrogen can be produced at \$2.16/kg.

Further reductions in electrolyzer and renewable energy costs will bring the costs of producing green hydrogen below \$1.50/kg by 2030. Production costs of this magnitude are highly competitive. In the long term, the cost of green hydrogen production may reach \$1/kg or below by 2050. This outcome can occur if electrolyzer costs drop further to \$400 per kilowatt, with renewable energy costs falling below \$10/MWh.

The cost of hydrogen from natural gas using steam methane reforming (usually referred to as 'grey hydrogen') is about \$0.90/kg. This estimate is based on the current gas price of \$1.25 per million British thermal units (MMBtu). Adding carbon capture and storage (CCS) to turn grey hydrogen to blue hydrogen increases the cost to \$1.34/kg. CCS technology is likely to exhibit further cost reductions as it scales. Thus, the cost of producing blue hydrogen can reach \$1.13/kg by 2030 if domestic natural gas prices remain unchanged.

Saudi Arabia has abundant renewable energy potential and significant natural gas resources. Thus, it is uniquely positioned to produce both green and blue hydrogen at the most competitive rates in the world. Saudi Arabia has great potential to leverage its resources to produce zero- and low-carbon hydrogen for domestic use. It can also help other countries achieve their decarbonization goals by exporting hydrogen.

Domestically, about 100 terawatthours of additional electricity generation for electrolysis are needed to source 5% of final energy consumption from hydrogen energy by 2030. In a green-only scenario, about 44 gigawatts (GW) of solar photovoltaic capacity are needed. A blue-only scenario will require 0.9 billion cubic feet of gas per day to produce the necessary hydrogen to achieve this goal.

By 2030, green hydrogen will be competitive with grey hydrogen at the current domestic natural gas price of \$1.25/MMBtu and a carbon price of about \$65 per tonne.					

## **Summary**

n energy transition discussions, policymakers are increasingly viewing hydrogen as a preferred emissions-free substitute for oil, natural gas and coal in hard-to-abate sectors. However, hydrogen is not a primary energy source but rather is a carrier of energy. Many factors, including its source and the technology used to manufacture it, influence its production costs. Currently, hydrogen manufacturing processes themselves have significant carbon footprints. Thus, for hydrogen to be accepted as a low-carbon fuel source, its production methods must also be decarbonized.

Two main technological pathways are being pursued for carbon-free hydrogen production. The first is water electrolysis using low-carbon power generation technologies, such as solar and wind, which is also referred to as 'green hydrogen.' The second is steam methane reforming using carbon capture, and sequestration and storage (CCS) technologies to capture the associated carbon dioxide. This method is known as 'blue hydrogen.'

Saudi Arabia is one of the few places worldwide with resource endowments for producing both blue and green hydrogen inexpensively. Moreover, renewable power prices are expected to continue to fall, and electrolyzer and CCS technologies are expected to scale up. These trends will likely translate to noticeable drops in the costs of producing green and blue hydrogen. At the current gas price of \$1.25 per million British thermal units (MMBtu), blue hydrogen's production cost is expected to fall by 16% from \$1.34 per kilogram (kg) today to \$1.13/kg by 2030.

The cost of producing green hydrogen is about \$2.16/kg, based on a benchmark price of \$18.3 per megawatthour (MWh) for solar energy. This cost is expected to drop to \$1.48/kg by 2030.

The benchmark solar energy price is the average auction price of seven new solar photovoltaic projects in round two of the National Renewable Energy Program in 2020. This price is approximately 22% lower than that of Saudi Arabia's first solar independent power producer project (i.e., \$23.4/MWh).

Saudi Arabia's low levelized cost of hydrogen provides a comparative advantage in hydrogen economies. It has advantages in the global hydrogen trade and in decarbonizing domestic carbon-intensive sectors to export carbon-neutral finished goods, such as ammonia, steel and cement. From a resource perspective, Saudi Arabia can theoretically pursue a solely green or blue hydrogen strategy. However, developing both pathways simultaneously may provide a low-cost solution. Saudi Arabia's geographical resource distribution suggests that the eastern region is more likely to produce and export blue hydrogen. In contrast, green hydrogen production is well suited for regions far from oil and gas clusters, such as the western region.

During its presidency of the G20, a group of leading rich and developing nations, Saudi Arabia endorsed the circular carbon economy framework. This framework calls for a technology-agnostic approach for mitigating carbon emissions, lending more support to blue and green hydrogen development in Saudi Arabia. However, enabling polices to promote the use and manufacturing of low-carbon hydrogen are needed to facilitate the Kingdom's hydrogen development. At the current natural gas price (i.e., \$1.25/MMBtu), a carbon price of \$145/tonne can incentivize green hydrogen production. By 2030, however, the cost of carbon dioxide mitigation only needs to be \$65/tonne.

### 1. Introduction

ydrogen can, theoretically, replace hydrocarbon molecules in a wide range of applications without producing carbon dioxide emissions. However, about 99% of the hydrogen produced today is sourced from hydrocarbons using energy-intensive processes. Hydrogen production contributed 800 million tonnes of carbon dioxide, or over 2% of global carbon emissions, in 2018 (IEA 2020a). The Hydrogen Council expects hydrogen demand to increase tenfold across a variety of applications by 2050 in a two-degree warming scenario. Hydrogen is expected to comprise 18% of total final energy demand (Hydrogen Council 2017). If this target is met, it will contribute to the elimination of 6 gigatonnes of carbon dioxide by 2050 (Hydrogen Council 2017).

Policymakers are turning to hydrogen as a potential energy carrier to accelerate the transition to a low-carbon world. However, its production process must be decarbonized for hydrogen to be considered a clean fuel. Over the past few years, interest has grown in leveraging hydrogen's potential to improve environmental sustainability and achieve net-zero greenhouse gas (GHG) emission goals. Since 2019, several countries and regions, mostly in Europe, have announced plans to provide significant policy support for producing and using zero- or low-carbon hydrogen. These plans take the form of hydrogen roadmaps and typically use carbon capture and storage (CCS) or renewable electricity.

At the regional level, the European Hydrogen Strategy for a climate-neutral Europe was unveiled in July 2020. It sets a target of at least 6 gigawatts (GW) of renewable hydrogen electrolyzers by 2024 (European Commission 2020). Hydrogen is expected to become an intrinsic part of the European Union's (EU's) integrated energy system in the future. Thus, this target is set to be raised to

at least 40 GW of renewable hydrogen electrolyzers by 2030 (European Commission 2020). After 2030, renewable hydrogen is likely to be deployed at a large scale across all hard-to-decarbonize sectors (European Commission 2020). The EU's hydrogen strategy places significant importance on renewable hydrogen, which is considered to have major EU-wide decarbonization potential, in achieving its climate neutrality goals. In the short and medium terms, however, other forms of low-carbon hydrogen are expected to play a role in phasing out existing hydrogen production. Low-carbon hydrogen will support the uptake of hydrogen from renewable sources (European Commission 2020).

As of September 2021, 13 countries have released national-level hydrogen strategies. Nine of them were announced in 2020. An additional 19 countries are preparing similar strategies (BNEF 2021; Government of UK 2021; WEC 2021). If these strategies are funded and implemented, demand for hydrogen is expected to increase, and it may become a globally traded commodity. The German Hydrogen National Strategy, for example, recognizes that a large portion of its hydrogen demand targets will have to be met by imports (BMWi 2020). Likewise, the Netherlands has identified the potential for hydrogen imports into the Dutch and European markets as part of its hydrogen strategy. It foresees the Port of Rotterdam playing a key role in facilitating the supply of imports and distribution of hydrogen across the continent (Government of the Netherlands 2020). In Japan and South Korea, energy imports comprise 94% and approximately 84% of primary energy consumption, respectively (FEPC 2021; Yep 2020). These countries will, therefore, need to import significant amounts of hydrogen. They both aim to develop commercial-scale supply chains to facilitate hydrogen imports by 2030 (H2EVA 2018; METI 2017).

Chile has the most ambitious plans for embedding hydrogen in its future energy mix. It aims for 25 GW of green electrolysis by 2030 and 25 million tonnes of green hydrogen per year by 2050 (Ministerio de Energía 2020). Chile's National Green Hydrogen Strategy also calls for the country to become a major exporter of green hydrogen and its derivatives. Its annual green hydrogen revenues are expected to reach \$2.5 billion by 2030 (Ministerio de Energía 2020). In June 2021, Kazakhstan announced plans to develop the world's largest green hydrogen project. It aims to use 45 GW of wind and solar energy to support 30 GW of electrolyzers producing about 3 million tonnes of green hydrogen annually (Blain 2021). In Australia, a consortium of companies has unveiled plans for a wind and solar energy project with a combined capacity of up to 50 GW. They plan to produce up to 3.5 million tonnes of green hydrogen or 20 million tonnes of ammonia annually (Greenhalgh 2021).

Saudi Arabia received attention for its announcement of plans to build the world's largest export-oriented green ammonia plant in the city of Neom.¹ Neom sits in the northwest region of the country. The partners in the project, which include Neom, Air Products and ACWA Power, plan to build 4 GW of dedicated renewable electricity. This electricity will produce 650 tonnes of hydrogen daily via water electrolysis in a process known as 'green' hydrogen. This hydrogen will be used to produce 1.2 million tonnes of ammonia per year. The produced ammonia will be shipped from Saudi Arabia's western coast to markets in Europe and Asia.

