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Hydrogen cooperation potential between Saudi Arabia and Germany

A joint study by the Saudi-German Energy Dialogue

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Executive Summary

This joint study looks at the clean hydrogen cooperation potential between Saudi Arabia and Germany. Clean hydrogen refers to renewable and low-carbon hydrogen derived from a production process in which carbon emissions into the atmosphere are avoided and mitigated or captured and utilised. The study also looks at the opportunities and challenges for Germany and Saudi Arabia to cooperate along the hydrogen value chain, i.e., production, supply, distribution, and applications.

Germany and Saudi Arabia are a natural fit for cooperating on hydrogen. Germany is a global leader in the patenting and manufacturing of hydrogen technologies along the entire value chain. Saudi Arabia is a global leader in low-carbon fossil fuel production, has vast CO_2 storage capacity, and excellent solar and wind potential. Both Germany and Saudi Arabia host many companies that provide the expert advice, capital, and infrastructure required to scale up the hydrogen market. Together, Germany and Saudi Arabia possess the resources, infrastructure, and skills to produce cost-competitive hydrogen by cooperating across different value chain parts.

Germany's and Saudi Arabia's energy policies combine security of supply, affordability, environmental sustainability, and climate protection. In May 2021, Germany raised its climate ambition and now aims to cut GHG emissions by 65% by 2030 compared to 1990 levels and become climate neutral by 2045. Hydrogen is essential for meeting these targets. Hydrogen is predominately used in refining fossil fuels and producing basic chemicals (e.g., ammonia), but new applications are rapidly emerging, e.g. to make green steel. Against this backdrop, Germany's hydrogen strategy intends to accelerate the market ramp-up of hydrogen technologies by 2030, e.g., by providing €9 billion in funding (including €2 billion for international cooperation). The strategy foresees a growing hydrogen demand from 55 TWh–60 TWh today to 90 TWh–110 TWh by 2030. Around 20 TWh–25 TWh of demand is expected to be met by domestic production of hydrogen. Hence, Germany will heavily rely on imports. The solar energy potential in Saudi Arabia is estimated at almost 1,000 TWh, nearly 17 times larger than the solar potential in Germany. The wind energy potential of Saudi Arabia is estimated at 145 TWh.

"The potential of hydrogen has always been there, but now it is entering the mainstream of strategic energy thinking."

HRH Prince Abdul Aziz bin Salman, Minister of Energy, Saudi Arabia

In October 2021, Saudi Arabia announced that the Kingdom's goal is to reach Net Zero carbon emissions by 2060. Under its 'Net-Zero-by-2060' target, Saudi Arabia aims to produce 4 million tonnes of blue and green hydrogen annually by 2030.[1]

Saudi Arabia is currently developing a national hydrogen strategy that focuses on production, export, and domestic use of hydrogen. The strategy aims to establish: I) essential aspects of the green and blue hydrogen production process; II) domestic hydrogen demand use cases in transportation (heavy duty and light duty vehicles); III) using hydrogen in products with export potential (synthetic fuels, steel, etc.); and IV) hydrogen export to potential markets in Europe, Asia, and the rest of the world. The Saudi government views hydrogen applications as a critical component of the Circular Carbon Economy (CCE), especially as a key enabler in decarbonising hard-to-abate sectors.

Several enabling mechanisms are needed to support the deployment of hydrogen across Germany's and Saudi Arabia's value chain of domestic production and demand and international export, including:

- Support and enforcement mechanisms.
- Demonstration, pilots, and R&D.
- Standards and technical regulations, including standardised certifications or guarantees of origin for renewable and low-carbon hydrogen.
- Awareness and partnership building across the value chain globally.

In this context, a Memorandum of Understanding (MoU) on Saudi-German hydrogen cooperation was signed in March 2021. To facilitate the MoU's implementation, stakeholders from both sides are collaborating in three dedicated working groups:

- **Business:** The private sector's role is critical in the large-scale deployment of hydrogen projects through business-to-business cooperation such as joint ventures (JVs), expert workshops and roundtables, delegation visits and study tours, and shared pilot programmes.

- **Technology:** Technology maturity is a crucial success factor for the hydrogen industry. These objectives can be achieved through joint studies, expert workshops and roundtables, delegation visits and study tours, and education programmes.

- **Regulatory:** The regulatory working group aims to promote a regulatory architecture that is suitable to promote the hydrogen industry. Instruments for an exchange on these issues include joint studies, expert workshops, roundtables, and delegation visits and study tours.

1. Saudi-German Hydrogen Cooperation and Energy Dialogue

On 11 March 2021, the Energy Minister of Saudi Arabia, HRH Abdulaziz bin Salman Al Saud, and Peter Altmaier, the then German Minister for Economic Affairs and Energy, signed a Memorandum of Understanding (MoU) to promote bilateral cooperation in the production, processing, application, and transportation of renewable and low-carbon hydrogen. Low-carbon hydrogen is based on natural gas, where carbon emissions are captured, stored, and utilised (CCS/CCU, i.e., either 'blue' or 'turquoise') while renewable hydrogen is produced from renewables-based electricity (i.e., ‘green’).

The MoU was signed in the context of the German-Saudi Energy Dialogue and underscores both countries’ commitment to achieving the targets of the Paris Agreement by promoting clean hydrogen as part of the energy transition.

The collaboration between both countries involves relevant stakeholders from research institutions, the private sector, and public sector entities. The aim is to support joint projects such as NEOM’s green ammonia plant and promote mutual knowledge sharing and transfer of technological know-how to Saudi stakeholders for the deployment and localisation of new technologies in Saudi Arabia with a focus on the hydrogen sector. These efforts should contribute to the development of a hydrogen-based energy sector in Saudi Arabia, promote the use of German technologies, and facilitate the development of a hydrogen market in Germany and beyond. The dialogue also covers the regulatory and financing framework conditions necessary to promote a hydrogen sector.

As part of the MoU, the German Federal Ministry for Economic Affairs and Climate Action (BMWK) declared its interest in exploring the prospect of importing hydrogen and its derivatives, such as ammonia or synthetic kerosene, from Saudi Arabia. The Ministry of Energy of Saudi Arabia (MoEnergy) welcomed the involvement of German companies and the use of German technologies in the production and further processing of hydrogen in Saudi Arabia.

Both sides are exploring the possibility of drafting innovation clusters with leading research institutes and companies from both countries and an innovation fund to promote hydrogen.[2] The signing took place as a virtual event and was attended by business representatives from both countries. The implementation of the Saudi-German Hydrogen Cooperation will follow an agreed-upon roadmap and include three working groups on business, technology, and regulatory matters. The Riyadh-based German-Saudi Arabian Liaison Office for Economic Affairs (GESALO) and Guidehouse are supporting this cooperation.

2. Government strategies on hydrogen in Saudi Arabia and Germany

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2.1 The German National Hydrogen Strategy[3]

Key Points

- Germany's National Hydrogen Strategy anticipates a hydrogen demand of 90 TWh–110 TWh by 2030. Imports will meet a substantial share of demand. Germany has set aside €7 billion to fund the market ramp-up of hydrogen technologies in Germany and earmarked an additional €2 billion for international cooperation.
- One of the German government's first commitments was offering ThyssenKrupp an innovation fund for Element One in NEOM.
- Saudi Arabia wants to emulate Germany's success with renewable energy and is planning to convert half of its power sector to gas and the other half to renewables by 2030. Saudi Arabia also has the ambition to become a pioneer in hydrogen production, as demonstrated in their flagship project NEOM and their demonstration shipment of blue ammonia to Japan.

The German energy transition aims to combine security of supply, affordability, environmental sustainability, and climate protection. Besides energy efficiency and renewable energies, the energy transition heavily relies on CO_2-free and CO_2-neutral gaseous and liquid energy carriers like hydrogen. Hydrogen enables the further reduction of CO_2 emissions, especially in industrial applications. The German Federal Government recognises hydrogen as a vital component of the future energy system.

By providing an action plan for the National Hydrogen Strategy, the Federal Government lays a solid foundation for private investment in cost-effective and sustainable hydrogen generation and transport. The National Hydrogen Strategy consists of two phases. Phase one, which runs until 2023, is set to kick off the market ramp-up and build the basis for a well-functioning hydrogen market while simultaneously addressing critical issues such as R&D and international trade. Phase two will run from 2024 – 2030 and focus on strengthening the newly developed market. An updated version of the National Hydrogen Strategy is expected in the second half of 2022.

In addition to tackling climate change, hydrogen technologies can provide future-proof jobs and new value-added potential. German companies are already well-established in the field (e.g., water electrolysis). Germany aims to continue being a leader in hydrogen technologies.

To accelerate the application of these technologies, the government supports research, funds implementation, and develops political strategies. Between 2006 and 2016, the National Innovation Programme for Hydrogen and Fuel Cell Technology supported research on green hydrogen technologies with €700 million in funds. The 7th Energy Research Programme, which was introduced in 2018, also promotes hydrogen-related research activities. The German Federal Government also set-up government-funded regulatory sandboxes (so-called 'Reallabore') to test implementation of hydrogen technologies. In the initial phase, €100 million per year was made available for pilot projects from 2019 to 2022. Ten out of the 20 selected projects are hydrogen related. In addition to this, the hydrogen strategy provides a further €7 billion to be made available for the market ramp-up of hydrogen technologies in Germany and €2 billion for international partnerships, including with Saudi-Arabia.

To initiate the required work on political strategies in this field, the BMWK has been coordinating a stakeholder dialogue called Gas 2030, which assesses the role of gas in the energy transition since 2019. A key finding is that Germany will remain an energy importer over the coming decades and that the first hydrogen imports are expected to come online in the coming years.

In line with the recommendations from the Gas 2030 dialogue, the German Federal Government adopted the National Hydrogen Strategy on 10 June 2020. The strategy aspires to bolster the scale up of hydrogen production and usage. The German Federal Government only considers hydrogen produced based on renewable energies (green hydrogen) to be sustainable in the long term. It expects the demand for hydrogen and its derivatives (hydrogen-based energy carriers such as ammonia, synthetic methane, methanol, and synthetic fuels) to reach between 90 TWh and 110 TWh in 2030 and 110 TWh-380 TWh by 2050. The current strategy targets a domestic electrolysis capacity of at least 5 gigawatts (GW) to be installed by 2030 and another 5 GW by 2035. The coalition treaty of the new German government elected in 2021 has increased this ambition targeting 10 GW electrolysis capacity by 2030.[4] Domestic hydrogen production alone will not be sufficient to cover Germany's hydrogen demand hence, the majority will need to be imported.

Hydrogen's international trade and its derivatives pose a significant geopolitical objective, so efforts to facilitate global partnerships are intensified. As an energy importer, Germany will depend on reliable partners along the value chain and import infrastructure. Besides collaborating on new hydrogen technologies and markets with partner countries, possibilities and opportunities to switch production and the export of fossil fuels to hydrogen are also explored.

2.2 Current hydrogen potentials in Saudi Arabia

Saudi Arabia is well-positioned to play a leading role and become a significant hydrogen producer and exporter (Table 1, Figure 1):

Table 1: Saudi Arabia's hydrogen ecosystem resources

Green hydrogen:
Lowest global renewable electricity prices. (e.g. the Al Shuaiba PV Project at $0.0104/kWh).
Large availability of non-arable land areas suitable for the development of renewable projects.
Blue hydrogen:
Around 233.8 trillion cubic feet (or 6,62 trillion cubic meters) of natural gas available at low-cost suitable for blue hydrogen production.
Storage capacity potential of 25 Gt of CO_2 (with 90% of the deep saline formations in the Middle East).
Hydrogen export:
Existing infrastructure to globally export Hydrogen in the form of ammonia.
Strategic location between key importing markets in the UK, EU, and East Asia (e.g. Japan, South Korea).
Potential domestic uses:
Local use cases in heavy duty transport and high-utilisation vehicles.
Production of green steel using hydrogen.

