مركز الملك عبدالله للدراسات والبحوث البترولية
King Abdullah Petroleum Studies and Research Center

CLINGENDAEL INTERNATIONAL ENERGY PROGRAMME

The Path Toward a Hydrogen Economy: How Industry Can Broaden the Use of Hydrogen

October 2020

Doi: 10.30573/KS--2020-WB10

About KAPSARC

The King Abdullah Petroleum Studies and Research Center (KAPSARC) is a non-profit global institution dedicated to independent research into energy economics, policy, technology and the environment across all types of energy. KAPSARC's mandate is to advance the understanding of energy challenges and opportunities facing the world today and tomorrow, through unbiased, independent, and high-caliber research for the benefit of society. KAPSARC is located in Riyadh, Saudi Arabia.

This publication is also available in Arabic.

Legal Notice

Key Points

Hydrogen is seen as a potential solution in reaching climate goals and decarbonizing hard-to-abate sectors like industry, buildings, and heavy-duty transport. It is also currently perceived as an energy vector, one that facilitates energy storage and can be used in the production of synthetic fuels. This makes it an essential component of a circular carbon economy and advancing the transition to cleaner and sustainable fuels.

The support for hydrogen as an energy carrier on a regional and national level is encouraging investment from capital markets. However, the investor community needs to see more long-term offtake contract agreements between suppliers and end-users of carbon-neutral hydrogen to guarantee the funding of hydrogen projects.

To create carbon-neutral hydrogen value chains (i.e., blue and green hydrogen), establishing new markets for hydrogen beyond the current industrial sector is as important as decarbonizing the current industrial hydrogen markets.

Enabling a smooth transition to a hydrogen economy necessitates decarbonizing existing fossil-based hydrogen production. It also requires repurposing existing natural gas pipeline grids, where possible, to connect producers and consumers and develop storage facilities.

On-road heavy-duty mobility and industrial applications are the sectors where carbon-neutral hydrogen can achieve the largest deployment and scale-up in the initial stages of market development. In some jurisdictions, low-temperature heating is a competitive decarbonization option.

Supportive policy measures and significant production and consumption support schemes are required to develop the hydrogen economy. Large infrastructure projects can only pass their initial investment phases when sufficient production and consumption has been committed to.

Saudi Arabia recently announced it was building the world’s largest green ammonia plant. This, combined with its vast amount of low-cost hydrocarbons and geological pore space, means the country is poised to become a major carbon-neutral hydrogen-exporting hub. There is substantial potential in the North Sea to generate offshore wind power. This, alongside the North Sea region’s petrochemical clusters and pore space, means that it is also poised to become an important European carbon-neutral hub.

Summary

In the past couple of years, it became evident that hydrogen would need to play a pivotal role in a carbon-free energy system. It would help decarbonize hard-to-abate sectors and act as an energy carrier to manage large variability in renewable energy production and enhance energy security. In most cases, its transportation and storage over a certain distance and timeframe is cheaper than that of electricity. For hydrogen to make an impact, it needs to expand its utility beyond its existing applications. Currently, hydrogen is mostly used as a feedstock to produce ammonia and methanol, and in refinery processes. However, it needs to expand to other sectors such as steel manufacturing, low-temperature heating for the built environment, where other low carbon options are more expensive, the power sector and heavy-duty transport. But support is required to help hydrogen evolve to fulfill these roles. At the moment, the bulk of research and development funding in low-carbon energy technologies is focussed on low-carbon power generation, electrification and energy efficiency. While the development of these technologies is important, more attention needs to be directed toward the harder-to-electrify sectors. These sectors are major contributors to carbon emissions, and hydrogen could play a role in reducing their current emissions.

Many countries, mostly in Europe and around the Pacific, have drafted policies and roadmaps to foster hydrogen economies, and they are adopting carbon-neutral hydrogen as part of their pathway to zero emissions. The COVID-19 pandemic has provided an opportunity to accelerate these initiatives, with large sums of national and regional economic stimulus packages earmarked for hydrogen development. There has been collaboration in the North Sea region to strengthen national strategies aimed at developing carbon-neutral hydrogen value chains and creating a functioning regional hydrogen market. Hydrogen imports will also be important for countries in Europe and Asia to reach their national emission targets. This opens up an opportunity for countries in the Middle East and North Africa (MENA) region, notably Saudi Arabia, to become part of the solution in the energy transition. With vast amounts of low-cost hydrocarbons, geological pore space, and an abundance of renewable energy resources, the MENA region is poised to take a leading role in supplying low-cost hydrogen.