A mere two months later, Saudi Aramco, Saudi Arabia's national oil and gas company, also achieved a milestone in this space. It announced the world's first shipment of low-carbon ammonia, which was exported to Japan from the country's east coast. The hydrogen used to create the ammonia via the Haber-Bosch process was sourced from a steam methane reformer whose processed carbon emissions were captured and utilized. This process is known as 'blue hydrogen.' Some of the carbon dioxide was partly diverted to a nearby methanol plant in the industrial city of Jubail. The remainder was injected underground for enhanced oil recovery operations in the Uthmaniyah oil field. Both announcements demonstrate the Kingdom's intent to play a major role in driving a hydrogen economy. Most importantly, Saudi Arabia aims to become a major hub for exporting carbon-neutral hydrogen.

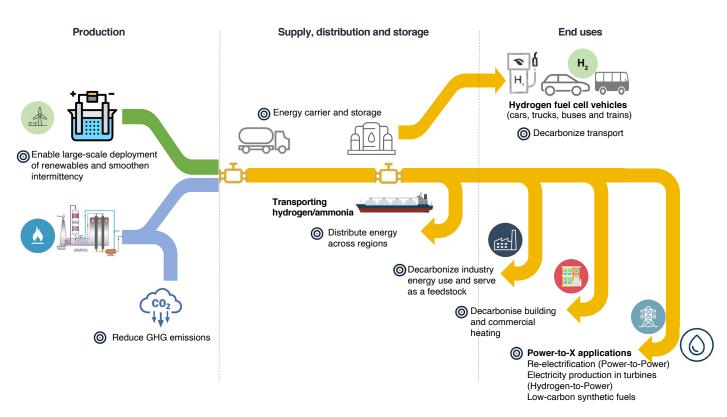
This study examines the economics of low carbon hydrogen production and estimates the feedstock requirements in terms of renewable energy and natural gas resources. Section 2 presents a brief background on hydrogen and its emerging value chain. Section 3 discusses the role of hydrogen in the context of the circular carbon economy (CCE). Section 4 examines the current and future costs of clean hydrogen production in Saudi Arabia. Section 5 describes Saudi Arabia's hydrogen resources and the business potential for hydrogen in the Kingdom. Section 6 concludes.

## 2. Background: The emergence of hydrogen and its role in decarbonization

ydrogen is the simplest and lightest known element. It is also the most common element in the universe, present on Earth in abundant quantities within water. In its diatomic form (i.e., two atoms of the same element), it exists as gas. Hydrogen is traditionally used as a feedstock in many non-energy industrial applications. In the chemical industry, it is used as a raw material to make ammonia for agricultural fertilizer. It is also contained in methanol, which is used in the production of many polymers and pharmaceuticals. In refineries, hydrogen is used to desulphurize oil products. Hydrogen gas is also used to produce carbon steel, glass sheets and semiconductors (RSC 2021).

Hydrogen has rarely been used as an energy carrier in the past. However, economies worldwide are under pressure to decarbonize, and hydrogen is viewed as a front-runner solution for hard-to-abate sectors. Thus, there is tremendous support for hydrogen to play a global role as an energy carrier in the future. Figure 1 shows the hydrogen value chain from production to current and emerging end-use applications. It also highlights the expected energy sustainability objectives that may be achieved if fossil fuel-based energy is replaced by cleaner and flexible hydrogen energy.

Figure 1. Emerging hydrogen value chain.



Source: Authors' illustration.

Relatively little hydrogen gas exists naturally on earth, and energy is required to produce it. Steam methane reforming (SMR) is widely used, contributing to approximately 75% of direct hydrogen production, as it is currently the most cost-effective hydrogen production method. Hydrogen is also derived from the gasification of coal (about 23%) and water electrolysis (about 1%) (IEA 2019). In 2020, approximately 120 million tonnes (Mt) of hydrogen were consumed. Of them, 75 Mt were produced in pure form, and 45 Mt were produced as mixtures with other gases. The latter were usually produced as byproducts from coke mills, ethylene plants and refineries (IEA 2020a).

Current hydrogen production processes are energyintensive, and their associated carbon emissions are vented into the atmosphere. Hydrogen produced in this way is usually referred to as 'grey hydrogen.' Grey hydrogen also includes grid-connected water electrolysis for which the power mix significantly relies on hydrocarbons. Cleaner hydrogen production methods capture the associated carbon emissions. For example, the steam reforming of hydrocarbons combined with carbon capture, utilization and sequestration or storage (CCUS) technologies can minimize atmospheric carbon dioxide emissions. This process results in blue hydrogen. Alternatively, hydrogen can be produced from water electrolysis using renewable electricity to free the hydrogen atoms from the oxygen molecules. This process is referred to as 'green hydrogen.' Green hydrogen is presently expensive. However, the declining costs of renewable energy and improved performance and economies of scale for electrolyzers may make it competitive in the long run (IRENA 2020a).

## 3. Saudi Arabia's adoption of the CCE and its support for clean hydrogen

ver the last decade, Saudi Arabia has pursued low-carbon hydrogen through a variety of national and international events and policies. The Kingdom's Vision 2030 aims to improve the efficiency of Saudi Arabia's energy system. Its strategies include deploying renewable energy, promoting fuel substitution (mainly from oil to gas) and implementing energy efficiency measures. The latter include reforms to domestic fuel and electricity prices.

Saudi Arabia held the presidency of the G20, a group of leading rich and developing nations, in 2020. During its term, it took the lead in promoting a pragmatic global approach to managing fugitive carbon emissions, namely, the CCE framework. This framework was endorsed by the energy ministers of the G20 member countries and is seen as a holistic solution to mitigating emissions (SPA 2020).

The linear economy is based on the traditional 'take-make-dispose' concept. In contrast, the CCE adds circularity and focuses on energy and carbon flows to move toward sustainability. The CCE is based on four pillars: reduce, reuse, recycle and remove. Each pillar's contribution to mitigating carbon emissions depends on the available technology, resource availability and a country's circumstances and enabling policies (KAPSARC 2020). Because no single solution fits all countries, a technology-agnostic approach, such as the CCE, is crucial for reducing atmospheric carbon emissions at the lowest cost.

Hydrogen is a cross-cutting enabler in the CCE (IEA 2020a). Given its versatility in various applications and low-carbon production pathways, it can span the four pillars, as Figure 2 shows. Replacing grey hydrogen production with blue or green production can reduce carbon emissions on the supply side.

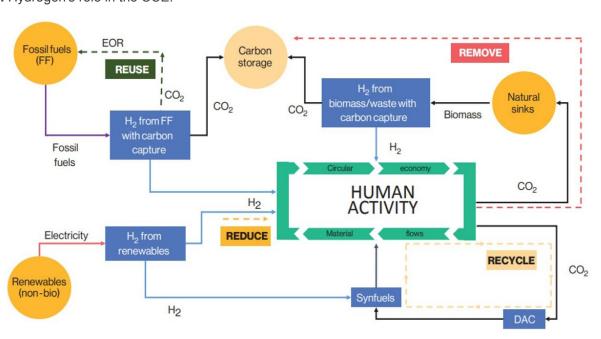


Figure 2. Hydrogen's role in the CCE.

Source: IEA (2020a).

Note: EOR: enhanced oil recovery; DAC: direct air capture

On the demand side, it can replace hydrocarbons in the mobility and industrial sectors. Combining hydrogen with carbon dioxide enables carbon dioxide recycling by creating synthetic fuels, such as synthetic diesel and kerosene. The captured carbon dioxide from hydrogen production can be reused for other applications, such as enhanced oil recovery. Alternatively, carbon can be removed and placed in geologic storage.

Both the green ammonia project in Neom and the blue ammonia demonstration shipment to Japan fall within the CCE's reduce, reuse and recycle pillars. Saudi Arabia has vast hydrocarbon resources, great renewable energy potential and industrial expertise in energy. Thus, it may become a major hub for low-carbon hydrogen and carbon dioxide utilization and storage.

## 4. Economics of hydrogen production in Saudi Arabia

production technologies: alkaline electrolyzers, the SMR process (usually referred to as 'grey hydrogen') and SMR with CCS (referred to as 'blue hydrogen'). We use the levelized cost of hydrogen production (LCOH), estimated by the discounted cash flow method, to compare hydrogen production technologies. All cost variables are in real dollar values (i.e., net of inflation). The analysis assumes a uniform real discount rate of 8% for all technologies and countries for comparison.

Some of the main parameters that affect the cost of producing hydrogen are upfront capital expenditures (capex), replacement costs (where applicable) and operational expenditures (opex). Other key parameters are conversion efficiency, input energy and feedstock costs, and the plant's utilization rate. The conversion efficiency values for these technologies are broadly accepted. However, capex cost assumptions vary across analyses to some degree. We list the technology cost, technical and operational assumptions used in recent studies in tables A1 to A3 in Appendix A. Table A4 presents the representative energy prices used to estimate the cost of hydrogen production. We use these prices to assess the LCOH's global competitiveness, especially among countries that have issued hydrogen strategy roadmaps or pledged to develop zero-carbon economies.