Source: KAPSARC. *CO_2 storage capacity: 25 Gt[5]

Figure 1: Saudi Arabia's hydrogen 'ecosystem'

Source: KAPSARC. © Anton Balazh / Shutterstock.com

Currently, the Kingdom is developing a national hydrogen strategy that focuses on production, exports, and domestic uses of hydrogen. This strategy aims to establish:

- Essential aspects of the green and blue hydrogen production process.
- Domestic hydrogen demand use cases in transportation (heavy duty and light duty vehicles).
- Using hydrogen in products with export potential (synthetic fuels, steel, etc.).
- Hydrogen export to potential markets in Europe, Asia, and the rest of the world.

On the domestic front, the Saudi government is looking into the following enablers to help bridge the cost gap between fuel cell vehicles (FCVs) and internal combustion engines (ICEs); and where FCVs outperform battery electric vehicles (BEVs):

- Adoption of long haul, heavy duty, and high utilisation vehicles (e.g., trucks, buses), including a substantial percentage of public buses in the Kingdom to run on clean hydrogen and all airport taxis in two to four of the largest airports, which includes Riyadh and Jeddah.[6]

A longer-term focus, i.e., beyond 2030, aims at building capacity through pilots and R&D and includes following:

- Hydrogen-based green steel via the direct reduced iron (DRI) process, including a pilot plant and commercialisation expected after 2030.
- Synthetic fuels for aviation that combine hydrogen with CO_2, including R&D (commercialisation expected after 2035).
- Ammonia and methanol as marine fuels, which help decarbonise and meet International Maritime Organization regulations, with commercialisation expected after 2035.

To support the deployment of hydrogen across Saudi Arabia's value chain for domestic use and international export, several enabling mechanisms are currently being considered, including:

- Support and enforcement mechanisms.
- Demonstration, pilots, and R&D.
- Standards and technical regulations.
- Awareness and global partnership building across the value chain (e.g. with Germany).

On renewables, Energy Minister HRH Prince Abdulaziz bin Salman Al Saud stated in January 2021 that Saudi Arabia wants to emulate Germany's success with renewable energy as it is planning to convert half of its power sector to gas and the other half to renewables by 2030.

These ambitions in renewables are essential in the following two ways:

- Scaling up renewables is crucial in the context of installing gigawatt-scale electrolyser capacity for hydrogen projects like NEOM Helios.
- Hydrogen could play a long-term storage solution to manage the increasing penetration of variable renewable energy sources in Saudi Arabia's power system.

Saudi Arabia's energy minister also expressed the Kingdom's ambition to become a pioneer in both renewable and low-carbon hydrogen production. For this purpose, it is working with many countries on hydrogen projects.[7] Saudi Aramco is leading the nation's efforts in low-carbon hydrogen.

Shortly after the Saudi government pledged to neutralise planet-warming emissions within its borders by 2060, it announced that it would use a large portion from the $110 billion Jafurah project, a field estimated to hold 200 trillion cubic feet of gas, for the production of blue hydrogen.[8]

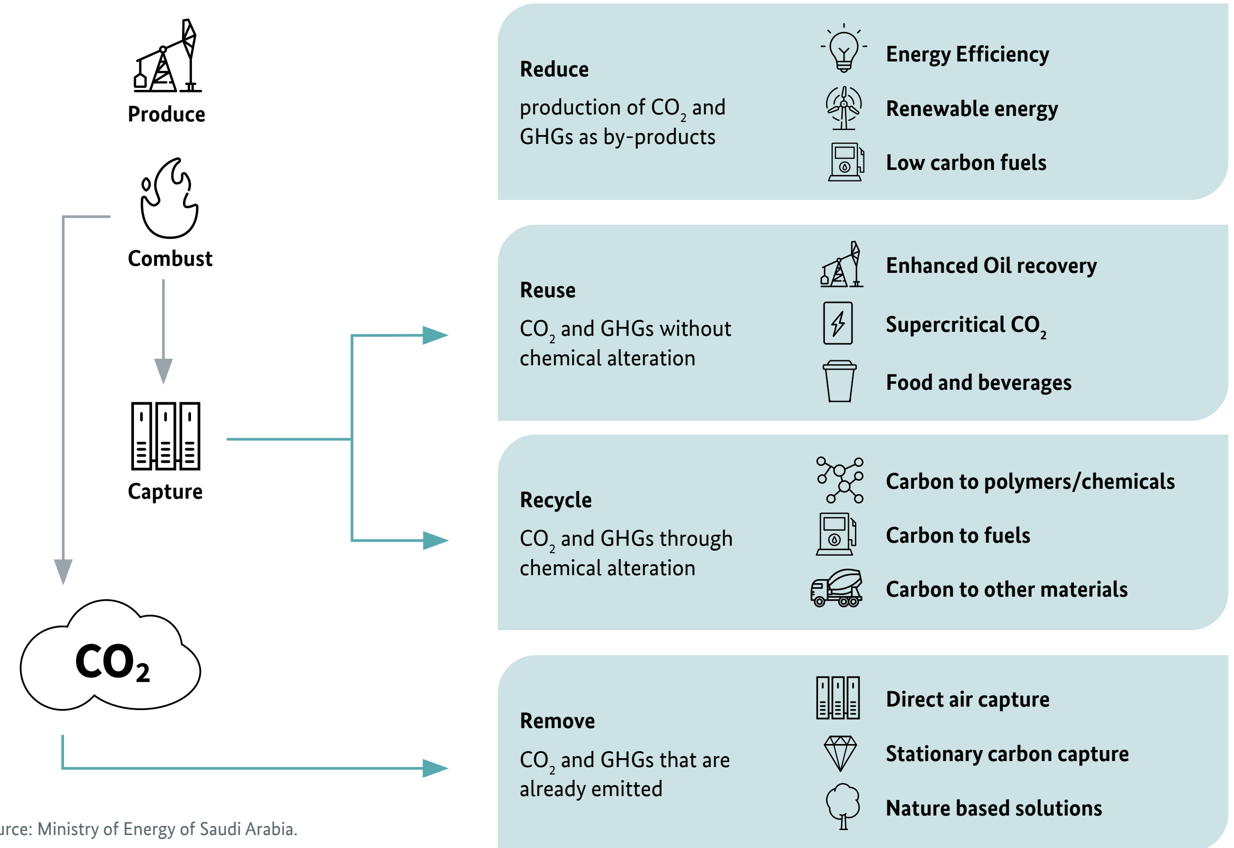
On green hydrogen, NEOM is scheduled to be part of any future Saudi hydrogen ecosystem. The first planning phase clarifies that NEOM aims to be a hydrogen hub to provide the basis for clean feedstock used in the production of fertilisers, chemicals, and oil derivatives; this in collaboration with mega-players like the Saudi Basic Industries Cooperation (SABIC) and Aramco.

NEOM Helios, a joint venture between Air Products, ACWA Power, and NEOM is the world's largest renewable hydrogen-to-ammonia facility. Scheduled to go onstream in 2025, the facility will take advantage of the high direct normal irradiance and wind speeds along the Red Sea in the country's northwest. Equipped with 4 GW of solar and wind, Helios will run at a high load factor, with an output of green ammonia estimated at 1.2 Mt/year. Air Products will be the exclusive off taker. The company intends to transport the ammonia and dissociated it into hydrogen (and nitrogen) at delivery, for use in the transportation sector.[9] The Helios facility is preceded by the smaller pilot project Element One with 20 MW electrolysis. The German company ThyssenKrupp was contracted to supply the electrolysers for the pilot, and the BMWK is supporting the investment with a €1.5 million grant.

Beyond its national borders, Saudi Arabia is a leading member in international CCUS collaborations such as the Clean Energy Ministerial, CCUS initiative, and the Carbon Sequestration Leadership Forum. In April 2021, Saudi Arabia and four other major oil & gas producing countries (i.e., the US, UAE, Qatar, and Canada) announced a Net-Zero Producers Forum. The Forum aims to develop pragmatic strategies for methane abatement, CCS development, and advancing the CCE. It also offers a platform for discussions on how producing countries can "support the implementation of the Paris Agreement on climate change and the goal of achieving its balanced emission goal."[10]

Aligned with the Kingdom's CCUS efforts, King Salman announced the launch of the Kingdom's National Program for the CCE at the end of Saudi Arabia's 2020 G20 presidency "to consolidate and accelerate the current efforts to achieve sustainability in a comprehensive manner."[11] Saudi Arabia's CCE concept is based on the four Rs of reduce, reuse, recycle and remove (Figure 2).

Figure 2: The Four Rs of the Circular Carbon Economy



Source: Ministry of Energy of Saudi Arabia.

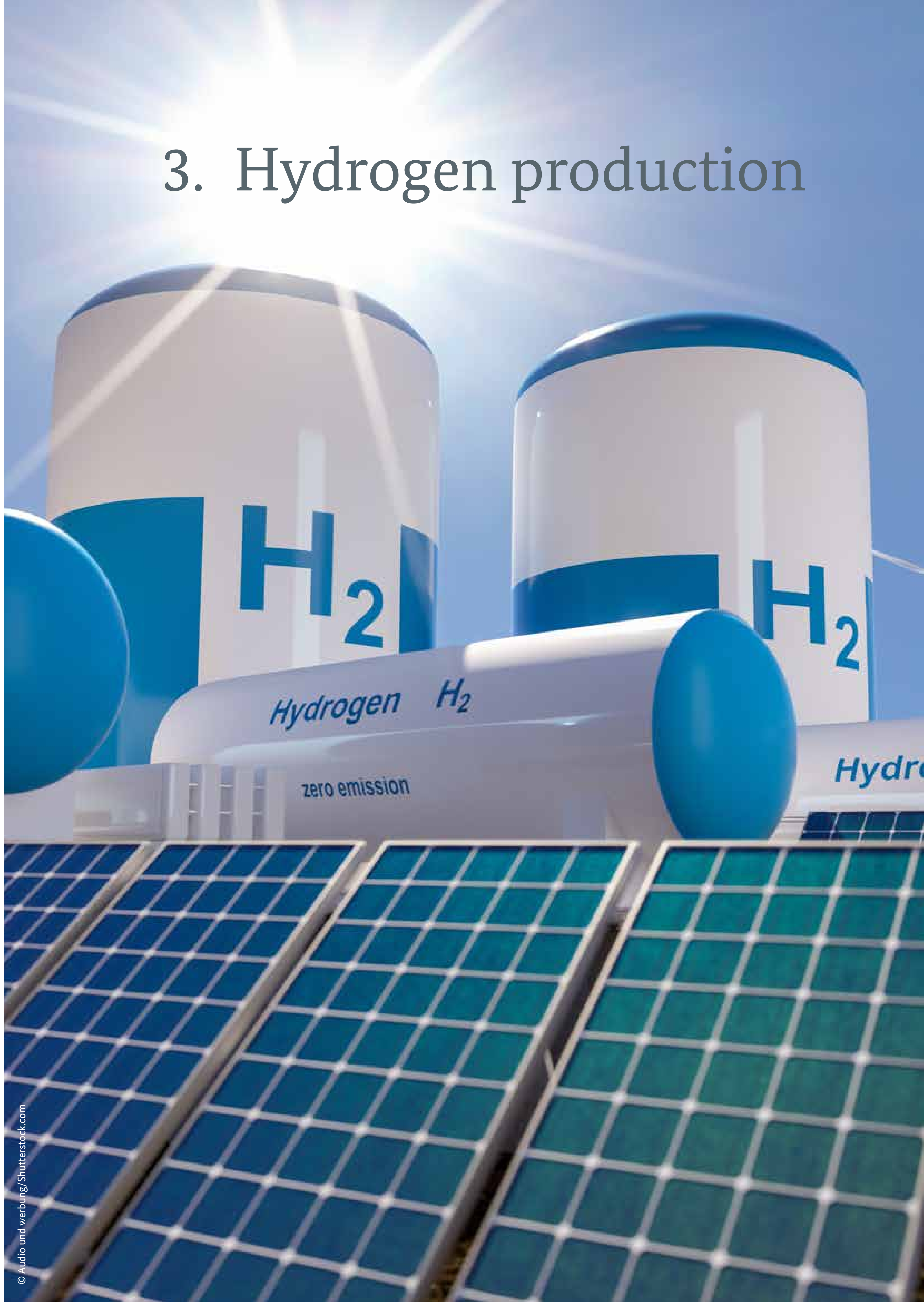
The Saudi government views hydrogen applications as a critical component of the CCE, especially as a key enabler in decarbonising hard-to-abate sectors:

- **Reduce:** Renewables-based hydrogen without directly emitting CO_2.
- **Recycle:** Renewables-based hydrogen is used to produce e-fuels, thus recycling CO_2 through chemical alterations.
- **Reuse:** CO_2 is captured during fossil-fuel-based hydrogen production and reused in applications such as carbon cured concrete.
- **Remove:** CO_2 is captured during fossil-fuel-based hydrogen production and removed through geologic storage.