Large investments are required to scale up hydrogen production to reduce its costs. These investments are needed along the whole value chain, including production, retrofitting and converting the existing hydrogen infrastructure. While the appetite for financing large hydrogen projects is growing, the investment community needs to see more long-term offtake agreements to guarantee a return on its investments and lower financing costs.

Background to the Workshop

From July 8 to 9, KAPSARC hosted a virtual workshop in partnership with the Clingendael International Energy Programme (CIEP). It explored the pathways toward a hydrogen economy, including hydrogen's industrial applications, its supply chain and the creation of a new hydrogen market. Discussions also revolved around the key policy instruments required to incentivize the fast deployment of carbon-neutral hydrogen production. The timing of this workshop was critical, given the launch of the European Union's hydrogen strategy on July 8 and the ambitious step Saudi Arabia has recently announced of developing carbon-neutral hydrogen at what will be the world's largest green ammonia plant, situated in Neom. This workshop gathered experts in the field of hydrogen and carbon management from industry, academia, and the investment community to discuss and investigate:

- The role of hydrogen in a circular carbon economy
- Supply chain challenges and security of supply
- Future business and investment models for hydrogen

Throughout this report we refer to the following terms to explain the hydrogen production process:

Grey hydrogen: Hydrogen produced from fossil fuels through reformation or gasification **without** carbon capture, utilization and storage (CCUS)

Blue hydrogen: Hydrogen produced from fossil fuels with carbon management using CCUS

Green hydrogen: Hydrogen produced via electrolysis using renewable energy

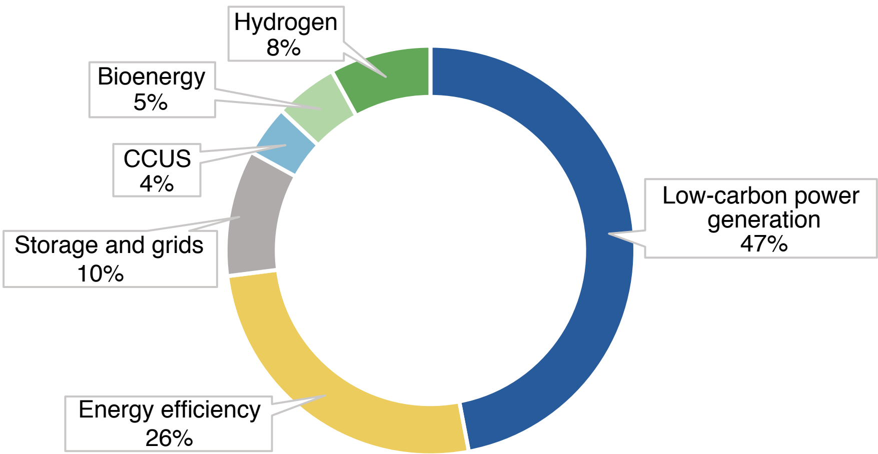
Carbon-neutral hydrogen: blue and green hydrogen

Hydrogen Initiatives Gathering Momentum: Spearheaded by Europe, Opportunities for Saudi Arabia

The use of hydrogen as an energy carrier has had several false starts for commercial and technological reasons. However, there is currently a confluence of factors to make the current momentum behind hydrogen use different from previous attempts to make hydrogen a solution for meeting climate targets. Strong initiatives, policies and detailed roadmaps are helping the push for hydrogen. The availability of low-cost renewable energy, the need to manage intermittency and integration costs in the power system, and the need to transport and store large quantities of energy have contributed to the improved commercial position of hydrogen technologies. Moreover, hydrogen also has the potential to become an international tradeable commodity. Climate change and air pollution problems in urban areas and cities have also boosted societal support for hydrogen as a solution to cut emissions in energy-intensive industries.

Despite the falling cost of renewable power production, the cost of carbon-neutral hydrogen production is still high compared to fossil fuel-based production. Financial incentives are required, as an initial push, to scale up carbon-neutral hydrogen generation technologies and bring down their costs. This is analogous to the solution of the renewable energy industry to a similar challenge, where the scale-up and the deployment of wind and solar photovoltaic technologies, through policy support, achieved dramatic cost declines. The International Energy Agency released a timely report discussing the funding and status of clean energy innovation: around $17 billion of public funding worldwide went into the research and development of low-carbon energy technologies (IEA 2020). As Figure 1 shows, about three-quarters of that funding went into low-carbon power generation and energy efficiency technologies. However, to reduce emissions in the hard-to-abate sectors, more focus needs to be given to electrification, carbon capture, utilization and storage (CCUS), bioenergy and carbon-neutral hydrogen.