SMR technology is the most widespread hydrogen production process. Its capacity can range from 300 normal cubic meters (Nm³) to over 200,000 Nm³ per hour of hydrogen production. To assess the economics of hydrogen production, we assume that an SMR plant has a capacity of 100,000 Nm³ per hour. Applying CCS to both the process and energy emissions streams is assumed to reduce carbon emissions by up to 90%, compared to SMR without

CCS. Although SMR technologies are mature, CCS technologies and the associated costs are expected to improve with large-scale implementation. The capital costs of SMR with CCS are expected to fall from \$1,680/kW today to \$1,360/kW by 2030 and \$1,280/kW in the long term (IEA 2019).

The economics of green hydrogen are driven by three main components: the cost of renewable electricity, the cost of the electrolyzer and the electrolyzer's capacity factor. Capex estimations for alkaline technology currently range from \$900 to \$1,000 per kilowatt (kW). As policy support for hydrogen continues to increase and economies of scale are achieved through automation in electrolyzer manufacturing, costs are expected to drop significantly. By 2030, investment costs are expected to decrease to between \$600/kW and \$725/kW. To determine the LCOH, this study uses \$900/kW as a current benchmark for capex. For the medium and long terms, we set capex equal to \$650/kW and \$400/kW, respectively.

Currently, most alkaline electrolyzers have single-digit megawatt (MW) capacities. Thus, the sizes of electrolyzer units must increase substantially to achieve significant cost reductions through economies of scale. A 10 MW-class single-stack alkaline water electrolysis system was commissioned in 2020 by Asahi Kasei and its subsidiaries in Japan. This system is one of the largest green hydrogen production units in operation worldwide. It has a designed capacity to produce hydrogen at a rate of 1,200 Nm<sup>3</sup> per hour (Colthorpe 2020). Several green hydrogen projects are under development in Europe (S&P Global Platts 2020). A consortium led by the chemical company Nouryon is close to starting the construction of a 20 MW green hydrogen electrolyzer plant in the Netherlands. This plant will be the first of its kind to be developed at

this scale in Europe (Nouryon 2020). This study uses costs and other technical assumptions relevant to an alkaline electrolysis system with a capacity of 2 MW to 3 MW.

## Cost of grey hydrogen (electrolysis and SMR)

In Saudi Arabia, the estimated levelized cost of electrolysis-based hydrogen production is about \$3.63 per kilogram (kg). This estimate reflects current conditions, including grid electricity for grey hydrogen at the applicable industrial tariff of \$48 per megawatthour (MWh) (i.e., 18 halalah per kilowatthour) (SEC 2018). With the expected reductions in electrolyzer costs, the cost of producing grey hydrogen may decline to about \$3.15/kg by 2030 (Figures 3 and 4). The cost of electricity is one of the largest components of grey hydrogen's production costs. Thus, the LCOH cannot be reduced significantly without lower electricity costs.

At Saudi Arabia's prevailing natural gas price of \$1.25/million British thermal units (MMBtu), SMR without CCS is the least expensive hydrogen production option. Its current cost is \$0.90/kg. However, a jump in natural gas prices can increase this cost significantly. For example, the cost of producing grey hydrogen via SMR is \$1.50/kg when the natural gas price is \$5.25/MMBtu (Figure 3). This cost is nearly 58% and 75% lower than the costs of green and grid-based grey hydrogen, respectively.

## Cost of green hydrogen (electrolysis)

In January 2021, the Saudi government finalized power purchase agreements (PPAs) for seven solar power projects with an average price of about

\$18.3/MWh (Bellini 2021; Martin 2020; Renewables Now 2021; Saudi Gulf Projects 2021). This average price is not significantly different from that of the 400 MW Dumat Al-Jandal Wind farm project that was awarded a PPA price of \$19.9/MWh in 2019. If we use \$18.3/MWh as a benchmark for renewable energy in the Kingdom, the cost of producing green hydrogen is \$2.16/kg (Figure 3).

This cost assumes that the average capacity utilization rate is 60%. The maximum capacity utilizations for both solar and wind energy production are below this level. However, producing green hydrogen with standalone solar or wind power is not preferable except in remote areas. Instead, a combination of solar and wind energy can achieve the desired level of electrolyzer utilization. Standalone green hydrogen from solar energy is simply for comparison purposes. It does not include balancing costs, transmission costs, substations or storage costs. It also does not account for other types of renewables that can produce electricity continuously to achieve the hydrogen production utilization assumption.

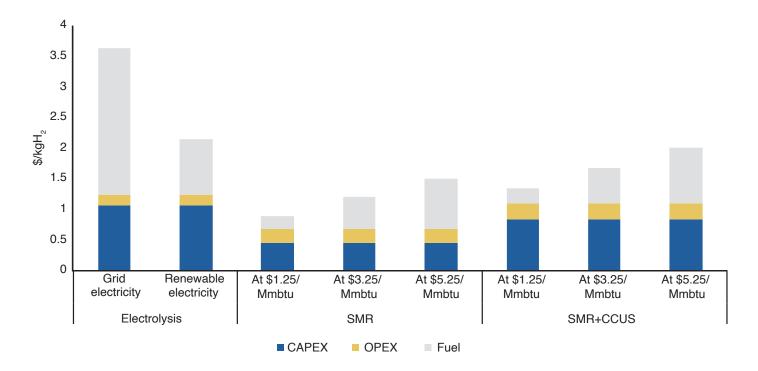
With a production cost of \$2.16/kg, green hydrogen ranks third in terms of overall economics among hydrogen production methods. However, this cost is expected to fall the most in the coming decades as the costs of electrolysis technology and renewable electricity fall. Some proponents of the new solar projects are proposing tariffs below this threshold, meaning that green hydrogen in Saudi Arabia may soon become even cheaper. If renewable energy costs fall to \$13/MWh by 2030, the cost of producing green hydrogen may fall to about \$1.48/kg (Figure 4). The cost reductions will primarily come from lower capex and a lower cost of renewables. If the electrolyzer costs drop further to \$400/kW in the long term, the cost of renewables may fall below \$10/MWh. In that case, the cost of green hydrogen

#### 4. Economics of hydrogen production in Saudi Arabia

may reach \$1/kg or below by 2050 (Figure 5). These cost reductions, combined with increased efficiency, may deliver a 31% reduction in hydrogen costs by

2030 and a 53% reduction in long-term hydrogen costs (Figure 5).

Figure 3. Current hydrogen production costs in Saudi Arabia.



Source: Authors' estimation.

Notes: For electrolysis, capex is \$900/kW and the low heating value (LHV) efficiency is 67%. For SMR, capex is \$910/kW, and the LHV efficiency is 76%. For SMR+CCUS, capex is \$1,680/kW, and the LHV efficiency is 69%. We assume utilization rates of 60% and 80% of total capacity for electrolysis and SMR, respectively. The discount rate is 8%.

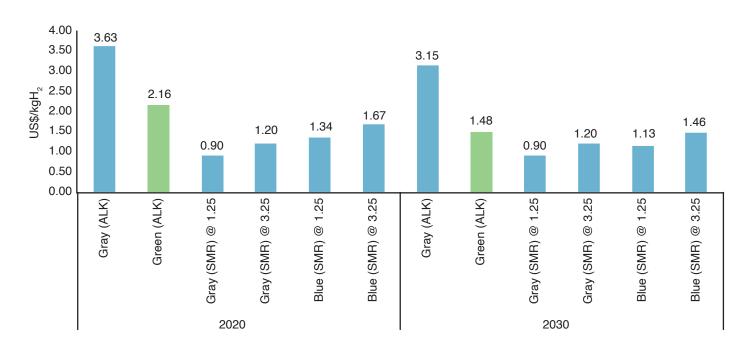


Figure 4. Current and projected hydrogen production costs in Saudi Arabia.

Source: Authors' estimation.

Notes: For electrolysis, the LHV efficiency is 67% and 69% for 2020 and 2030, respectively. The LHV efficiencies are 76% and 69% for SMR and SMR with CCUS, respectively. For electrolysis, capex is \$900/kW and \$650/kW for 2020 and 2030, respectively. Capex is \$910/kW for SMR. For SMR with CCUS, capex is \$1,680/kW and \$1,360/kW for 2020 and 2030, respectively. The plant utilization rate is 60% for electrolysis and 80% for SMR and SMR with CCUS. The discount rate is 8%.

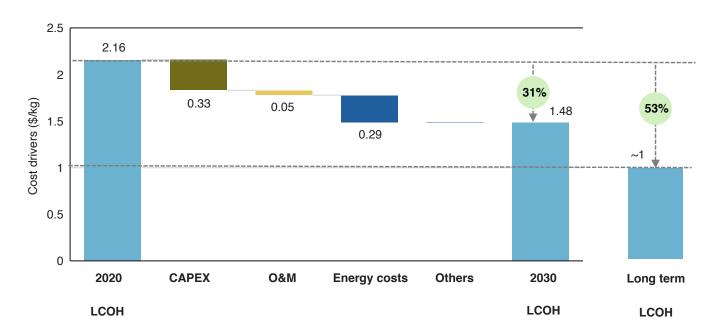


Figure 5. Future production cost reductions for green hydrogen.