According to the Saudi government, carbon capture, utilization and storage, direct air capture, and hydrogen and low-carbon fuels are the necessary ingredients for cutting emissions. Under its 'Net-Zero-by-2060' target, therefore, Saudi Arabia aims to produce 4 million tonnes of clean hydrogen annually by 2030.

In March 2022, the Public Investment Fund announced that five leading Saudi Arabian businesses, i.e., Aramco, SAUDIA, ACWA Power, Ma'aden, and ENOWA (a subsidiary of NEOM), have each signed a separate non-binding MoU to become the first potential partners of the MENA regional Voluntary Carbon Market (VCM).[12] The VCM will connect the supply of carbon credits with demand from investors, corporations and institutions wanting to reduce their carbon footprint by offsetting carbon emissions they generate. Further partners on both the demand and supply side will be on boarded in the coming months, ahead of an introductory round of auctions that is planned for Q4 of 2022.[13] Carbon trading through the VCM can help with accelerating the usage of removal technologies and reduce emissions from hard-to-abate sectors through the usage of clean hydrogen as a fuel and a feedstock within and beyond the Kingdom.

3. Hydrogen production



3.1 Production routes of renewable and low-carbon hydrogen and its derivatives

Key Points

- Grey hydrogen production from fossil energy, in particular natural gas, is still the dominant mode of production. Blue hydrogen can mitigate around 60%–95% of GHG emissions through carbon capture technologies. Turquoise hydrogen production does not emit CO_2 but produces solid carbon as a by-product. Green hydrogen from renewable power only requires electricity and water as input. Derivatives are produced when hydrogen is combined with further molecules, e.g. nitrogen to produce ammonia or CO_2 to produce synthetic fuels.
- While Saudi Arabia has an abundant potential for green and blue hydrogen production, Germany's potential is limited. Saudi Arabia has recently started scaling up its installed renewable electricity capacity for green hydrogen production.
- The difference in potential is also reflected in the anticipated costs of hydrogen production. While Germany expects costs of €4/kg–€5/kg of hydrogen, Saudi Arabia's production costs are considerably lower at €1/kg–€2/kg of hydrogen.

Hydrogen can be produced in many different ways (Figure 3) but is only sustainable if specific criteria are met. For green hydrogen, the feedstock electricity has to be renewable and water sustainably sourced. For blue hydrogen, the captured CO_2 must be stored in suitable locations. For carbon-containing derivatives, the origin of CO_2 is essential. Global hydrogen demand of 90 Mt in 2020 was met almost entirely by fossil fuel-based hydrogen, with 72 Mt H2 (79%) coming from dedicated hydrogen production plants. The remainder (21%) was by-product hydrogen produced in facilities designed primarily for other products, mainly refineries in which the reformation of naphtha into gasoline results in hydrogen.[14] Hydrogen is mainly consumed in non-energy applications and is an essential feedstock in the refining industry and the making of ammonia, methanol, and steel. Almost all the hydrogen produced today is sourced from hydrocarbons without carbon mitigation technologies. The most common route to make hydrogen is from natural gas through steam methane reforming (SMR), which is energy-intensive, and CO_2 is vented into the atmosphere. This production pathway is usually referred to as **grey hydrogen**. For hydrogen to be accepted as a clean fuel and a solution to a low-carbon future, the process of hydrogen-making must be decarbonised.

One option to manage fugitive carbon emissions is to add CCS-technologies to a SMR plant. Hydrogen produced from hydrocarbons combined with CCUS is called blue hydrogen. The captured CO_2 can be either utilised in chemical processes or sequestered in a geologic formation. As of 2020, seven commercial **blue hydrogen** facilities are operational and with one being planned.[15]

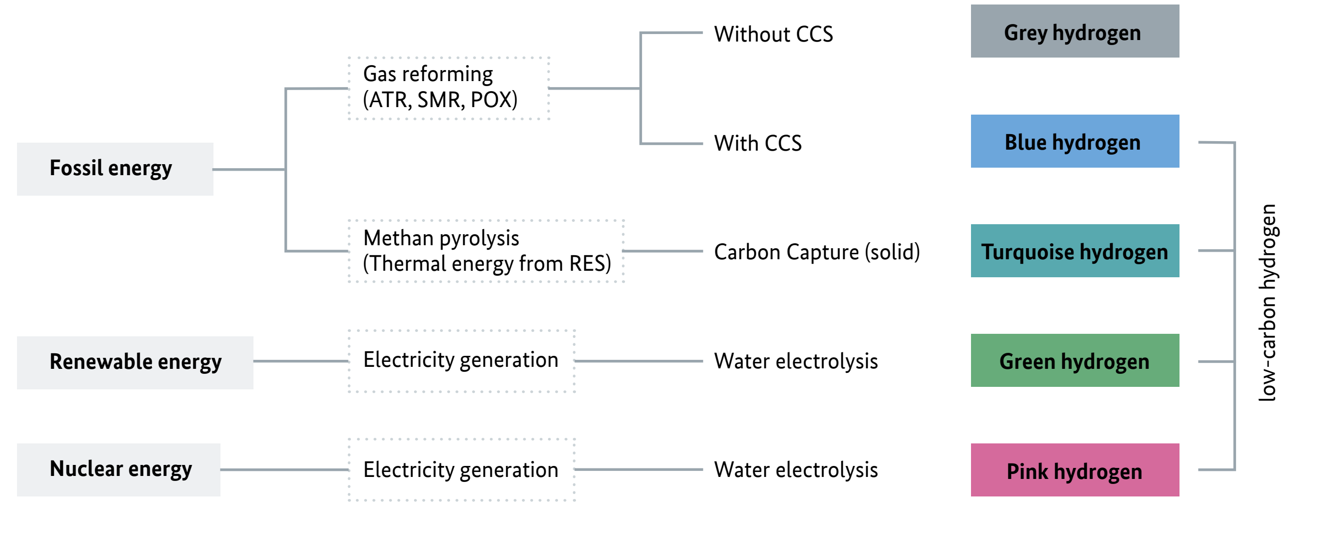
Methane pyrolysis is another technology pathway to derive low-carbon hydrogen from natural gas, known as **turquoise hydrogen**. The process converts methane into hydrogen and solid carbon instead of CO_2. Solid carbon (or carbon black) is a valuable co-product for many industrial applications and can improve hydrogen production economics. However, the technology readiness level (TRL) of methane pyrolysis is currently too low for large-scale commercialisation but is expected to increase in the coming years.[16]

Alternatively, hydrogen can be obtained from water via electrolysis. Electrolysis is the process of using an electric current to split water into hydrogen and oxygen. If the source of electricity is provided by renewable energy such as solar or wind, it is referred to as **green (renewable) hydrogen**.

Although there are already more green than blue hydrogen facilities, the total number is still low today. However, the continuous cost decline of renewable energy and improved electrolyser technology make this hydrogen production pathway promising.

Hydrogen is a significant feedstock and building block for many end use chemicals such as ammonia and methanol. Sourcing the hydrogen from clean technological pathways mentioned above reduces these products' greenhouse gas (GHG) intensity. Synthetic fuels, such as synthetic methanol, kerosene, and diesel, can also be made by combining green hydrogen with CO_2 and be carbon-friendly if the CO_2 is recycled or derived from the atmosphere through direct air capture (DAC) technology.

Figure 3: Hydrogen production pathways



Source: Guidehouse

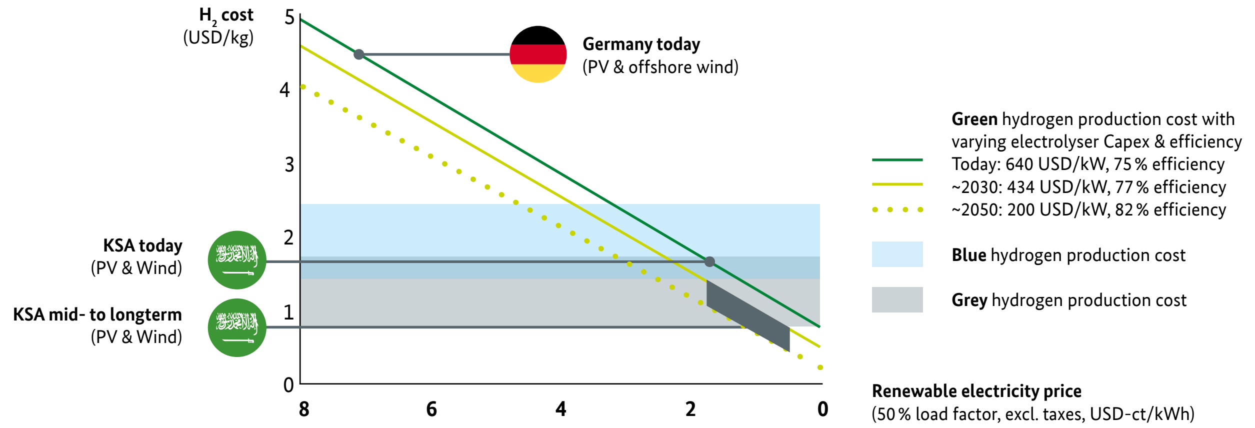
3.2 Cost of hydrogen production

The costs of hydrogen production are mainly determined by the CAPEX and OPEX. OPEX, i.e. feedstock electricity, makes up the large share of the levelised costs for green hydrogen production. At electricity prices of around US$2 ct/kWh, green hydrogen becomes cost-competitive with blue and grey hydrogen in some parts of the world. At prices below US$1 ct/kWh, green becomes the cheapest hydrogen option (Figure 4). On average, renewable electricity prices today in Saudi Arabia range between US$1.99 ct/kWh for wind (e.g. LCOE for Dumat Al Jandal) and US$1.6 ct/kWh for solar PV.[17] However, recent renewables tenders have achieved record-breaking prices. In April 2021, the 600 MW Al Shuaiba PV project drew the record low bid of US$1.04 ct/kWh.[18] Next to feedstock electricity prices, the costs of the electrolyser and the load factor are significant cost parameters. Electrolyser system costs are expected to decrease from around US$640/kW today to around US$200/kW in 2050.

Given the significantly higher prices for renewable electricity in Germany, costs of green hydrogen production are currently around US$5/kg—almost 3 times as high as in Saudi Arabia (Figure 4).

Blue hydrogen costs range from US$1.5/kg to US$2.5/kg of hydrogen.[19] The levelised cost of blue hydrogen based on a typical SMR plus CCUS configuration is mainly dependent on the natural gas price. While in a location with access to low-cost natural gas such as in North America, the Middle East, and Russia, natural gas accounts for approximately 40% of the levelised costs. In regions with generally higher natural gas prices they can equate to up to circa 60% of hydrogen production costs.[20]

Figure 4: Production cost of hydrogen in Germany and Saudi Arabia



Own calculation assuming 6% WACC, 15 yr lifetime, fixed Opex 1.5% of Capex

Source: Guidehouse, IEA.