Figure 1. Global public funding allocations for low-carbon energy research and development for specific technology areas, 2019.



Source: IEA (2020).

In 2019, various countries, including the European Union (EU), Canada, the Netherlands and Australia, announced hydrogen-supportive policies. The COVID-19 crisis threatened to derail efforts to develop the global hydrogen industry, as the health emergency and the need to mitigate the outbreak put pressure on government budgets. However, the pandemic seems to be giving hydrogen initiatives across the world a second wind. Many of the economic recovery plans put forth to deal with the pandemic were integrated with green stimulus packages, the most ambitious of which came from the European Commission and was boosted on a national level by some European countries. Europe currently has about 1 gigawatt (GW) of electrolyzer capacity. The European Commission released their hydrogen strategy on July 8, 2020, in which it detailed plans to install 6 GW of electrolyzers and produce up to 1 million tonnes of renewable hydrogen ('green' hydrogen) by 2024. By 2030, it will ramp up its electrolyzer capacity to 40 GW, with the aim of producing 10 million tonnes of green hydrogen. During these phases, it will also decarbonize its existing fossil-based hydrogen production using CCUS technology ('blue' hydrogen) to accelerate the scale-up of carbon-neutral hydrogen production. Both the Netherlands and Germany have launched ambitious hydrogen strategies with similar objectives, involving strong bilateral cooperation. For example, offshore wind power from Germany is to be used for the production of green hydrogen in the Netherlands, and repurposed natural gas pipelines will deliver hydrogen to industrial users in Germany and the Netherlands. This collaboration is intended to be expanded to include all countries around the North Sea, develop integrated hydrogen value chains and create a regional hydrogen market. There are also significant salt caverns that can be used to store hydrogen in Germany and the Netherlands.

The European hydrogen strategy also recognizes that Europe cannot meet its hydrogen targets by relying solely on domestically-produced hydrogen. Thus, imports of hydrogen from outside the continent will play a very important role. The Middle East and North Africa (MENA) region is ideally situated for hydrogen development, as it has vast amounts of low-cost hydrocarbons. It also has a significant amount of pore space and saline aquifers for storing carbon, making it ideally placed to supply blue hydrogen. Coincidentally, the MENA region is endowed with renewable energy resources and is home to projects with record low renewable energy costs. On July 7, 2020, Saudi Arabia announced the world's largest green ammonia project at its mega project Neom, establishing itself as an important hydrogen player. In partnership with Air Products and ACWA Power, the project will have the capacity to produce 650 tonnes per day of green hydrogen, utilizing 4 GW of renewable energy for water electrolysis. This will enable the plant to produce 1.2 million tonnes of ammonia per year. It is strategically located on the Red Sea along popular shipping routes and is in close proximity to the Suez Canal.

Given its low-cost hydrocarbon base, Saudi Arabia also has the opportunity to supply blue hydrogen, which is currently cheaper to produce than green hydrogen. As the Kingdom expands its natural gas production, hydrogen generation through methane reforming and CCUS presents another option for monetizing the Kingdom's gas reserves. Light hydrocarbons such as liquefied petroleum gases (LPGs) and naphtha also present an economic case for hydrogen generation. From a logistical perspective, LPGs and carbon dioxide (CO_2) transport can offer very good synergies. For example, shipping LPGs from Saudi Arabia to Japan and producing the hydrogen close to the end-user market, while bringing the CO_2 back to Saudi Arabia for utilization purposes or sequestration, makes blue hydrogen a good value proposition. Leveraging the extensive LPG infrastructure currently in place and LPG transportation methods can help provide a low-cost source of blue hydrogen from Saudi Arabia. The semi-refrigerated tankers used to transport LPGs have temperatures of between -40 degrees Celsius (oC) to -50oC and pressures in the range of 4-8 bars, similar temperatures and pressures to liquid CO_2. As this is the case, CO_2 can be brought back to Saudi Arabia in the same tankers as LPGs. There is a 30% cost reduction in taking the LPG to Japan for reforming and then bringing the CO_2 back, rather than reforming it in Saudi Arabia and transporting the liquid hydrogen. Using LPG carriers rather than liquefied hydrogen tankers would enable this to happen now, as liquefied hydrogen tankers have not yet reached the deployment phase. Using such a business model allows blue hydrogen to be produced competitively and can kick-start the hydrogen economy.