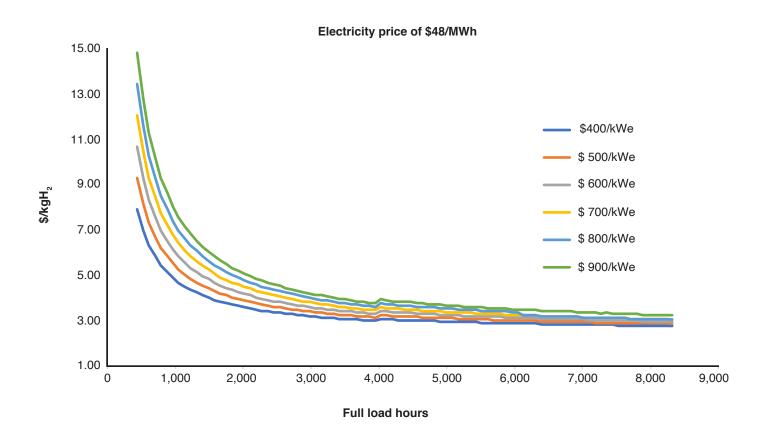
Source: Authors' assessment.

#### 4. Economics of hydrogen production in Saudi Arabia

Figures 6 and 7 show the levelized costs of grey and green hydrogen production in various scenarios. We consider different future capex reductions and fuel costs (i.e., grid and renewable electricity costs). The unit cost of production is lowest between 40% (about 3,500 hours) and 80% (about 7,000 hours) of a hydrogen production facility's full load capacity

(Figures 6 and 7). The cost of hydrogen production increases sharply below a utilization rate of 40%. However, the costs of both renewable energy and electrolyzers are likely to decline further in the future. Thus, green hydrogen may be produced for far less than \$1.5/kg (Figure 8).

Figure 6. Levelized cost of grey hydrogen production for different electrolyzer investment costs.



Source: Authors' estimation.

Notes: kWe=kilowatt-electric. Estimates are based on an electrolyzer efficiency of 67% (LHV) and a discount rate of 8%. The minor increase in the LCOH near 4,000 hours is due to additional future capex for stack replacement.

Figure 7. Levelized cost of green hydrogen production for different electrolyzer investment costs.

Source: Authors' estimation.

1000

2000

3000

1.00

Notes: kWe=kilowatt-electric. Estimates are based on an electrolyzer efficiency of 67% (LHV) and a discount rate of 8%. The minor increase in the LCOH near 4,000 hours is due to additional future capex for stack replacement.

4000

**Full load hours** 

5000

6000

7000

8000

9000

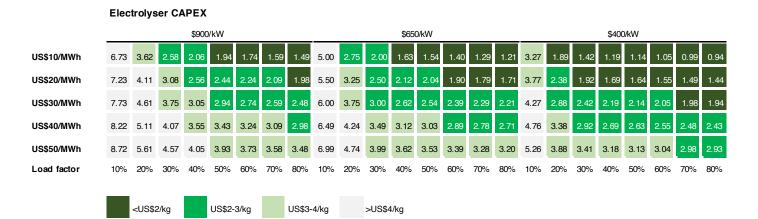


Figure 8. Levelized cost of the hydrogen spectrum for different electrolyzer capex and electricity prices.

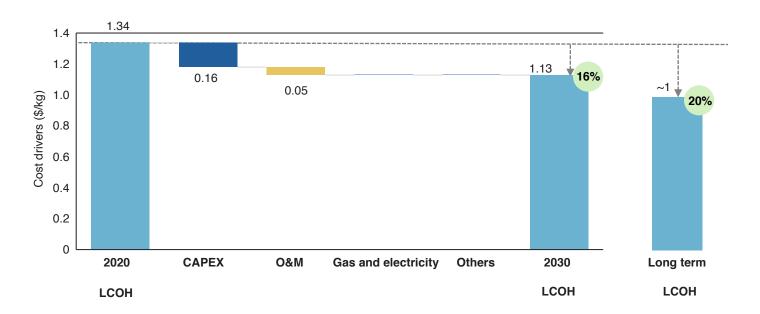
Source: Authors' assessment.

#### Cost of blue hydrogen (SMR+CCS)

Integrating SMR with CCS facilities to produce blue hydrogen increases costs by about \$0.44/kg. With a production cost of \$1.34/kg, blue hydrogen is currently the second most cost-effective hydrogen production method. With a gas price of about \$1.25/MMBtu, blue hydrogen is nearly 49% more expensive to produce than grey hydrogen from SMR. However, this gap may shrink to about 26%

by 2030 (Figure 4). According to industry experts, the cost of CCUS technology is likely to fall further in the future as economies of scale are achieved (Baylin-Stern and Berghout 2021). Future technology cost forecasts suggest that the levelized cost of blue hydrogen may fall to \$1.13/kg by 2030 (at the current gas price of \$1.25/MMBtu) (Figure 9). The Kingdom has access to low-cost natural gas, meaning that natural gas accounts for merely 15% of the LCOH of blue hydrogen (Figure 3). By comparison, it accounts for 30% to over 50% of this cost in other regions (Figure 10).

Figure 9. Future cost reductions for blue hydrogen.



Source. Authors' assessment.

Note: O&M = operations and maintenance.

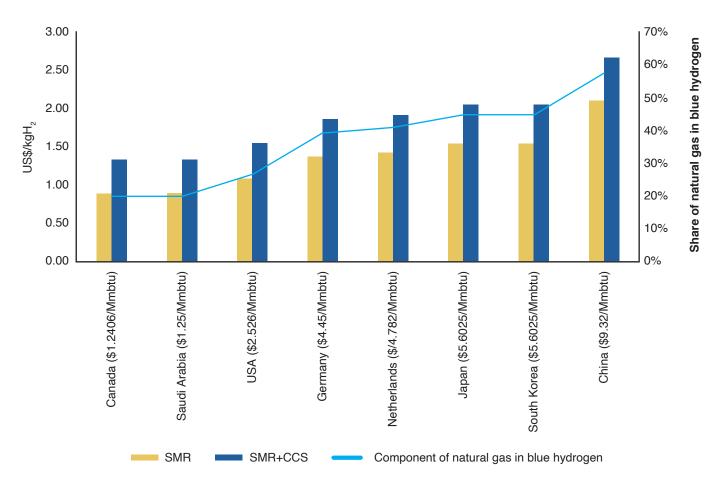


Figure 10. Comparison of production costs for grey (SMR) and blue (SMR+CCUS) hydrogen.

Source. Authors' assessment.

Notes: Estimates are based on current capex and efficiency levels for SMR with and without CCUS. The LCOH corresponds to a utilization rate of about 80%. Natural gas prices for 2019 are from Bloomberg L.P. The reported costs do not include any storage or transportation costs.

Based on locally relevant natural gas prices, the estimated cost of producing grey and blue hydrogen in Saudi Arabia is among the lowest worldwide.<sup>2</sup> The comparison countries in Figure 10 have either promulgated strategies to promote hydrogen energy or have pledged to achieve netzero GHG emissions. Under our cost assumptions for blue hydrogen in 2030, a \$1/MMBtu increase in the natural gas price increases blue hydrogen's production costs by about 14%.

Green hydrogen may achieve cost parity with blue hydrogen by 2030 at a gas price of about

\$3.4/MMBtu (Figure 11). The current estimated cost of producing green hydrogen in Saudi Arabia is about \$16/MMBtu in terms of its heat content. This cost is likely to decline to about \$11/MMBtu by 2030. In comparison, average gasoline prices in Saudi Arabia were \$17/MMBtu to \$18/MMBtu in 2021 (expressed in terms of the heat content). These prices correspond to the May 2021 retail fuel prices of \$0.55 per liter and \$0.59 per liter for 91 and 95 octane gasoline, respectively. Thus, the storage, transportation and distribution costs of hydrogen must be added to the production costs of green hydrogen to make proper comparisons.

#### 4. Economics of hydrogen production in Saudi Arabia

2.50 2.00 1.50 1.00 0.50 0.00 Blue Green Blue Green Blue Green hydrogen hydrogen hydrogen hydrogen hydrogen hydrogen (@\$6.2/MMBtu) (@current price) (@\$3.4/MMBtu) (@\$13/MWh) (@\$0.85/MMBtu) (@\$10/MWh) 2020 2030 2050

Figure 11. Comparison of blue (SMR and CCUS) and green (electrolysis and renewable electricity) hydrogen costs.

Source: Authors' estimation.

Notes: Estimates are based on current and future capex and efficiency for SMR with CCUS and alkaline electrolysis. The LCOH corresponds to plant utilization rates of 60% for electrolysis and 80% for SMR and SMR with CCUS. The discount rate is 8%.

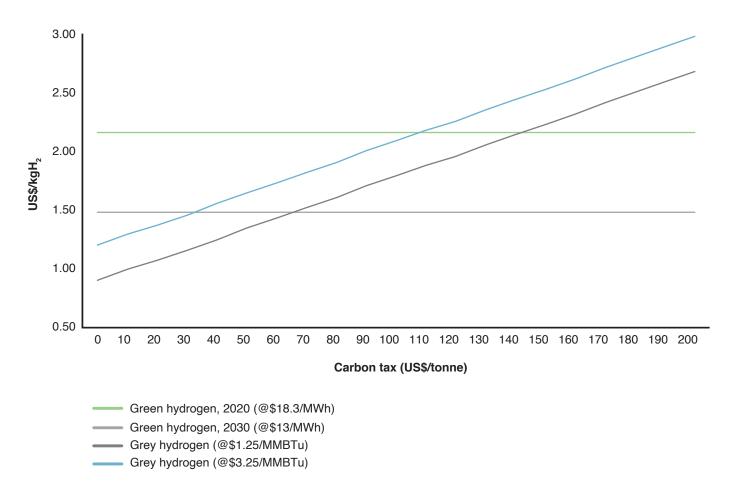
■ OPEX Fuel

CAPEX

To incentivize carbon-neutral hydrogen production, the costs of externalities must also be considered. Saudi Arabia may adopt a carbon price policy. If so, green hydrogen will be competitive with grey hydrogen in the local market at a carbon price of about \$145 per tonne. The corresponding gas

price for this estimate is \$1.25/MMBtu. As green hydrogen production costs fall, however, a carbon price of only about \$65 per tonne of carbon dioxide may be sufficient by 2030. Higher gas prices along with a carbon price will make grey hydrogen less competitive relative to green hydrogen (Figure 12).