3.3 Production potential in Saudi Arabia and Germany

Given its vast hydrocarbon resources, abundant availability of geologic formations for CO_2 storage, renewable energy potential, and extensive expertise across the CCUS value chain, Saudi Arabia is one of the few countries in the world that can produce both green and blue hydrogen cost-effectively. Saudi Arabia already produces significant volumes of hydrogen to supply its domestic refining industry. This industry can act as a base or 'hub' for scaling up blue hydrogen production in the Kingdom, which has one of the largest gas reserves in the world, i.e. around 233.8 trillion cubic feet (or 6,62 trillion cubic meter).[21] As part of its economic diversification efforts under Vision 2030, Saudi Arabia plans to double its natural gas production within the decade and expand its gas infrastructure.[22] Natural gas contributes enormously to the local hydrogen production for making ammonia, methanol, and uses in its local refineries. Saudi Arabia can store significant amounts of CO_2 in its subsurface to enable blue hydrogen production. Saudi Aramco operates one of the largest CO_2-enhanced oil recovery plants globally, i.e. the Uthmaniyah demonstration plant around the giant Ghawar oil field. This CCS plant can capture 0.8 million tonnes of CO_2 per year. There is about 25 gigatons of potential CO_2 storage capacity in the Kingdom's existing major oil & gas fields.[23] However, the country's ultimate CO_2 storage potential is significantly higher if saline aquifers and other depleted oil & gas reservoirs are included.

Solar energy in Saudi Arabia is estimated to have a potential of around 35,000 petajoules per year (PJ/a), almost 17 times larger than the solar potential in Germany.

In September 2020, and in partnership with SABIC, Aramco shipped the world's first blue ammonia to Japan. Forty tonnes of blue ammonia were shipped from Saudi Arabia to Japan for zero-carbon power generation. The blue ammonia was created by converting natural gas into hydrogen, then converted into ammonia for shipping and combustion at power plants. CO_2 emitted from natural gas extraction to the burning of ammonia was captured and turned into methanol and used in enhanced oil recovery (EOR) operations in Saudi Arabia.[24] This blue ammonia shipment showcases how the Kingdom can use its existing infrastructure to ramp-up blue hydrogen production.

Similarly, renewable resources in the Kingdom are among the highest in the world. Solar energy in Saudi Arabia is estimated to have a potential of around 35,000 petajoules per year (PJ/a), almost 17 times larger than the solar potential in Germany.[25] Wind energy potential, on the other hand, is estimated at 520 PJ/a. A combination of solar and wind energy can achieve higher capacity factors for electrolyser plants in Saudi Arabia, which is an essential component in reducing the cost of hydrogen production. The area of NEOM, in the north-western region of the country, is best suited to generate significant volumes of solar and wind energy.[26]

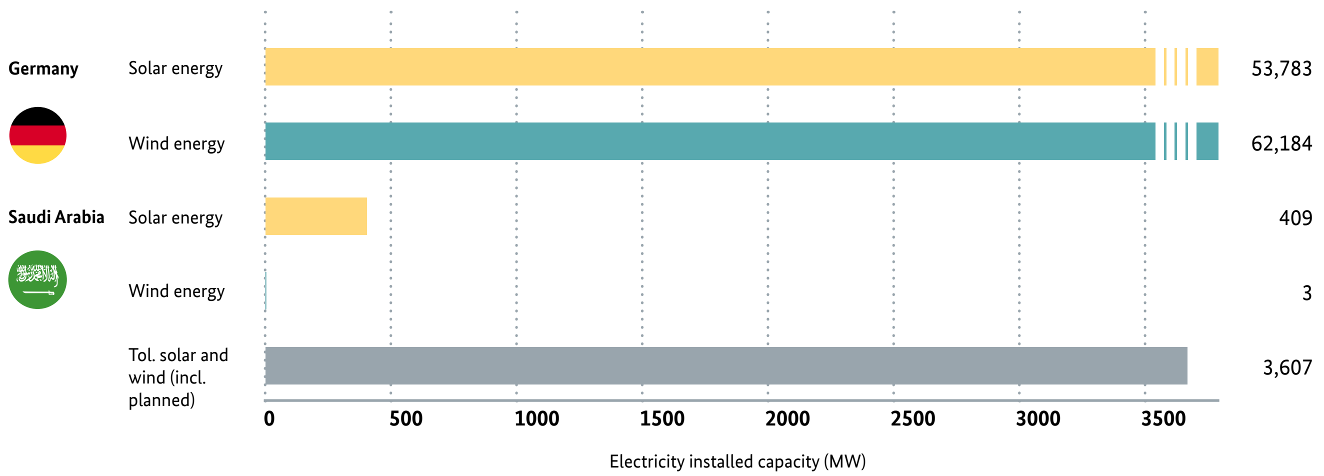
The situation in Germany is different. Renewable electricity is scarce and needed for the ongoing electrification of the transport, buildings, and industry sectors. Offshore wind in northern Germany is likely to be suitable for local hydrogen production, which can also contribute to grid-side relief at grid nodes or feed-in points without sufficient transmission capacity for large amounts of offshore wind power. It is also conceivable that wind turbines could be connected exclusively to electrolysis capacities and thus forego a connection to the electricity grid. Instead, these plants could feed their production indirectly in the form of hydrogen. Agora Energiewende estimates 19 TWh of green hydrogen production in Germany by 2030, going up to 96 TWh by 2045.[27] For a transitional period, blue hydrogen can play a significant role until the corresponding renewable power generation capacities are available. Domestic hydrogen production at this scale requires sites with appropriate connections to shipping routes for CO_2 removal.

However, the question arises as to which of the existing steam reformers can be retrofitted with CCS technology and if, given the high plant age of steam reformers in Germany, such an investment option wins out over the new construction of optimised production plants for fossil hydrogen with carbon capture in a favourable location to CO_2 repositories. Additionally, CCS technologies are a controversial debate in Germany. Therefore, the use of the technology is not guaranteed.

Figure 5 summarises the renewable installed electricity capacity for solar and wind energy in Germany and Saudi Arabia.

Having expressed the ambition to emulate Germany's success with renewable energy while matching its vast resources with the necessary means of production, the Saudi government recently announced significant power purchasing agreements for seven large-scale solar power projects in various regions of the country. More renewable energy projects will follow, driven by a strong government ambition in scaling up government's ambitions in green hydrogen production.

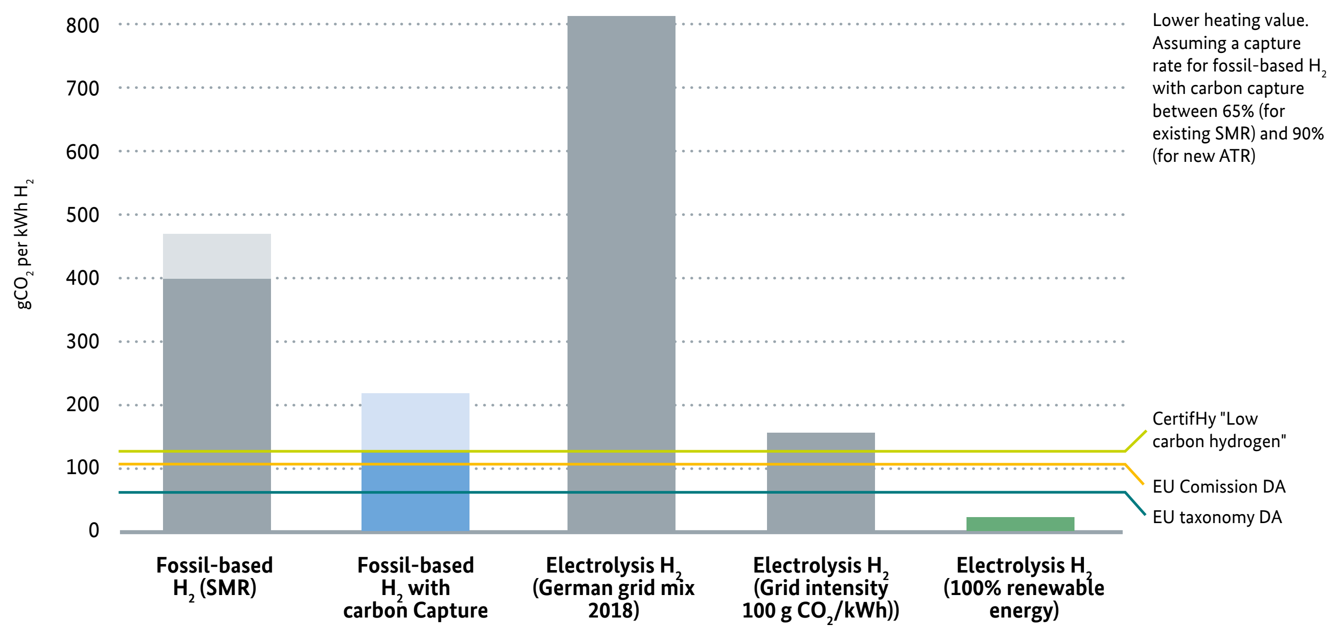
Figure 5: Renewable installed electricity capacity (MW) in Germany (2020) and Saudi Arabia (2020 and planned).



Source: IRENA 2021[28] and Bellini 2021[29].

3.4 Sustainability criteria for hydrogen and its derivatives

Figure 6: Average lifecycle CO_2 emissions of hydrogen production in g CO_2 per kWh of hydrogen.



Source: Climate Action Network (2021), EC (2020), ÖkoInstitut (2019), Greenpeace Energy (2020), CertifHy (2019)[32]

Hydrogen is not an inherently climate-neutral energy carrier. If sourced from carbon-intensive electricity, it can increase CO_2 emissions. In Germany, producing 1 kWh of electrolysis-based hydrogen from current grid mix electricity would emit about 800 g of CO_2, which is more than three times higher than the 250 g CO_2/kWh emitted when conventional fossil gasoline is burned.[30] Figure 6 presents the average CO_2 emissions of various hydrogen production methods in g CO_2 per kWh of hydrogen. The EU's GHG threshold (102 g CO_2/kWh of hydrogen) as set by the European Commission can only be fulfilled by blue hydrogen with below-average emissions and green hydrogen from renewable electricity.[31]

To ensure that hydrogen contributes to the fight against climate change, a standardised, robust, and mutually recognised certificates or guarantees of origin (GO) system for hydrogen is needed. This avoids mislabelling or double counting environmental impacts and covers CO_2 equivalent inputs to hydrogen-based fuels and feedstocks.

A GO system provides a clear label for the hydrogen product that increases consumer awareness and accurately describes the value of the commodity and can also facilitate market valuation and international trade of hydrogen. The latter is of crucial importance to countries with high hydrogen export ambitions like Saudi Arabia.

The Hydrogen Production Analysis Task Force (H2PA TF) of the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE) is developing a technical and analytical methodology that can be used for these purposes, including "for the purchase of hydrogen across regions and to identify the emissions footprint of the various sources of hydrogen."[33] Although the results of the H2PA TF efforts are non-mandatory and subject to each member's discretion, the longer-term aim is to contribute to "the definition of low-carbon hydrogen."[34]

As a future net-importer of hydrogen, and under the EU's regime of strict energy and climate regulatory requirements, Germany will want to make sure that the hydrogen it is importing, is within the acceptable regulatory boundaries of what is considered as clean along all parts of the value chain. In its capacity as one of the first countries worldwide to signal its plan to produce and export hydrogen, Saudi Arabia stands to benefit from participating in ongoing efforts to set up a standardised GO system for hydrogen.

3.4.1. Sustainability criteria for green hydrogen

Electricity

The EU's Renewable Energy Directive II (RED II) sets the requirements for synthetic fuel, including hydrogen.[35] It specifies that synthetic fuels must achieve at least 70% in GHG reduction compared to conventional fuels. It also specifies that there must be a "temporal and geographical correlation" between renewable electricity generation and synthetic fuel production as well as an "element of additionality" to the renewable electricity input. The latter means that new renewable electricity capacities must be built for synthetic fuel production. If there is a direct connection between renewable electricity generation and synthetic fuel production, then it may also be counted as renewable if grid electricity is not used. The certification will be based on voluntary schemes and supervised by the EU Member States.

The EU aims to incorporate these principles into a detailed, legally binding methodology in 2022. It remains to be seen to what degree the RED II criteria will function as a blueprint for international sustainability criteria. It is yet to be determined how hydrogen produced from electrolysis powered by nuclear energy will be accounted for in the EU.