Business Models and Investment Appetite

Hydrogen business models will be driven by the symbioses hydrogen has with electricity generation. Electricity will gradually dominate the energy landscape, with low-carbon hydrogen playing a role in decarbonizing hard-to-abate sectors. It will also complement the electricity sector by providing flexibility services such as dispatchable power generation, renewable energy storage and network constraint mitigation. Hydrogen business models that evolve from or are integrated into electricity generation models will have the largest chances of early success.

In the near term, there are two main potential markets for hydrogen: on-road heavy-duty mobility, and industry. There could be a good business case for hydrogen use in the heavy-duty transportation sector, where electric vehicles may face limitations. The heavier the vehicle and the more hours it operates for per day, the more likely hydrogen-based vehicles are to be a viable solution. Hydrogen fuel cell vehicles are technologically proven and ready. However, the challenge, as with any new technology, is its acceptance and the availability of supportive infrastructure. The world has been slow to adopt hydrogen technology for use in heavy transport due to a lack of commercial innovation. One of the most significant barriers to the adoption of fuel cell vehicles is its capital cost. Hydrogen fuel cell companies must target deployments that can recoup investments through high utilization and 'back-to-base' vehicles until hydrogen infrastructure is built out. Since the cost of operating and maintaining these vehicles are low, the total cost of owning them can approach that of traditional diesel vehicles, provided that a green hydrogen supply partner is involved. Offering packaged vehicle leases, where the fleet operator need only worry about the operating costs of the vehicles and the provider of the equipment deals with the maintenance, is emerging as a popular business model and removes another significant barrier in the adoption process.

Decarbonizing the existing hydrogen value chain in the industrial sector would help scale up carbon-neutral hydrogen production. About 96% of today's hydrogen production is grey hydrogen, most of which is used in the industrial sector, sometimes on a large scale. This makes the industrial sector a good place to start to deploy carbon-neutral hydrogen production by retrofitting the existing fleet with CCUS, building new factories with lower CO_2 footprints and developing electrolyzers using renewable electricity. The Netherlands' hydrogen strategy includes decarbonizing its existing hydrogen production fleet. It has proposed a support scheme to scale up its hydrogen production, starting with converting existing hydrogen production to blue and green hydrogen in the industrial clusters in the ports of Rotterdam and Amsterdam. The plan is to connect all those industrial clusters with repurposed gas pipelines into what they call the 'hydrogen backbone,' which is expected to be ready by 2027.

The main challenge in supporting such large-scale projects is the need for long-term offtake contracts. The policy frameworks and different support schemes for carbon-neutral hydrogen production vary by country. However, there is still a need for a long-term vision for promoting hydrogen energy applications. From an investor perspective, long hard-term offtake contracts are needed in order to finance deep infrastructure projects and help encourage investment in capital-intensive hydrogen projects.

Long-term offtake contracts are important for scaling up projects and reducing costs. Investors are looking for a guaranteed return from their investments as building hydrogen supply projects and selling hydrogen on the spot market alone is risky. Mobility applications, for example, are a potentially lucrative market for hydrogen, and it is not customary to have long-term offtake contracts with refueling stations with fixed prices. However, long-term contracts will make such investments attractive and facilitate the roll-out of hydrogen fuel cell vehicles, especially for return-to-base vehicles. Long-term contracts are also needed for industrial applications such as clean fertilizer production or refineries. Securing long-term offtake contracts may be challenging in the absence of a carbon price or border adjustment taxes to level the playing field. There is a lot of debate on how to create markets for carbon-neutral hydrogen in order to facilitate hubs, suppliers and investments. Existing carbon policies and initiatives, such as the EU's Emission Trading System (ETS), only take into account the production cost of green electricity, not green hydrogen; the latter is more expensive and requires an additional conversion step. Transport and storage costs elevate the costs of green hydrogen above the current price of CO_2 set by the ETS. The ETS's CO_2 price is currently too low to incentivize hydrogen projects.