Figure 12. Cost of grey hydrogen production with a carbon price.



Source. Authors' calculation.

## 5. Resource wealth and hydrogen production in Saudi Arabia

audi Arabia enjoys the unique advantage of having both significant hydrocarbon reserves and high renewable energy potential. Thus, its hydrogen production costs are among the lowest in the world. This advantage may allow Saudi Arabia to become a major producer and a low-cost global marginal supplier of low-carbon hydrogen if international trade in hydrogen develops. In this section, we briefly discuss Saudi Arabia's natural gas resources, geologic carbon dioxide storage potential and renewable resource potential for hydrogen production. We consider hypothetical growth in hydrogen demand to illustrate the green energy and natural gas requirements for hydrogen production in Saudi Arabia.

## 5.1 Natural gas resources and future plans

Saudi Arabia has one of the largest gas reserves in the world. It is estimated to contain about 233.8 trillion cubic feet of gas, concentrated in the country's Eastern Province (Saudi Aramco 2019). In 2019, gas consumption in Saudi Arabia reached nearly 11 billion cubic feet per day, making it the sixth-largest gas market worldwide (BP 2020). Plans are underway to almost double Saudi Arabia's gas supply within this decade. However, this gas is expected to be sourced from non-associated and unconventional gas resources, which are more expensive than associated gas (Fattouh and Shabaneh 2019).

Because of its gas resources, Saudi Arabia's Eastern Province is ideal for blue hydrogen production. It has a concentration of gas fields, distribution pipelines and proximity to potential carbon dioxide storage and utilization sites. A first-order assessment estimates that the Middle East may theoretically accommodate about 2,511 gigatonnes of carbon dioxide storage.

Most of this storage potential is concentrated in deep saline aquifers, a substantial majority of which are found in Saudi Arabia (Liu et al. 2012). Furthermore, the existing refineries and chemical complexes in Saudi Arabia's eastern region can be converted into facilities for producing blue hydrogen. Appendix B provides additional details on natural gas consumption and the gas grid.

## 5.2 Renewable energy resources and future plans

Much of Saudi Arabia's landscape has strong solar and wind endowments. Saudi Arabia has an estimated solar energy potential of about 33,888 petajoules (PJ) per year from commercial solar arrays (or 'farms'). It has additional potential of 845 PJ/year from solar panels fitted on buildings (SAGIA 2018; Shell 2021). Thus, it has the sixth-highest potential for producing solar energy in the world, after Algeria, Libya, China, Sudan and Australia (Shell 2021).

With an average of 8.9 hours of sunshine per day, it receives daily horizontal solar radiation of 5,600 watthours per square meter (Wh/m²) on average. This is well above the average irradiation of 250 Wh/m² in high-potential areas globally (SAGIA 2018). Most Saudi provinces receive sufficient sunshine to harness solar energy. However, the western inland region, where the city of Neom, with a green ammonia project, is situated, receives average daily solar radiation of 6,474 Wh/m². By comparison, eastern locations receive average daily solar radiation of 5,510 Wh/m² (Zell et al. 2015).

With an estimated wind potential of 520 PJ/year, Saudi Arabia ranks 13th in the world in terms of onshore wind energy resources (Shell 2021). The onshore wind speed range is between 6.0 and 8.0 meters per second (m/s). However, many areas enjoy onshore wind speeds above 7 m/s, which is well above the standard speed for economic viability (SAGIA 2018). Saudi Arabia's wind potential is concentrated in the northeast and central regions and the mountains in the western region (SAGIA 2018).

The renewable energy potential in PJ/year can support more than 4,800 GW of solar (utility-scale solar capacity) and 36 GW of wind installations in the country. The output from solar and wind plants may vary across locations. Thus, we use representative average electricity generation values from utility-scale solar and wind projects to estimate the renewable energy potential. Despite Saudi Arabia's great potential, however, renewable sources presently contribute a small but growing fraction of its energy mix. The existing installed solar capacity is about 413 MW, which includes the 300-megawatt Sakaka Solar independent power producer plant (IRENA 2021). The 400-megawatt Dumat Al Jandal project, when fully commissioned in 2022, will be Saudi Arabia's first utility-scale wind farm. It will also be the largest wind farm in the Middle East (Malek 2020). However, momentum for renewable energy is increasing. Seven new solar projects were announced in line with the objective to generate 50% of power from renewable energy by 2030 (Reuters 2021).

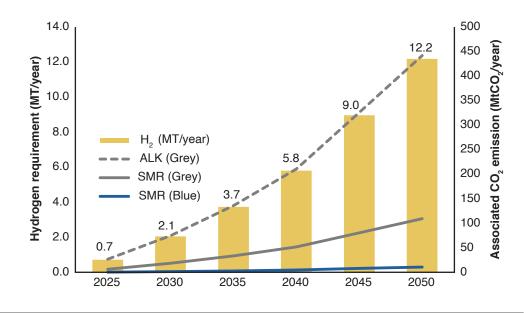
5.3 Hydrogen demand scenarios and feedstock requirements

Given the hydrogen market's nascency, various institutions provide a range of hydrogen demand projections. The IEA forecasts that global hydrogen demand will reach 30 exajoules by 2050 in its sustainable development scenario. The demand is expected to reach about 62 exajoules in its net-zero scenario (IEA 2020c, 2021). A report by the Hydrogen

Council expects hydrogen demand to increase almost tenfold by 2050 in a two-degree scenario, reaching 78 exajoules (Hydrogen Council 2017). It is estimated that this will meet 18% of final global energy demand in various sectors, including transportation, industrial energy, power generation and heat for buildings. If we extend and apply this assumption to the Kingdom's future energy needs over a similar time horizon, sourcing 18% of Saudi Arabia's total primary energy consumption from hydrogen will require about 12 million tonnes of hydrogen per year by 2050. We also assume that annual total final energy consumption growth is 2.5%. Figure 13 shows the projected hydrogen demand and the associated requirements for the gradual integration of hydrogen into the energy mix based on these assumptions. In a green-only scenario, the demand for electricity from renewable energy resources will increase by about 600 terawatthours (TWh) by 2050. Similarly, in a blue-only scenario, about 5.3 billion cubic feet (bcf) per day of natural gas will be needed by 2050 to meet hydrogen demand. Given Saudi Arabia's gas reserves and renewable energy potential, the Kingdom will be able to meet the projected hydrogen demand with green or blue hydrogen alone. However, a combination of both pathways may provide a lower-cost solution.

#### 5. Resource wealth and hydrogen production in Saudi Arabia

Figure 13. Assessment of Saudi Arabia's hydrogen penetration and resource requirements.



TT	H <sub>2</sub> as % of final energy consumption Green-only	2%	5%	8%	11%	15%	18%
	Electricity requirement (TWh) Associated RE capacity (GW)	36 16	102 44	185 80	288 124	445 192	604 260
<b>A</b>	Blue-only Natural gas requirement (bcf/day)	0.3	0.9	1.6	2.4	3.9	5.3

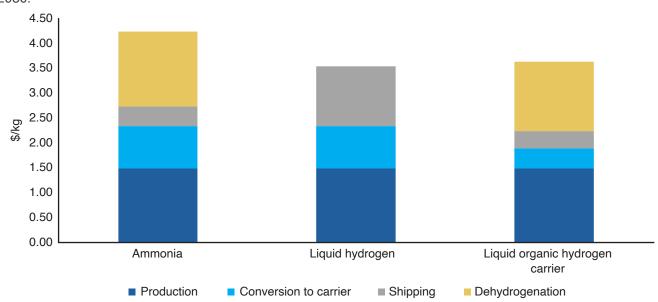
Source: Authors' assessment.

Note: The green-only scenario assumes a hybrid renewable energy supply. Solar energy contributes 70% of the electrolyzer's electricity needs, with the remainder coming from wind energy.

## 5.4 Hydrogen energy and export opportunities

As the world reduces its carbon use, Saudi Arabia's low-cost hydrogen production base presents tremendous opportunities. Saudi Arabia can monetize its resources in the form of exports or utilize hydrogen domestically in carbon-intensive

industries. Assuming a green hydrogen production cost of \$1.48/kg by 2030, the delivered cost of hydrogen (including conversion to carrier, shipping and dehydrogenation) from Saudi Arabia's western region to the Port of Rotterdam via the Suez Canal will average between about \$3.50/kg and \$4.50/kg, as Figure 14 shows. The cost will depend on the hydrogen carrier used.



**Figure 14.** Estimated delivered cost of hydrogen from Saudi Arabia's west coast to Rotterdam by hydrogen carrier in 2030.

Source: Hydrogen Council and McKinsey & Company (2021) and KAPSARC.