Carbon

Synthetic gas or liquids require carbon input. There are three options to source this carbon, with varying impacts on the carbon footprint:

- Bio-based carbon would be considered green, but biofuels would likely be subject to further sustainability criteria (e.g., lifecycle assessment).
- Carbon from DAC would also be counted as green if the energy required for the process is renewable. This technology is still at an early stage and relatively expensive.
- Using fossil carbon captured from unavoidable process emissions, e.g. from the cement sector, could reduce the need for additional fossil primary energy. The technology could be deployed in the short term if double counting of emission savings is to be avoided.[36] Fossil CCU should be limited to unavoidable process emission; otherwise, the lifetimes of fossil emitters such as conventional power plants could be unnecessarily prolonged. There is currently no comprehensive policy framework in the EU for carbon accounting and requirements of recycled carbon fuels. The CCE programme mentioned in Chapter 2.2 is an example of such a policy. Additionally, when an industrial process or power plant already fully operates on biomass, CCU could be added to capture this CO_2 from biological origin, an example being the green fuels for Denmark project.[37]

3.4.2 Sustainability criteria for blue hydrogen

Upstream emissions of methane

Methane creates various substantial upstream emissions due to energy required for production, purification, and transport, including liquefaction and regasification.[38] Methane also has a global warming potential 28-36 times greater than CO_2 over 100 years.[39] In order to produce blue hydrogen in a sustainable manner, methane emissions have to be reduced drastically and transparently monitored.

Carbon capture rate

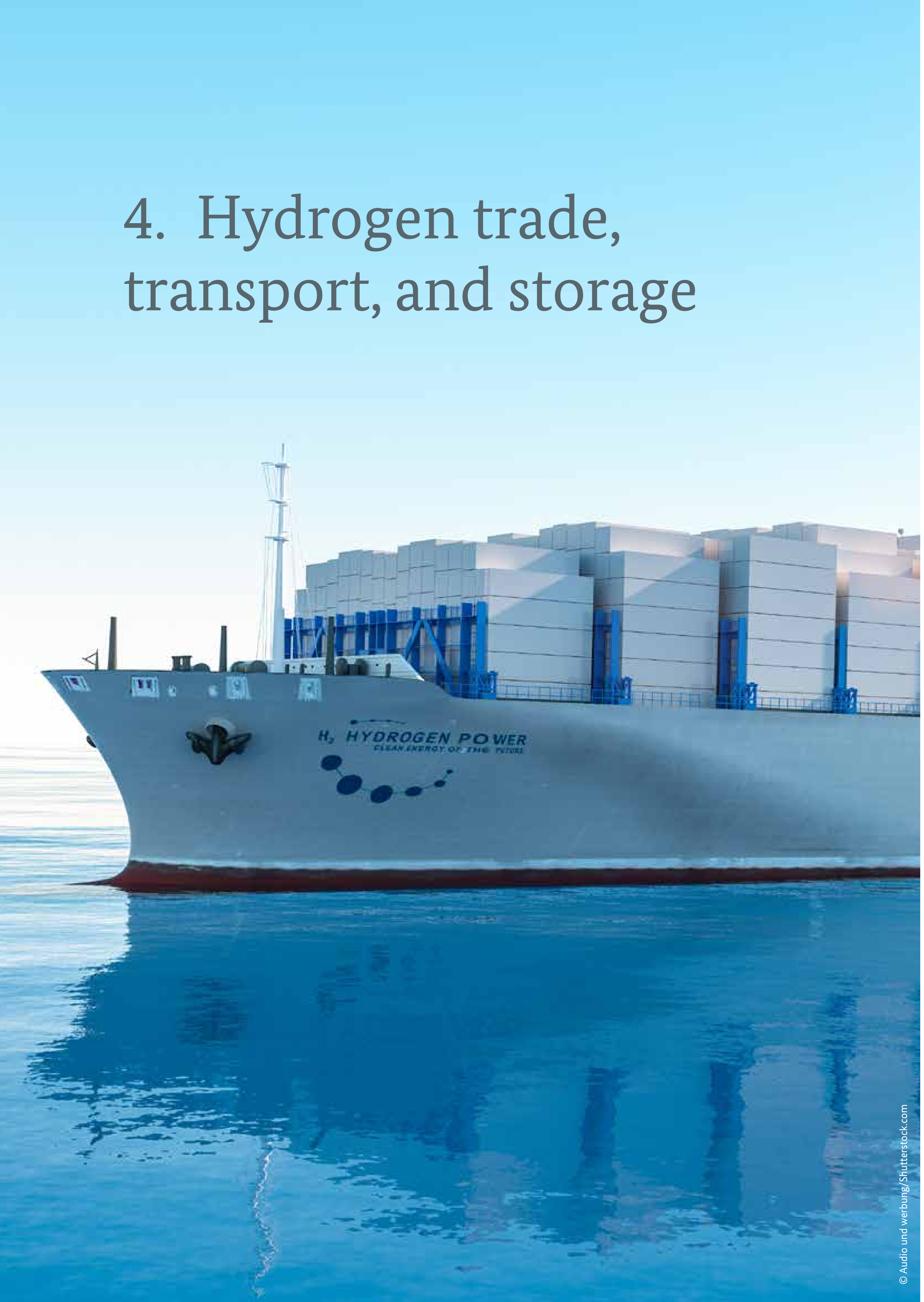
The carbon capture rate describes the captured fraction of CO_2 emissions and varies depending on the process applied but will never reach 100%. SMR plants coupled with CCS can capture 60%–90% of CO_2.[40] The higher percentage applies to the capture of both combustion CO_2 and output stream CO_2. Autothermal reforming (ATR) plants can achieve up to 95% carbon capture rates, but this technology has not been applied on a large commercial scale.[41] In both cases, additional energy in the form of heat and electricity is required for CCS.

CO_2 leakage from CCS reservoirs

CO_2 will have to be stored underground for a long time. Therefore, the risk of CO_2 leakage must be considered , also because of the toxicity of highly concentrated CO_2. Optimistic estimates set emissions from CO_2 leakage at 3 g CO_2 equivalent per MJ of hydrogen. At an Energy Dialogue workshop, industry experts also stated that EOR is associated with underground CO_2 retention rate of 30%–90%[42] . In many instances, EOR may not be able to fulfil GHG criteria for low-carbon hydrogen.

CO_2 that would have been stored anyway, for example, at EOR facilities already using CO_2, should not count towards CO_2 savings. Otherwise, there would be a reallocation of negative emissions on the balance sheet without new negative emissions offsetting those from hydrogen production.

4. Hydrogen trade, transport, and storage



4.1 International hydrogen trade

Key Points

- With economies all over the world increasing their decarbonisation ambitions, the global hydrogen market could grow up to US$25 billion by 2030.
- Hydrogen can be transported in dedicated pipelines, blended in existing natural gas pipelines, shipped, or attached to carrier molecules. Pipelines offer the more cost-efficient transport option for high-volume and long-distance hydrogen imports from countries within Europe and neighbouring regions such as North Africa or Ukraine. Ship transport can work well for low volumes and imports outside Europe, e.g. the Gulf region.
- Transporting derivatives like ammonia or methanol is already possible today, as most existing transport infrastructure (e.g. oil, ammonia, or liquefied natural gas [LNG] tankers) can be reused.

The industrial use of hydrogen is already a significant global business, with a total global demand of around 120 million metric tons in 2018 (60% for pure hydrogen and 40% for hydrogen-based fuels) worth about US$135.5 billion. [43]

As the level of maturity of hydrogen technology and the commitment to take concrete policy action on climate change varies, we expect this industry to grow at different speeds across the globe. Additionally, the level of competition between hydrogen and other low-carbon technologies also differs between sectors. Hydrogen faces few competitors in industries such as aviation, shipping, or iron and steel production. However, in other areas, such as passenger vehicles, the competition will be more intense. Here direct electrification is already playing a more dominant role.

Nonetheless, conservative estimates of the mid-term opportunity for the hydrogen market represents US$1 billion to US$25 billion by 2030, then increasing rapidly towards 2050 and beyond.[44] As these estimates are based on current government plans only, the future market value of hydrogen is likely to be significantly higher. If, thanks to future government subsidies, even only half of the expected increase in demand for hydrogen above the current levels is covered by decarbonised sources, the hydrogen market would (under conservative assumptions) be worth about US$25 billion by 2030. Future long-term prospects are even higher (Figure 7).

Figure 7: Applications for hydrogen classified by the theoretical, global size of the 2030 opportunity and the long-term potential.

Type of application	Application	Size of the 2030 opportunity (ktH_2/yr)	Long term potential scale
Major hydrogen uses today	Chemicals (ammonia and methanol)	Over 100	High
	Oil refineries and biofuels	Over 100	Medium
	Iron and steel (blending in DRI)	10–100	Low
New hydrogen uses for a clean energy system	Buildings (conversions to 100% hydrogen)	Over 100	High
	Road freight	Over 100	High
	Passenger vehicles	Over 100	Medium
	Buildings (blending in the gas grid)	Over 100	Low
	Iron and steel (conversion to 100% hydrogen)	10-100	High
	Aviation and maritime transport	Under 10	High
	Electricity storage	Under 10	High
	Flexible and back-up power generation	Under 10	Medium
	Industrial high-temperature heat	Under 10	Low

Source: IEA (2019)

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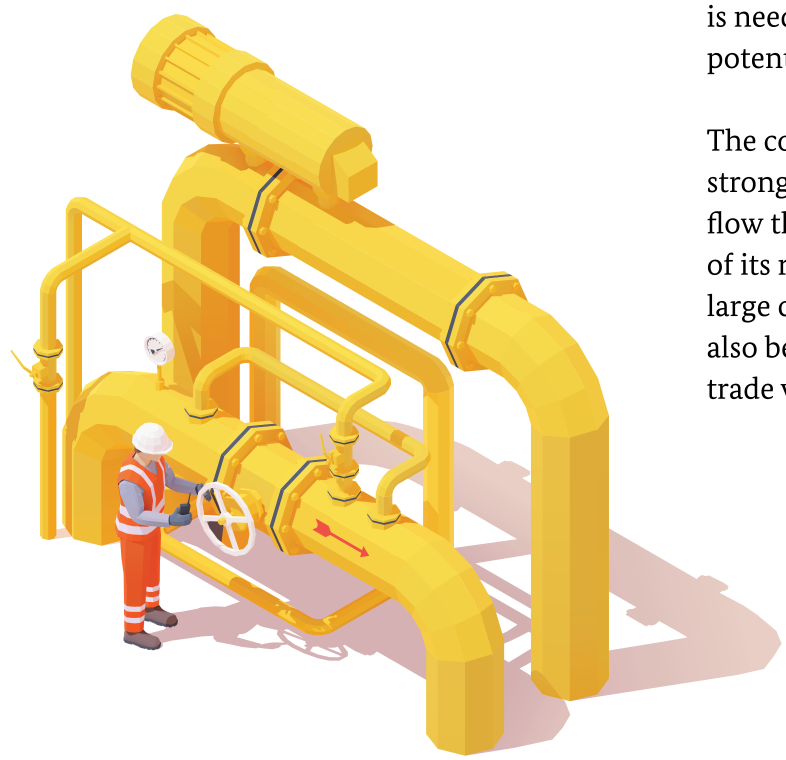
4.2 Long-distance hydrogen transport

Trading green hydrogen internationally entails multiple economic benefits for countries with smaller renewable energy potential. Trade also creates export opportunities for countries with excess renewable energy potential.[45] A physical necessity to realise such trade is the long-distance transport of hydrogen. This section examines the two main options for long-distance transport of hydrogen:

- Pipelines
- Ships
  - *Liquified hydrogen*
  - *Liquified organic hydrogen carriers*
  - *Ammonia*

Synthetic fuels (e.g. methanol or kerosene) can be transported and used like their fossil-based equivalents. This means they can be transported via pipeline, ships, or trucks. Due to the high energy density, low volatility, and the fact that they do not have to be liquefied, they are easy and cheap to transport.