Infrastructure and Supply Chain Challenges

As mentioned earlier, hydrogen imports – whether into Europe or Asia – will be a very important part of meeting future hydrogen demand in these regions. Europe does not have the space it needs to produce the wind and solar energy required for green hydrogen production. Europe is going to predominantly use pure hydrogen (rather than blended with natural gas) for steel making, chemical production, refining or new demand from mobility and heating. There is going to be a case for blending hydrogen with natural gas to create immediate demand initially, before bringing hydrogen production and use to scale. Research in France, Germany and the Netherlands has shown that blending hydrogen in natural gas pipelines can be done to some extent before the embrittlement of pipelines, compressor fitness and flow meters start stressing the system. However, there is an increasing body of evidence of limitations in end-use applications. Some studies have shown that up to 6% of hydrogen can be blended into the natural gas infrastructure in France at a low cost and with minor investments. However, end users may encounter challenges, such as compressed natural gas vehicles that are not certified to blend more than 2% of hydrogen in the natural gas mix. The proximity of salt caverns, where hydrogen can be stored, to end users is also a concern. They may be available in some parts of Europe, such as the Netherlands and Germany, but not available in other countries, such as France. Therefore, the deployment of hydrogen within a region must take into account the entire value chain.

The EU's hydrogen strategy has a long-term vision to repurpose some gas pipelines and salt caverns for hydrogen, which could be realized in the next 10 to 15 years. The EU could transport hydrogen through pipelines across Europe and even into North Africa. Europe's gas grid has over 200,000 kilometers (km) of gas pipelines. Around 40% of European households have gas connections, and, in some countries such as the Netherlands, this figure is close to 100%. It is important to note that it is more cost effective to transport hydrogen than electricity over a given distance. Transporting hydrogen over a distance of 2,500 km costs 0.005 euros per kilowatthour (euros/kWh) (or 0.2 euros per kilogram). Transporting electricity over the same distance costs around 0.04 euros/kWh to 0.05 euros/kWh. Pipelines offer the cheapest transport option, but they have limitations when transporting hydrogen over longer distances. For example, transporting hydrogen from the Middle East to Europe would require alternative methods such as liquefied hydrogen, or even using hydrogen carriers such as methanol or ammonia. However, using these hydrogen carriers would require hydrogen to be reconstituted to its pure form, which implies an extra conversion step and thus extra costs.

To enable a smooth transition to a hydrogen economy, it is important for hydrogen producers and consumers to work in tandem with supply chain partners. For example, there is no point in making hydrogen vehicles if there are no hydrogen production, infrastructure and distribution systems in place. Private companies are required to work together with end-to-end solutions to facilitate hydrogen penetration. Governments also need to provide the regulatory framework and schemes needed to level the playing field between hydrogen producers and fossil-based hydrogen supply chains.

There are also many unknowns regarding the safety of hydrogen power and its acceptance by the general public. The energy industry has a lot of experience in handling hydrogen, and hydrogen has a proven safety record. However, it is up to the energy industry to show that hydrogen can also be used safely outside industrial applications, and to reassure the general public that it is safe. Hydrogen pilot schemes that aim to satisfy these objectives are already underway.

Reference

International Energy Agency (IEA). 2020. “Clean Energy Innovation.” July 2. Accessed July 30, 2020. https://www.iea.org/reports/clean-energy-innovation.

About the Workshop

KAPSARC held a virtual workshop, in partnership with the Clingendael International Energy Programme, to investigate the pathways toward a hydrogen economy. The workshop gathered over 35 experts from various areas of expertise, including policy, research and investments.

List of participants

Jan Frederik Braun – Research Fellow, KAPSARC

Jason MacDowell – Senior Director Technology, Strategy and Policy, GE

Maria van der Hoeven – Senior Fellow, CIEP

Saumitra Saxena – Research Scientist, KAUST

Rami Shabaneh – Senior Research Associate, KAPSARC

Colin Ward – Visiting Research Fellow, KAPSARC

Tim Karlsson – Executive Director, IPHE

Jörg Gigler – Managing Director, TKI New Gas

Noé van Hulst – Hydrogen Envoy, Dutch Ministry of Economic Affairs and Climate Policy