Note: The production costs are the authors' calculations. The midpoints of the ranges provided in Exhibit 15 in Hydrogen Council and McKinsey & Company (2021) are used for conversion, shipping and dehydrogenation costs.

In Europe, the expected cost of hydrogen production in 2030 is estimated to be between \$3/kg and \$5/ kg (Lambert and Schulte 2021). Thus, hydrogen imports from Saudi Arabia may be competitively priced in some parts of Europe by 2030. Shipping hydrogen in the form of ammonia is currently the most convenient transport method. Ammonia has an established supply chain, technological maturity and higher volumetric density compared to liquified or compressed hydrogen. Additionally, the transport of hydrogen in liquid form or using a liquid organic carrier has not reached a commercial stage. However, using ammonia to carry hydrogen requires cracking the ammonia back to hydrogen (dehydrogenation) if pure hydrogen is needed. Thus, this method incurs an additional cost ranging from \$1/kg to \$2/kg (Hydrogen Council and McKinsey & Company 2021).

To avoid this additional cost, Saudi Arabia can instead trade blue or green ammonia for direct use. It can substitute for grey ammonia in international

markets (which is mostly used for fertilizers). It can also be used for new applications, such as the blue ammonia used in Japan for power generation. In 2019, Saudi Arabia was the largest exporter of ammonia, with over 4.8 million tonnes of exports (World Integrated Trade Solution 2020). It was also the world's largest exporter of methanol, another hydrogen-rich chemical suitable as an energy carrier, in 2019.

Decarbonizing existing ammonia and methanol plants using low-cost blue or green hydrogen is therefore a quick win for lowering Saudi Arabia's carbon footprint. Saudi Arabia can also provide carbon-neutral products to export markets.

These advantages can extend to other domestic energy-intensive industries, such as steel, cement and aluminum. Low-carbon hydrogen can reduce the carbon content embodied in these industries' finished products and safeguard these industries as carbon policies become more stringent.

### 6. Conclusions

lobally, many governments' decarbonization policies and the declining production costs of renewable energy are strengthening the case for hydrogen as an energy carrier and energy fuel. Hydrogen energy presents decarbonization opportunities. Thus, numerous countries have unveiled policies and plans to support the production and use of zero or low-carbon hydrogen. Currently, hydrogen production is dominated by the natural gas-based steam reformation process. However, this production is likely to shift toward lower carbon options. These options include water electrolysis using renewable energy and the integration of CCS with SMR to capture the carbon dioxide generated by the production process.

Saudi Arabia is the largest country in western Asia. With nearly 830,000 square miles of land area, it can leverage its resources to produce hydrogen for internal use or export. We estimated Saudi Arabia's production costs for green and blue hydrogen to be \$2.16/kg and \$1.34/kg, respectively. These costs are presently among the lowest in the world. For our estimation, we set \$18.3/MWh as a reference price for solar-based electricity and \$1.25/MMBtu as

a reference price for domestic natural gas. A trend of price discovery in the competitive selection of utility-scale solar photovoltaic projects is emerging in Saudi Arabia. Thus, it would not be surprising to achieve a levelized price below \$15/MWh in the next decade. Additionally, capex for electrolyzers are expected to decline. Thus, the cost of producing green hydrogen may be close to \$1/kg by 2030. Assuming the same reference gas price, the cost of blue hydrogen is projected to be about \$1.13/kg by 2030.

Saudi Vision 2030 (2016) deeply enshrines sustainability objectives in various economic activities. One such objective is the diversification of energy resources through the increased deployment of renewables and additional natural gas sources in the country's energy mix. Saudi Arabia's adoption of the CCE to reduce carbon emissions and its support for clean hydrogen are positive developments. This study has mainly focused on the economics of hydrogen production in Saudi Arabia. However, we intend to expand the scope of the analysis to include transportation and storage costs and other end-use sectors in future studies.

### **Endnotes**

<sup>1</sup> Neom, which means 'new future,' is a planned city and a model for the future. It encompasses a sustainable ecosystem for living and working. This project is in the Tabuk province of north-western Saudi Arabia and is planned to be entirely powered by renewable energy sources.

<sup>2</sup> This value is the generic cost of producing grey and blue hydrogen in Saudi Arabia. It does not represent the delivered cost of grey and blue hydrogen from Saudi Arabia to other markets.

#### References

ACWA Power. 2020. "Sakaka PV IPP." Accessed April 17, 2021. https://www.acwapower.com/en/projects/sakaka-ipp/.

Arab Petroleum Investments Corporation (APICORP). 2018. "Saudi energy price reform getting serious." APICORP Energy Research 3 (5). https://www.apicorp.org/Research/EnergyReseach/2018/APICORP\_Energy\_Research\_V03\_N05\_2018.pdf

Baylin-Stern, Adam, and Niels Berghout. 2021. "Is Carbon Capture Too Expensive?." *International Energy Agency*, February 17, 2021. https://www.iea.org/commentaries/is-carbon-capture-too-expensive.

Bellini, Emiliano. 2021. "Saudi Arabia's Second PV Tender Draws World Record Low Bid of \$0.0104/kWh." *PV Magazine*, April 8, 2021. https://www.pv-magazine.com/2021/04/08/saudi-arabias-second-pv-tender-draws-world-record-low-bid-of-0104-kwh/.

Blain, Loz. 2021. "World's Biggest Green Hydrogen Project Announced for Kazakhstan." *New Atlas*, June 28, 2021. https://newatlas.com/energy/worlds-biggest-green-hydrogen-project-planned-kazakhstan/.

Bloomberg New Energy Finance (BNEF). 2021. "1H 2021 Hydrogen Market Outlook - A Defining Year Ahead." Bloomberg New Energy Finance.

BP. 2020. Statistical Review of World Energy. London: BP. Accessed April 17, 2021. https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html.

Collodi, Guido, Giuliana Azzaro, Noemi Ferrari, and Stanley Santos. 2017. "Techno-Economic Evaluation of Deploying CCS in SMR Based Merchant H2 Production with NG as Feedstock and Fuel." *Energy Procedia*. 114, 2690-2712. DOI: 10.1016/j. egypro.2017.03.1533

Colthorpe, Andy. 2020. "Hydrogen Electrolysis Using Renewable Energy Begins at 10MW Fukushima Plant." *Energy Storage News*, April 20, 2020. https://www.energy-storage.news/news/hydrogenelectrolysis-using-renewable-energy-begins-at-10mw-fukushima-plant.

Dialogue on European Decarbonisation Strategies (DEEDS). 2020. "Industry - Hydrogen, Methanol, Synfuel." Accessed February 2, 2021. https://deeds.eu/wp-content/uploads/2020/05/ HydrogenMethanolSyngas\_web.pdf.

European Commission. 2020. "Questions and Answers: A Hydrogen Strategy for a Climate Neutral Europe." *European Commission Press Corner*, July 8, 2020. https://ec.europa.eu/commission/presscorner/detail/en/QANDA\_20\_1257.

Fattouh, Bassam, and Rami Shabaneh. 2019. "The Future of Gas in Saudi Arabia's Transitions." In *The Future of Gas in the Gulf: Continuity and Change*, edited by Jonathan P. Stern, 85–113. Oxford: Davidson Publishing.

Federal Ministry for Economic Affairs and Energy (BMWi). 2020. *The National Hydrogen Strategy*. Berlin: Federal Ministry for Economic Affairs and Energy, Public Relations Division. Accessed February 19, 2021. https://www.bmwi.de/Redaktion/EN/Publikationen/Energie/the-national-hydrogenstrategy.html.

The Federation of Electric Power Companies of Japan (FEPC). 2021. "Japan's Energy Supply Situation and Basic Policy." Accessed February 21. https://www.fepc.or.jp/english/energy\_electricity/supply\_situation/.

Fuel Cells and Hydrogen 2 Joint Undertaking (FCH 2 JU). 2017. "Development of Business Cases for Fuel Cells and Hydrogen Applications for Regions and Cities." Accessed January 25, 2021. https://www.fch.europa.eu/sites/default/files/FCH%20 Docs/171121\_FCH2JU\_Application-Package\_WG5\_P2H\_Green%20hydrogen%20%28ID%20 2910583%29%20%28ID%202911641%29.pdf.

Government of the Netherlands. 2020. "Government Strategy on Hydrogen." Accessed February 19, 2021. https://www.government.nl/documents/publications/2020/04/06/government-strategy-on-hydrogen.

Government of the United Kingdom. 2021. "U.K. hydrogen strategy." Accessed September 30, 2021. https://www.gov.uk/government/publications/uk-hydrogen-strategy

Greenhalgh, Keiron. 2021. "Australian Green Megaproject Pipeline Grows." IHS Markit, July 14, 2021. https://ihsmarkit.com/research-analysis/australiangreen-megaproject-pipeline-grows.html.

Hydrogen Council. 2017. "Hydrogen - Scaling up." Accessed February 7, 2021. https://hydrogencouncil.com/wp-content/uploads/2017/11/Hydrogen-scaling-up-Hydrogen-Council.pdf.

———. 2021. "Hydrogen Decarbonization Pathways - Potential Supply Scenarios." Accessed February 7, 2021. https://hydrogencouncil.com/ wp-content/uploads/2021/01/Hydrogen-Council-Report\_Decarbonization-Pathways\_Part-2\_Supply-Scenarios.pdf.