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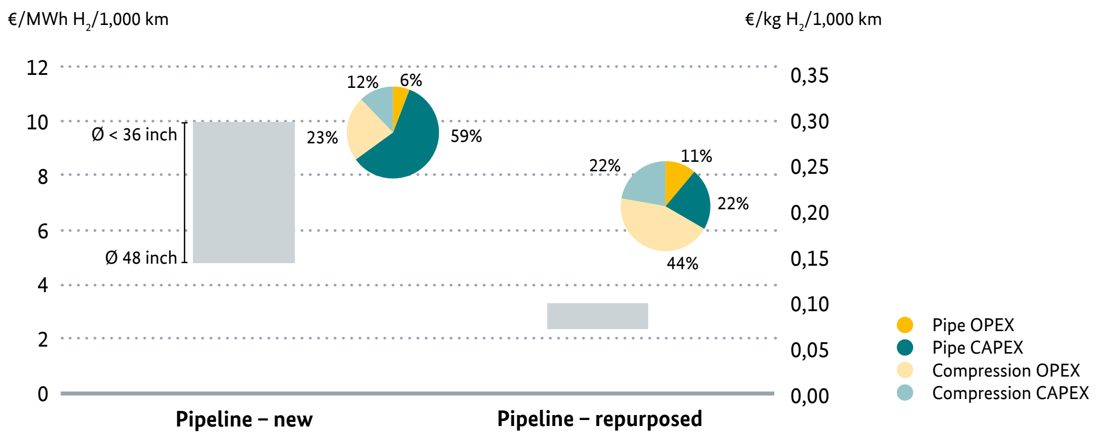
4.2.1. Hydrogen transport by pipelines

Hydrogen can be transported by either blending hydrogen in natural gas pipelines, repurposing existing natural gas pipelines to transport pure hydrogen, or building new, dedicated pipelines. Blending can be done at up to 2%. Blending ratios of up to 10% are also possible without significant effects on distribution networks or for end users.[46] Blending would relegate the value of hydrogen to that of natural gas, though. Furthermore, some off-takers cannot flexibly adjust to varying shares of hydrogen in the gas mix. It is not an option to gradually ramp-up hydrogen in the grid. Dedicated pipelines would be needed to transport more valuable, pure hydrogen. New dedicated hydrogen pipelines could be constructed with investment costs roughly 20% higher than natural gas pipelines.[47] Alternatively, existing natural gas pipelines could be retrofitted. Repurposing natural gas infrastructure for use with hydrogen is technically feasible. At around 10%–15% of the cost of construction of new hydrogen lines, this is also relatively affordable. However, the exact costs of repurposing are subject to more detailed engineering studies, and—where compression is needed—replacement of compressors and potentially drivers will be required.[48]

The cost of pipeline transport per tonne decreases strongly with the transported volume as energy flow through a pipe is proportionate to the square of its radius. Pipelines are usually constructed for large capacities only. Hydrogen pipelines would also be feasible only if the partners commit to large trade volumes upfront.

Figure 8: Cost comparison of new and retrofitted hydrogen pipelines



Sources: European Hydrogen Backbone, Bloomberg New Energy Forum, Agora, IEA.

Figure 8 shows that repurposed pipelines offer the most cost-effective solution for hydrogen transport, especially when using large diameters pipelines (48 inches). This makes them especially suitable for intra-European transport and imports from neighbouring countries with existing gas infrastructure, e.g. Morocco, Algeria, Ukraine, or even the Gulf region. Another advantage of retrofitting gas pipelines for hydrogen transport is the higher social acceptance of existing infrastructure than new pipelines.

Because pipelines are competitive only when transporting large volumes and based on high upfront investment, they tend to create supply oligopolies. The EU, for example, covers 82% of its natural gas imports from just three countries: Russia, Norway, and Algeria.[49] This creates geo-economic dependencies and a lack of market liquidity and should be avoided in the set-up of future international hydrogen markets.

When transporting hydrogen, safety aspects need to be considered. Hydrogen is highly flammable and explosive. Although it is not classified as toxic, hydrogen can be harmful in high concentrations. The safe handling of hydrogen pipelines and storage facilities, including periodic inspections and maintenance, is essential.

4.2.2. Hydrogen transport by ship

Hydrogen can also be transported over long distances by ship. However, hydrogen's low volumetric energy density (Table 2) presents a transport challenge for exporters like Saudi Arabia. Several methods of shipping are being investigated, and this study examines three of the most promising:

- Liquid hydrogen
- Liquid organic hydrogen carriers
- Ammonia

Table 2: Energy densities of selected energy carriers (higher heating value).

	Energy density (MJ per L)[50]
H_2 1 bar	0.01
H_2 700 bar	5.3
H_2 liquid	10.0
NH_3 liquid	15.3
LNG	22.2
Gasoline	34.2

Liquid hydrogen

Hydrogen could be transported at a pressure of 700 bar. Liquefied hydrogen, however, would yield an energy density twice as high, making it a more suitable option for shipping. It can also be used as fuel to power ships.

The downside of liquid hydrogen is that the boiling temperature of hydrogen is -253°C, much lower than that of natural gas (-162°C). Liquefication consumes approximately one-third of hydrogen's energy content.[51] For shipping of distances of 10,000 km or beyond, the conversion costs constitutes around 80% of the total cost. Economically, the cost to ship hydrogen is driven by the one-time energy loss rather than the shipping distance.

Shipping enables importers to obtain a higher level of diversity and therefore flexibility. As for LNG, once an importing terminal is installed, any exporting country with liquefication capacities can supply hydrogen. The relatively small effect of distance on shipping cost further increases flexibility when choosing suppliers of liquid hydrogen.

Shipping LOHC

Hydrogen can also be reacted with organic molecules like toluene to form an oil-like liquid, which is easier to transport. Hydrogen is removed from the carrier molecule at the destination, which can be shipped back and reused. LOHCs have the potential to reduce the cost of hydrogen shipping significantly.

Adding hydrogen to LOHC releases thermal energy which can be used for heating in the exporting region. As a downside, removing hydrogen from the LOHC after importing it requires an energy input of around one-third of its energy content.[52] Large shares of this energy are thermal energy, meaning that waste heat sources can improve the economics and environmental footprint of the method. However, ships must also be fuelled with a carbon-neutral fuel as the cargo cannot be used without emitting GHGs. Toluene is also a highly toxic compound. Alternative carrier molecules are being explored.

Shipping ammonia

Ammonia is a compound of nitrogen and hydrogen and does not generate CO_2 emissions when combusted. It is used today, mainly to produce fertilisers and explosives. Ammonia produced with carbon-neutral hydrogen could either replace the currently used ammonia or serve new applications, for example, as a shipping fuel.

Ammonia can be liquefied at -33°C, i.e., at a temperature that is substantially less low than the -253°C that is required for liquefying hydrogen. In addition, liquid ammonia has a 50% higher volumetric energy density than liquid hydrogen (Table 2). These characteristics make ammonia easier to transport than hydrogen. Ammonia also already has a well-established international transmission and distribution network, including pipelines and transport in trucks and tankers. Globally, more than 200 million tons of ammonia are produced every year.[53] German ports, e.g. Hamburg, Rostock, Bremen, Wilhelmshaven, Brunsbüttel and Stade are preparing for possible imports.

On the downside, energetic conversion losses are slightly lower than for other derivatives such as methane, methanol, and diesel but still well over 40%[54,55]. Further, there are safety and public acceptance issues associated with ammonia, as it is highly toxic, flammable, and corrosive. Leaking ammonia can form particulate matter or cause acid rain. These characteristics complicate the transport but can be resolved.

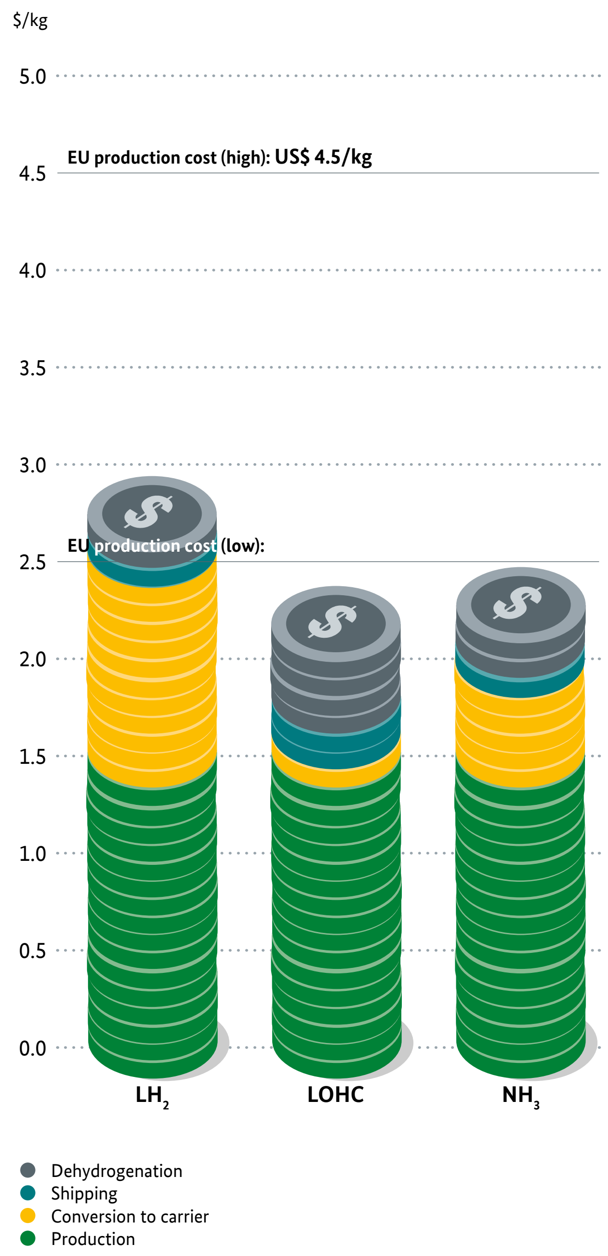
Ammonia could also be a carrier molecule, meaning that the hydrogen could be separated from the nitrogen in the importing country.

This process incurs further energy loss but may be worth the relative ease of transportation and storage.

Figure 9 shows the estimated delivered cost of green hydrogen from the western region of Saudi Arabia to Northwest Europe Rhine-Ruhr by 2030 using three different carriers: ammonia (NH3), liquid organic hydrogen carriers (LOHC), and liquid hydrogen (LH_2).[56]

The delivered cost of hydrogen from Saudi Arabia could be competitive with future European production costs, ranging between US$ 2.5/kg and US$ 4.5/kg. The expected 2030 production cost for green hydrogen in Saudi Arabia are US$1.5/kg. Shipping and reconversion adds around US$1/kg bring total cost to US$1/kg. If the demand for pure hydrogen takes off, LH_2 or LOHC would be an ideal carrier once the technology matures and becomes commercially viable. Direct use of ammonia is more feasible as the delivered cost can be much lower than even the production cost of hydrogen in Europe.

Figure 9: Estimated delivered cost of green hydrogen from the western region of Saudi Arabia to Northwest Europe (2030).



Source: Guidehouse (2021).