Frank Wouters – Senior Director and Global Lead Low-Carbon Hydrogen, Worley

Fahad Alturki – VP Research, KAPSARC

Laura Koppen – Business Development Manager, Vopak

Alena Fargere – Principle, SWEN Capital Partners

Aqil Jamal – Chief Technologist, Saudi Aramco

Coby van der Linde – Director, CIEP

Jitendra Roychoudhury – Research Fellow, KAPSARC

Wa'el Almazeedi – Co-founder, Avance Labs

Majed Al-Suwailem – Senior Research Associate, KAPSARC

Ralph de Haan – Director Business Development, Neom

Karoline Steinbacher – Associate Director, Guidehouse

Ad van Wijk – Professor, TU Delft

Jabbe van Leeuwen – Researcher, CIEP

Floor van Dam – Researcher (intern), CIEP

Jacob Rookmaaker – Senior Advisor Public Affairs, RWE

Craig Knight – CEO, Horizon Fuel Cell Technologies

Yoshiaki Shibata – Senior Economist, The Institute of Energy Economics Japan

Bart Kuijlman – Manager Participations and Partnerships, Engie

Masakazu Toyoda – CEO and Chairman, The Institute of Energy Economics Japan

Majed Sammak – Lead Energy Engineer, GE Power

Folmer de Haan – Deputy Director, Council for the Environment and Infrastructure (RLI)

Murali Krishna Kalaga – Senior Technologist, GE Power and Water

Lucie Boost – Advisor European Policy and Regulation, Equinor

Alaa Dawood – Director, GE Power Services

Mattijs Slee – Hydrogen Commercial Manager, Shell

Notes

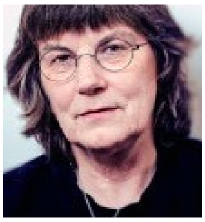
Notes

Notes

About the Team

Kaushik Deb

Kaushik is an applied economist and a research fellow at KAPSARC. He is currently responsible for defining and operationalizing the research agenda for KAPSARC's Markets and Industrial Development team. Kaushik was previously the head of global gas markets in the Group Economics team at BP, where he oversaw the analysis that formed the basis for BP's natural gas investment and trading strategy. Before BP, Kaushik worked at IDFC Bank, where his portfolio included policy research and advocacy on infrastructure and environmental economics issues. These issues included low-carbon infrastructure, decentralized electricity services in rural areas, and organized intermediate public transport systems for small towns. Kaushik holds a doctor of sciences (D.Sc.) degree from ETH Zurich. He has also guided and implemented research in applied economics at TERI University, India, where he was also the program director of its two MBA programs.



Coby van der Linde

Coby is the director of the Clingendael International Energy Programme (CIEP). Her areas of expertise include international oil and natural gas markets, energy system transition including hydrogen, security of supply and other energy policy issues. She had a long career in academia and has authored numerous publications on energy. She also has experience as an independent (non-executive) director in various energy companies and has advised the Dutch government on various energy policy issues. She holds an M.A. in international relations and public law and a doctorate in economics from the University of Amsterdam.

Rami Shabaneh

Rami Shabaneh is a senior research associate with a focus on global gas and liquids markets. Rami has over 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, providing analytic support on specific issues affecting North American gas, natural gas liquids and condensate markets. His work informed 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 an M.Sc. in sustainable energy development and a B.Sc. in actuarial science from the University of Calgary.

Jabbe van Leeuwen

Jabbe has been a researcher at CIEP since 2018, and his main research focus is on hydrogen and decarbonization pathways for industry. He was seconded to the IEA in 2019 to work on its hydrogen report for the G-20 meeting in Japan. He holds a B.Sc. in mechanical engineering from the Technical University Delft and an M.Sc. in energy science from Utrecht University.

Majed Al-Suwailem

Majed is a senior research associate at KAPSARC with a focus on sustainable energy, energy security and energy infrastructure. He has over 15 years of experience in the oil and gas industry at Chevron and Saudi Aramco. His industry experience has included simulation and modeling, subsurface asset management, hydrocarbon reserves estimation, disruptive technologies and business planning.

Majed holds a B.Sc. degree in petroleum engineering from the University of Tulsa in the United States. He also holds an M.Eng. degree in petroleum engineering from Texas A&M University and an M.Sc. in reservoir geosciences and engineering from the Institut Français du Pétrole (IFP School).

About the Project

Hydrogen is emerging as an important energy vector that can accelerate the path toward net-zero emissions. Given its diverse application and its potential to abate carbon emissions, it is ideally suited to be an enabler of 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.

KAPSARC

مركز الملك عبدالله للدراسات والبحوث البترولية

King Abdullah Petroleum Studies and Research Center

www.kapsarc.org