Hydrogen Council and McKinsey & Company. 2021. "Hydrogen Insights: A Perspective on Hydrogen Investment, Market Development and Cost Competitiveness." Accessed April 14, 2021. hydrogencouncil.com/wp-content/uploads/2021/02/Hydrogen-Insights-2021-Report.pdf. Hydrogen Electric Vehicle Consumer Association (H2EVA). 2018. "Hydrogen Roadmap Korea." Accessed February 21, 2021. http://www.h2eva.org/download.php?file=20181112\_visualization\_of\_key\_results.pdf.

International Energy Agency (IEA). 2019. "The Future of Hydrogen: Seizing Today's Opportunities." Accessed April 17, 2021. https://webstore.iea.org/download/direct/2803.

——. 2020a. *Cross-cutting: Hydrogen*. Paris: IEA. Accessed February 14, 2021. https://www.cceguide.org/wp-content/uploads/2020/08/07-IEA-Cross-cutting.pdf.

———. 2020c. "World Energy Balances." Accessed January 12, 2021. https://www.iea.org/data-and-statistics/data-product/world-energy-balances.

——. 2021. "Net Zero by 2050: A Roadmap for the Global Energy Sector." https://iea.blob. core.windows.net/assets/4719e321-6d3d-41a2-bd6b-461ad2f850a8/NetZeroby2050-ARoadmapfortheGlobalEnergySector.pdf.

International Renewable Energy Agency (IRENA). 2018. "Hydrogen from Renewable Power: Technology Outlook for the Energy Transition." Accessed January 25, 2021. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Sep/IRENA\_Hydrogen\_from\_renewable\_power\_2018.pdf.

———. 2020a. "Scaling up Electrolysers to Meet the 1.5°C Climate Goal." Abu Dhabi: IRENA. Accessed March 10, 2021. https://irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA\_Green\_hydrogen\_cost\_2020.pdf

#### References

———. 2020b. "Making Green Hydrogen a Cost-Competitive Climate Solution." Accessed April 17, 2021. https://www.irena.org/newsroom/pressreleases/2020/Dec/Making-Green-Hydrogen-a-Cost-Competitive-Climate-Solution#:~:text=Today%2C%20green%20 hydrogen%20is%202,capture%20and%20 storage%20(CCS).&text=While%20low%2Dcost%20 electricity%20is.facilities%20must%20fa.

——. 2021. "Renewable Capacity Statistics 2021." Accessed April 17, 2021. https://www.irena.org/publications/2021/March/Renewable-Capacity-Statistics-2021.

KAPSARC. 2020. "CCE Guide Overview." Accessed February 11, 2021. https://www.cceguide.org/wp-content/uploads/2020/08/00-CCE-Guide-Overview.pdf.

Lambert, Martin, and Simon Schulte. 2021.

Contrasting European Hydrogen Pathways: An

Analysis of Differing Approaches in Key Markets.

Oxford: Oxford Institute for Energy Studies. Accessed

April 14, 2021. https://www.oxfordenergy.org/wpcms/
wp-content/uploads/2021/03/Contrasting-European-hydrogen-pathways-An-analysis-of-differing-approaches-in-key-markets-NG166.pdf.

Liu, Hengwei, Berenice Garcia Tellez, Tarek Atallah, and Murad Barghouty. 2012. "The Role of CO<sub>2</sub> Capture and Storage in Saudi Arabia's Energy Future." *International Journal of Greenhouse Gas Control* 11:163–71. DOI: 10.1016/j.ijggc.2012.08.008

Malek, Caline. 2020. "Saudi Wind Farm's Progress Heralds a New Era in Clean Energy." *Arab News*, October 6, 2020. https://www.arabnews.com/node/1744636/saudi-arabia.

Martín, José Rojo. 2020. "Bids of US\$0.0162/kWh Emerge as Saudi Arabia Shortlists Firms for 1.47GW Solar Tender." *PV-Tech*, April 6, 2020. https://www.pv-tech.org/bids-of-us0-0162-kwh-emerge-as-saudiarabia-shortlists-firms-for-1-47gw-sol/.

Ministry of Economy, Trade and Industry (METI). 2017. "Basic Hydrogen Strategy." https://www.meti.go.jp/english/press/2017/pdf/1226\_003b.pdf.

Ministerio de Energía. 2020. "National Green Hydrogen Strategy." Accessed April 17, 2021. https:// energia.gob.cl/sites/default/files/national\_green\_ hydrogen\_strategy\_-\_chile.pdf.

Nouryon. 2020. "Nouryon-led Consortium Wins EU Backing for Pioneering Green Hydrogen Project." January 22, 2020. https://www.nouryon.com/news-and-events/news-overview/2020/nouryon-led-consortium-wins-eu-backing-for-pioneering-green-hydrogen-project/.

O'Callaghan, Jonathan. 2018. "Storing CO2 underground can curb carbon emissions, but is it safe?" *Horizon: The EU Research & Innovation Magazine*, November 27, 2018. https://ec.europa.eu/research-and-innovation/en/horizon-magazine/storing-co2-underground-can-curb-carbon-emissions-it-safe

Renewables Now. 2021. "Acwa Power-led Team Inks PPA for 1.5-GW Saudi Solar Giant." April 9, 2021. https://renewablesnow.com/news/acwa-power-led-team-inks-ppa-for-15-gw-saudi-solar-giant-737444/.

Reuters. 2021. "Saudi Arabia Signs Agreements for Seven New Solar Projects -SPA." April 8, 2021. https://www.reuters.com/world/middle-east/saudiarabia-signs-agreements-7-new-solar-projects-spa-2021-04-08/.

Rievaj, Vladimír, Ján Gaňa, and František Synák. 2019. "Is hydrogen the fuel of the future?" *Transportation Research Procedia*. 40, 469-74. DOI: 10.1016/j.trpro.2019.07.068

Royal Society of Chemistry (RSC). 2021. "Hydrogen." Accessed April 17, 2021. https://www.rsc.org/periodic-table/element/1/hydrogen.

S&P Global Platts. 2020. "Dutch 20 MW Green Hydrogen Electrolyzer Project Secures EU Funding." January 24, 2020. https://www.spglobal.com/platts/en/market-insights/latest-news/electric-power/012420-dutch-20-mw-green-hydrogen-electrolyzer-project-secures-eu-funding.

Saudi Arabia General Investment Authority (SAGIA). 2018. "Invest Saudi: Renewable Energy." Riyadh: SAGIA. Accessed January 12, 2021.

Saudi Aramco. 2019. "Saudi Aramco Prospectus." Accessed February 25, 2021. https://www.aramco.com/-/media/images/investors/saudi-aramco-prospectus-en-051219.pdf.

Saudi Electricity Company (SEC). 2018. "Consumption Tariffs." Accessed March 2, 2021. https://www.se.com.sa/en-us/customers/Pages/TariffRates.aspx.

Saudi Gulf Projects. 2021. "Saudi Arabia Signed Power Purchase Agreement for 2,970MW Solar PV Projects." April 8, 2021. https://www.saudigulfprojects.com/2021/04/saudi-arabia-signed-power-purchase-agreement-for-2970mw-solar-pv-projects/.

Saudi Press Agency (SPA). 2020. "G20 Promotes the Circular Carbon Economy (CCE)." October 30, 2020. https://www.spa.gov.sa/viewfullstory.php?lang=en&newsid=2150034.

Saudi Vision (SV) 2030. 2016. "Saudi Vision 2030." Government of Saudi Arabia. Accessed April 17, 2021. https://www.vision2030.gov.sa/sites/default/files/report/Saudi\_Vision2030\_AR\_2017.pdf.

Shell. 2021. "Global Energy Resources Database." Accessed April 17, 2021. https://www.shell.com/energy-and-innovation/the-energy-future/scenarios/shell-scenarios-energy-models/energy-resource-database.html.

Water & Electricity Regulatory Authority. 2019. "Annual Statistical Booklet for Electricity and Seawater Desalination Industries." Accessed January 21, 2021. https://www.ecra.gov.sa/en-us/MediaCenter/doclib2/Pages/SubCategoryList. aspx?categoryID=5.

World Energy Council (WEC). 2021. "Working Paper I National Hydrogen Strategies. Hydrogen on the Horizon: Ready, Almost Set, Go?" September 2021. https://www.worldenergy.org/assets/downloads/Working\_Paper\_-\_National\_Hydrogen\_Strategies\_-\_September\_2021.pdf

World Integrated Trade Solution. 2020. "Ammonia; Anhydrous Exports by Country in 2019." Accessed April 12, 2021. https://wits. worldbank.org/trade/comtrade/en/country/ALL/year/2019/tradeflow/Exports/partner/WLD/product/281410#:~:text=In%202019%2C%20Top%20 exporters%20of,143%2C930.87K%20%2C%20 433%2C537%2C000%20Kg).

Yep, Eric. 2020. "South Korea Needs to Do More to Decarbonize Energy Supply: IEA." *S&P Global Platts*, December 2, 2020. https://www.spglobal.com/platts/en/market-insights/latest-news/electric-power/120220-south-korea-needs-to-do-more-to-decarbonize-energy-supply-iea.