4.3 Cost comparison hydrogen pipelines vs shipping

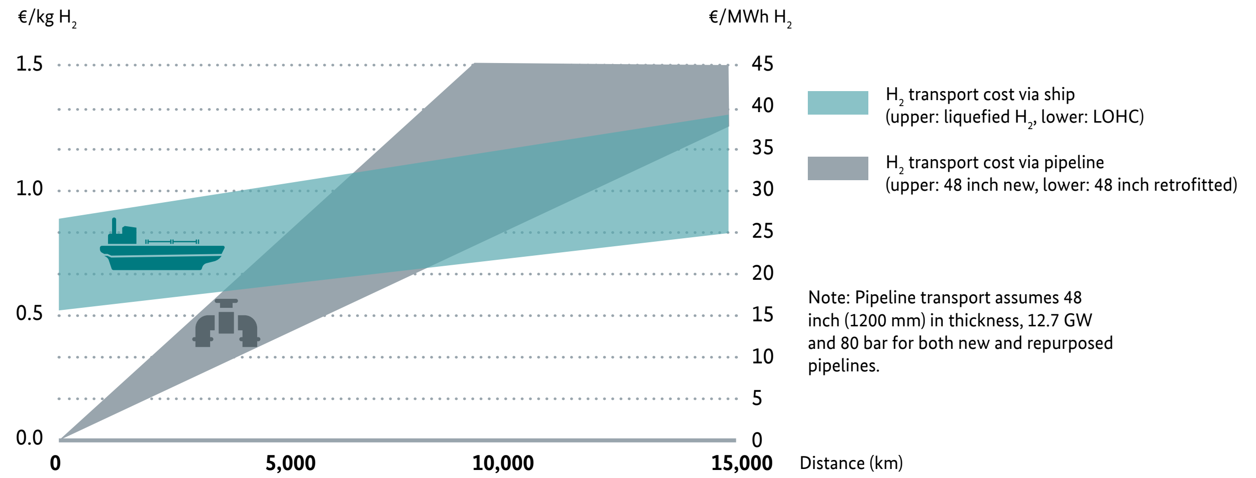
One-time energy losses from conversion drive the cost of shipping. For pipeline transport, cost correlates with distance linearly for each kilometre in length, one kilometre of pipeline needs to be built. At a certain distance, the cumulated cost for pipeline construction exceeds the cost induced by energy losses for liquefication or conversion. The exact location of this breakeven point between pipelines and shipping is still under debate. Regardless, it can be concluded that pipelines are more economical for short- and medium-distance transport while shipping is cheaper at longer ones (Figure 10).

Shipping is more suitable for low-volume imports than pipeline transport. That is because shipping is less dependent on economies of scale. The example of LNG shows that the largest current LNG terminal in Europe (Grain, UK) has an import capacity of 27.5 bcm per year.[57] Furthermore, shipping import terminals require less upfront investment than pipelines.

While the investment cost of Nord Stream 1, for example, was US$390 million per bcm of capacity,[58] LNG import terminals require an investment cost of around US$100 million per bcm capacity.[59] Although this does not include investments in liquefaction facilities in the exporting country and vessels, the lower upfront cost implies that an import terminal is economically less dependent on maximised utilisation than a pipeline.

In sum, pipelines offer the more cost-efficient transport option for high-volume and long-distance hydrogen imports from countries within Europe and neighbouring regions such as North Africa or Ukraine. However, ship transport can work well for low volumes and imports outside Europe, e.g. the Gulf region and countries far away like Australia or Chile. Given the high-cost impact of conversion and space constraints, the shipping route is most economical for importing derivatives as the final product.

Figure 10: Cost comparison of shipping and pipeline hydrogen transport routes.



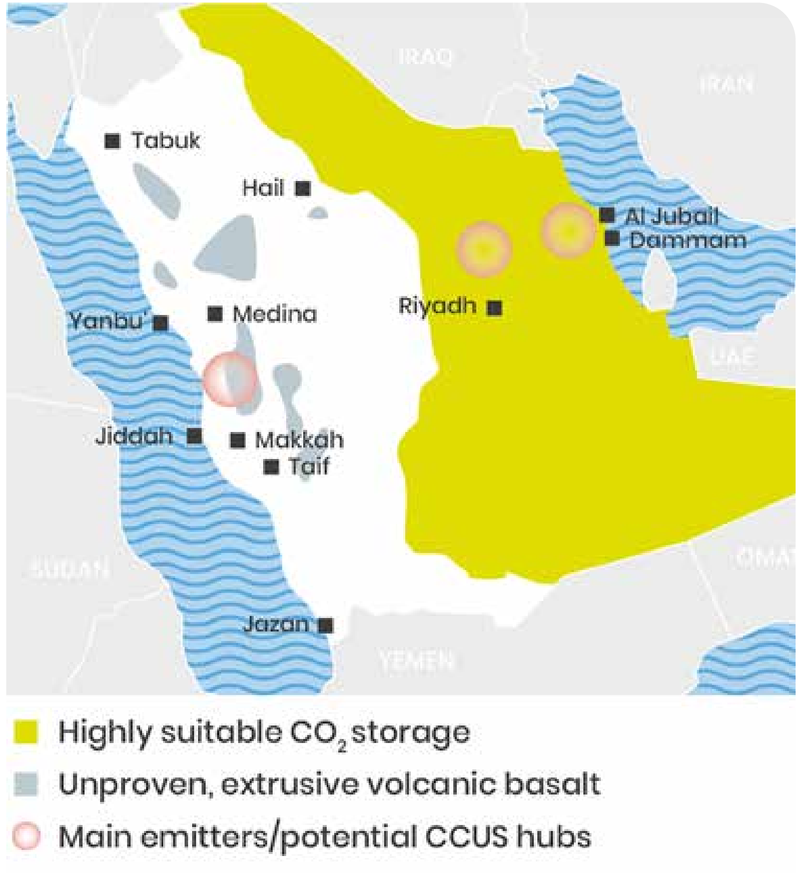
Source: Guidehouse / European Hydrogen Backbone (2021)

4.4 Storage options

Saudi Arabia's blue and green hydrogen ambitions require carbon sequestration and large-scale storage options in geological sites. Any blue hydrogen potential can only be fully realised with access to abundant CO_2 storage.[60] The Kingdom's typical geological features and extensive fossil-fuel required infrastructure offers across-the-board storage opportunities for CO_2 and hydrogen.[61] The mapping and detailed geological evolution of underground storage sites, including deep saline aquifers and depleted gas wells, are in progress within the Kingdom to identify potential storage sites. The Kingdom has a maximum storage capacity potential of 25 Gt of CO_2, with 90% of the deep saline formations in the Middle East.[62]

Figure 11 points out the Eastern (comprising Dammam and Jubail) and Central (around Riyadh) regions as highly suitable areas for CO_2 storage, which also includes potential CCUS hubs to realise economies of scale (Box 1).[63]

Figure 11: Map of CCUS hub locations and CO_2 geological storage suitability in Saudi Arabia.

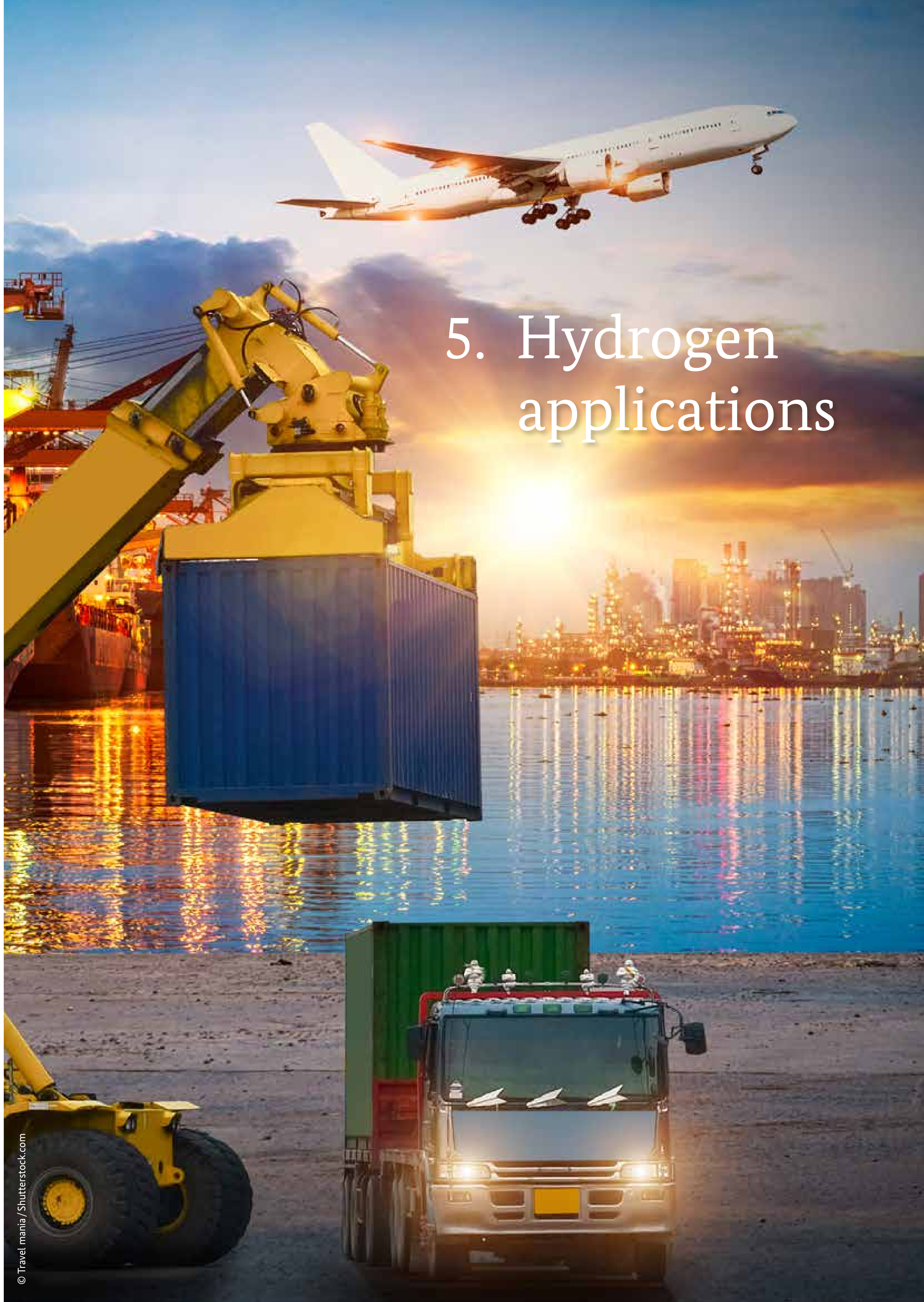


Source: OGCI 2021.

Box 1: What is a CCUS hub?

- Multiple industrial point sources of CO_2 are connected to a CO_2 transport and storage network.
- Access to sizeable geological storage resources with the capacity to store CO_2 safely and permanently from industrial sources (for decades).
- Economies of scale to deliver lower unit costs for CO_2 storage.
- Synergies reduce cross-chain risks and support commercial viability.
- CCUS infrastructure supports existing industries, attracts new clean industries, and enables innovation, utilisation, and negative emissions technologies.

Next to large-scale geological storage, small- to medium-scale storage forms a crucial link in the hydrogen value chain. The energy losses associated with the high-pressure compression, liquefaction, or boil-off can be significant. The technologies for chemical conversion to hydrogen carriers and metal hydrides are mostly at a low TRL.[64] Challenges associated with storage at such a scale must be addressed in the Kingdom. There is an enormous need to invest in R&D capacity and technology transfer in these areas to Saudi Arabia.



5. Hydrogen applications

5.1 Applications in the steel industry

Key Points

- Industry is the dominant user of hydrogen today. Grey hydrogen use, e.g., in refineries, could be substituted with clean hydrogen. Additionally, when combined with sustainable CO_2, hydrogen can replace fossil fuels. Further demand in industry is coming from the steel sector, where hydrogen can replace coking coal as a reducing agent.
- In the energy sector, hydrogen can be a factor in short- and long-term storage, reduce the necessity for grid expansion, and be used for space heating.
- In the transport sector, particularly long-distance transport and aviation, hydrogen and its derivatives can help reduce GHG emissions.

Germany is the world's eighth-largest crude steel producer (40.1 Mt in 2021). Saudi Arabia is the world's 21st largest producer with 8.7 Mt.[65] 70% of the steel produced in Germany uses the blast furnace (BF) route, with the balance being produced using the electric arc furnace (EAF). In the Kingdom the entirety of crude steel is made through the EAF.The Kingdom follows a steel production process whereby imported iron ore pellets are converted into DRI and then mixed with scrap steel and melted in an EAF using graphite electrodes. The steel melt is then cast according to market requirements as billets, long products, and flat products. The steel production process used has implications from a decarbonisation point of view. The steel industry is responsible for 7%–9% of global GHG emissions, predominantly due to coking coal used in the BF process. Globally, the high GHG emissions from the BF production route have increasingly made the steel industry explore GHG-neutral processes, primarily focused on DRI and carbon capture and storage. Compared with the conventional BF, the DRI process can use green hydrogen as a reducing agent instead of coal leading to an almost 97% reduction in GHG emissions.