#### References

Zell, Erica, Sami Gasim, Stephen Wilcox, Suzan Katamoura, Thomas Stoffel, Husain Shibli, Jill Engel-Cox, and Madi Al Subie. 2015. "Assessment of Solar Radiation Resources in Saudi Arabia." *Solar Energy* 119: 422–38. DOI: 10.1016/j.solener.2015.06.031

### **Appendix A**

In 2018, the International Energy Agency (IEA) published a detailed report titled "The Future of Hydrogen." This report, prepared for G20 Japan, provides an extensive and independent assessment of hydrogen production. It presents various assumptions that underpin the analyses of hydrogen economics. The IEA updated various cost and operational assumptions in 2020. These assumptions are presented in Tables A1 to A4, along with assumptions from other sources.

Table A1. Input parameters for hydrogen production using alkaline water electrolysis (ALK).

Technology	Year	Сарех	Opex (% capex/year)	Efficiency (%, LHV)	Stack lifetime (operating hours)	Source
Electrolysis	2017	€750/kW	2	65	80,000	(IRENA 2018)
(ALK)	2025	€480/kW	2	68	90,000	(IRENA 2018)
	2020	\$900/kW	1.5	64	95,000	(IEA 2019)
	2030	\$700/kW	1.5	69	95,000	(IEA 2019)
	Long term	\$450/kW	1.5	74	100,000	(IEA 2019)
	2017	€830/kW	2	64	80,000	(FCH 2017)
	2025	€600/kW	2	67	90,000	(FCH 2017)

Notes: Capex includes electrolyzer stacks, electric controls, purification and compression, construction and mobilization, and other balances of plant costs. The Fuel Cells and Hydrogen 2 Joint Undertaking collated publicly available sources for more than 90 European regions and cities. Based on these sources, the stack replacement cost ranges from 35% to 45% of capex (FCH 2017). This study assumes a stack replacement cost of 40% relative to total capex for electrolyzers. We use specific water consumption of 9 liters per kilogram, plant life of 20 years and a construction period of two years to assess the LCOH. Sources: Rievaj (2019); IRENA (2020a).

**Table A2.** Input parameters for hydrogen production using steam methane reforming (SMR).

Technology	Year	Сарех	Opex (% capex/year)	Efficiency (%, LHV)	Emission factor (kgCO <sub>2</sub> / kgH <sub>2</sub> )	Source
SMR	2020	\$910/kW	4.7	76	8.9	(IEA 2019)
	2030	\$910/kW	4.7	76	8.9	(IEA 2019)
	Long term	\$910/kW	4.7	76	8.9	(IEA 2019)

Notes: We assume specific water consumption of 10 liters per kilogram of hydrogen and specific electricity consumption of 0.5 kilowatthours per kilogram of hydrogen. We also assume a plant life of 25 years and a construction period of three years for assessing the LCOH.

Source: Collodi (2017).

Table A3. Input parameters for hydrogen production using SMR with carbon capture, utilization and storage.

Technology	Year	Capex	Opex (% capex/ year)	Efficiency (%, LHV)	Emission factor (kgCO <sub>2</sub> / kgH <sub>2</sub> )	Carbon dioxide capture rate (%)	Source
SMR with	2020	\$1,680/kW	3	69	1	90	(IEA 2019)
carbon capture	2030	\$1,360/kW	3	69	1	90	(IEA 2019)
	Long term	\$1,280/kW	3	69	1	90	(IEA 2019)
	2020	€1,500/kW	3	69	1	90	(DEEDS 2020)
	2030	€1,200/kW	3	69	1	90	(DEEDS 2020)
	2050	€1,150/kW	3	69	1	90	(DEEDS 2020)
	2025	€600/kW	2	67	90,000		(FCH 2017)

Notes: We assume specific water consumption of 10 liters per kilogram of hydrogen and specific electricity consumption of 0.5 kilowatthours per kilogram of hydrogen. We also assume a carbon capture rate of 90%, plant life of 25 years and a construction period of three years to assess the LCOH.

Sources: O'Callaghan (2018); Collodi (2017).

Table A4. Reference prices for feedstock and consumables in Saudi Arabia.

Item	Cost
Electricity price (\$/MWh), industrial tariff <sup>a</sup>	48
Electricity price (\$/MWh), solar PVb	23.42
Desalinated water (\$/m³)c	0.52
Natural gas price (\$/MMBtu)d	1.25

Sources: (Acwa Power 2020; SEC 2018).

Notes: a-corresponds to the industrial tariff of 18 halalah per kWh in Saudi Arabia. b-corresponds to Sakaka Solar's levelized tariff of 8.781 halalah per kWh. c-corresponds to the Shuqaiq 3 water desalination plant award cost of \$0.52 per Nm³. d-based on the current domestic natural gas price.

Source: APICORP (2018).

## **Appendix B**

Gas consumption in Saudi Arabia grew at an average annual rate of 4.8% between 2000 and 2019 (BP 2020). This rate is almost double the average annual growth rate of global gas demand over the same time period. The power generation sector accounts for the largest share of Saudi Arabia's natural gas consumption, comprising about 63% of the total. The industrial sector (including non-energy use) follows with about 32% of consumption (IEA 2020c). The strong growth in demand was driven by population, economic growth and low gas prices. In 1984, Saudi Arabia set natural gas prices at \$0.5 per million British thermal units (MMBtu). This price was increased to \$0.75/MMBtu in 1998 and again to \$1.25/MMBtu in 2016 (Fattouh and Shabaneh 2019).

Despite the rise in Saudi Arabia's gas prices in the last two decades, they are still the lowest in the world. These prices promote industrial competitiveness in the Kingdom. However, the supply of gas to power producers and other industrial end users is constrained by pipeline capacity. As Figure B1 shows, natural gas consumption is mainly concentrated in the eastern and central regions, which are closer to the gas supply. The western and southern regions have little to no gas consumption.

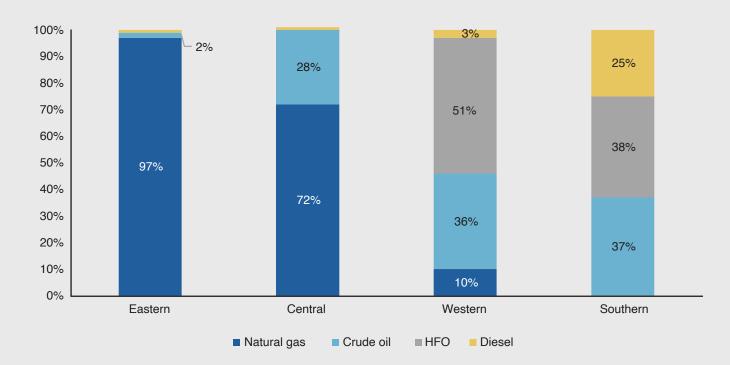
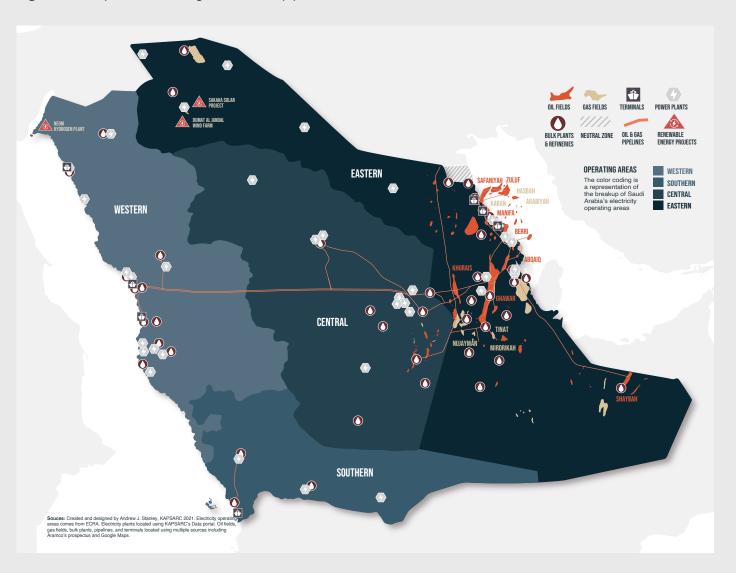


Figure B1. Fuel share for power generation and water desalination in Saudi Arabia by region, 2019.

Source: Water & Electricity Regulatory Authority (2019).

Figure B2. Map of the oil and gas fields and pipelines in Saudi Arabia.



Source: KAPSARC illustration based on information gathered from the Water & Electricity Regulatory Authority, Aramco and Google Maps, 2021.

## **Notes**

## **Notes**

#### **About the Authors**



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Shahid is a research fellow at KAPSARC. His current research focuses on electricity sector transitions and hydrogen economics, policy and regulatory issues in the Gulf Cooperation Council (GCC) member states. He also studies the development of regional electricity markets in the GCC, Middle East and North Africa region. He previously consulted extensively on policy, regulatory and market design for governments, electricity regulators, public utilities and the electricity industries in India and Southeast Asia.



#### Rami Shabaneh

Rami is a senior research associate who focuses on global gas and liquids markets. Rami has more than 13 years of research and industry experience analyzing energy markets and energy policy. Before joining KAPSARC, Rami worked at Cenovus Energy as a market fundamentals analyst. There, he provided analytic support on specific issues affecting North American gas, natural gas liquids and condensate markets. His work directly supported the company's hedging strategies. Before working at Cenovus Energy, Rami spent three years as an integral member of the fuels and power research team at the Canadian Energy Research Institute. He holds a Master of Science degree in sustainable energy development and a Bachelor of Science degree in actuarial science from the University of Calgary.

#### **About the Project**

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



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