The steel sector in the Kingdom is dominated by the SABIC-owned steel producer Saudi Iron and Steel Company (Hadeed), with a crude steel production capacity of 6 Mt.[66] Hadeed's DRI capacity stands at almost 5 Mt.[67] Hadeed's Jubail DRI facility is located close to other SABIC affiliates. Hadeed uses SMRs to produce hydrogen-rich syngas for use in its MIDREX™ and HYL™ modules in its DRI plant. Although Hadeed has extensive experience using the DRI-EAF process of steelmaking, its current energy usage for its operation and plant needs is still carbon intensive because of the usage of natural gas and electricity generated from fossil fuels.

The decarbonisation of the EAF-focused Saudi steel sector depends upon the decarbonisation of the Saudi electricity sector. The proposed Saudi DRI capacity near Jizan, Yanbu, and Jubail can use the local industrial sectors' green or blue hydrogen to reduce their GHG emissions footprint by blending it with natural gas or syngas as applicable.

5.2 Applications in oil processing and base chemicals

Refining processes

Refineries are one of the largest consumers today, using hydrogen mainly for hydrocracking and desulphurisation. Switching from grey hydrogen to renewable or low-carbon hydrogen does not require a fundamental change of production processes or infrastructure. The 'refinery transition' could commence by blending small amounts of low-carbon hydrogen into existing streams of grey hydrogen, leaving all other processes unchanged. The share of renewable or low-carbon hydrogen could then be increased over time.

According to the EU's directive RED II, conventional fuel suppliers are allowed to count renewable and low-carbon hydrogen that is used as an intermediate product to reduce the share of biofuels they are obliged to blend into the fuels they sell.[68] If biofuels from food waste (for example) are not available, it might be more cost-effective for fuel suppliers to use renewable or low-carbon hydrogen rather than more expensive biofuels.

Renewable and low-carbon hydrogen is already used by piloting refinery operators in Germany; among these operators are BP (Lingen refinery) and Shell (Rhineland refinery).

Replacing petrochemicals

The chemical industry can be decarbonised by replacing current fossil oil-based feedstocks with green hydrogen. In this Power-to-Chem process, green hydrogen reacts with CO_2 to produce methanol. This methanol is further processed to olefins, which are mainly used for plastics production (Methanol-to-Olefins, or MtO). Aromatic compounds like benzene or toluene can also be derived (Methanol-to-Aromatics, or MtA), opening the full range of products produced from petrochemicals today.[69]

The Carbon2Chem® project in Duisburg, Germany, is an early example of this technology.[70] A consortium consisting of ThyssenKrupp, BASF, Covestro, Linde, Evonik, and Siemens investigates how steel furnace exhausts can be converted into high-value chemicals. A renewable carbon source will be necessary in the long term.

Power-to-Chem's high costs represent its most significant barrier. Abatement costs of over €250/tCO_2 are much higher than the CO_2 price under the EU's Emission Trading System (ETS).[71]

Very high green electricity demand is another downside. For the European chemical industry, reducing 84% of its business-as-usual GHG emissions with Power-to-Chem in 2050 would require 1,900 TWh of green electricity,[72] a massive amount considering that total net electricity generation in 2017 in the EU was 3,100 TWh.[73]

Saudi Arabia has excellent potential to pioneer Power-to-Chem, in part because of its enormous and lowest-cost renewable electricity potential. The chemical industry is an intricate network of complex processes, so regions with existing chemical industries will have a competitive edge when adopting Power-to-Chem. Pioneering Power-to-Chem could be an opportunity for countries on the Arabian Peninsula.

Ammonia

Ammonia is currently a significant grey hydrogen consumer. Blue or green hydrogen can be utilised to decarbonise this sector. Using green hydrogen is associated with high CO_2 abatement costs of €110/tCO_2–€360/tCO_2 (assuming a hydrogen price of €2.8/kg–€5.0/kg),[74] while CCS is estimated to cost €60/tCO_2 to €110/tCO_2.[75] Green hydrogen price reductions and CCS availability will determine whether green hydrogen will play a role in decarbonising ammonia production. Thyssenkrupp Industrial Solutions currently provides the electrolyser capacity for the 2,2 GW green ammonia NEOM Helios project.[76]

In September 2020 Saudi Arabia shipped the world's first blue ammonia delivery.

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5.3 Applications in the energy sector

Synthetic fuels (mainly hydrogen) can play a significant role in electricity systems with high shares of intermittent renewable energy. Hydrogen can be a factor in short- and long-term storage, reduce the necessity for grid expansion, and be used for space heating.

Short-term storage

Short-term storage technologies are essential for energy systems with high shares of renewables to bridge variability in electricity supply and consumption. Since Saudi Arabia aims to depend largely on solar energy, there is also a need to determine how to cater to electricity demand at night.[77] Producing hydrogen during the day using solar electricity and re-electrifying at night could help bridge this gap.

Long-term storage

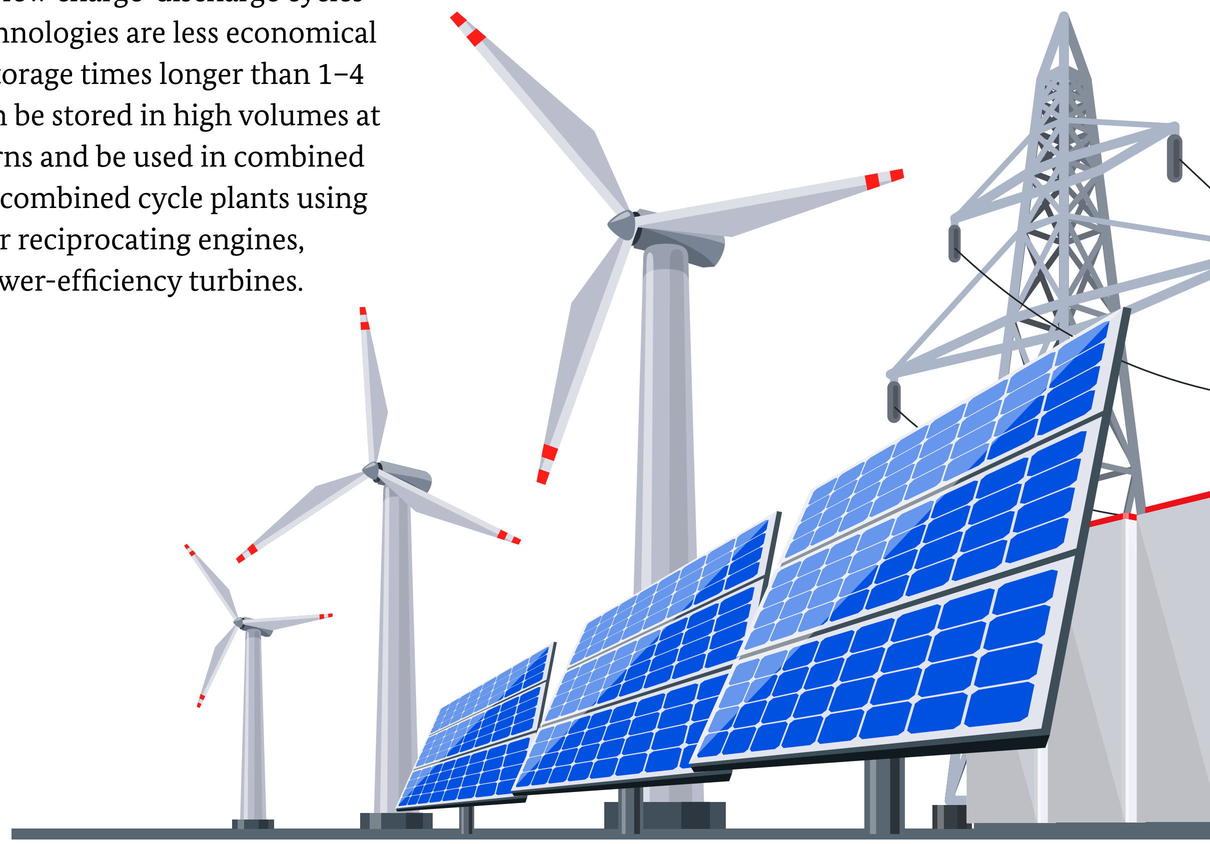
A crucial aspect of long-term storage economics is that there are only a few charge-discharge cycles per year. Battery technologies are less economical than hydrogen for storage times longer than 1–4 days.[78] Hydrogen can be stored in high volumes at low cost in salt caverns and be used in combined heat and power and combined cycle plants using hydrogen turbines or reciprocating engines, replacing existing lower-efficiency turbines.

Reducing the need for grid expansion

The relative investment costs of electricity lines are typically 2–10 times higher than gas pipelines.[79] It would be feasible to convert renewable electricity to hydrogen or methane and transport it through a pipeline instead of building an electricity line. The downside of this is the high conversion losses of hydrogen or methane production.

Space heating

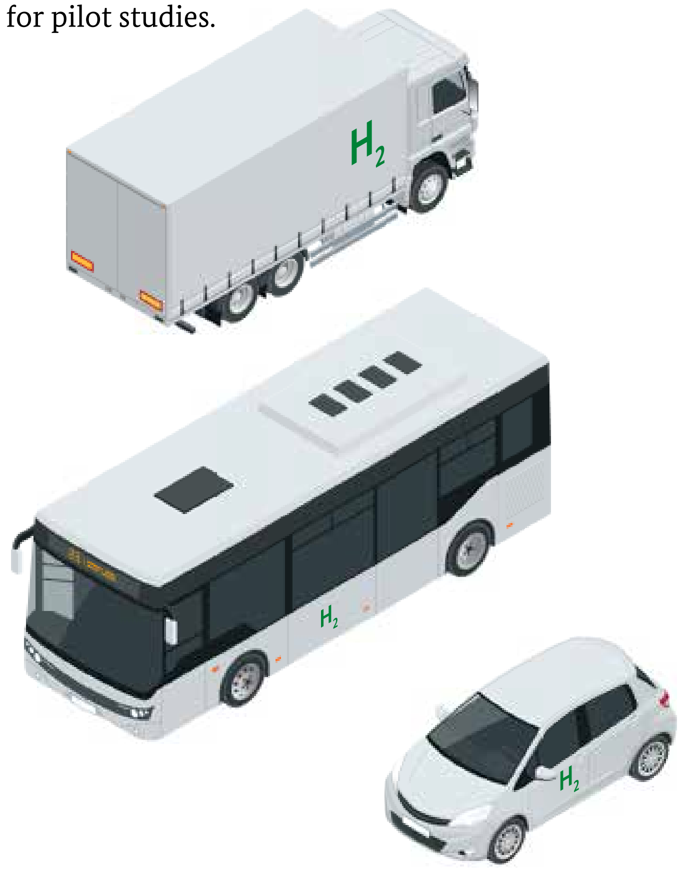
Hydrogen and its derivatives can be used in space heating, namely with gas or oil boilers. In contrast to Germany, this is less relevant for Saudi Arabia due to its negligent heating demand. In principle, green hydrogen or synthetic methane presents an option to decarbonise heating while using the existing infrastructure.



5.4 Applications in the transport sector

In 2020, the transport sector (24.1%) was the third largest contributor to CO2 emissions in Saudi Arabia, after the energy (27.7%) and the industrial (47.2%) sectors.[80] By comparison, German CO_2 emissions from the transport sector constitute at around 20% of the domestic total. With a transport sector wholly focused on oil, there are severe challenges the Kingdom faces in terms of reducing its transport-related carbon emissions footprint. Pure hydrogen or its derivatives can be used as a fuel to decarbonise the sector. Different transport modes on the road, waterways, and in the air will rely on other fuels and technologies, ranging from low-carbon fuels to carbon-neutral fuels. Technologies developed by Saudi Aramco, like Mobile Carbon Capture (MCC), could also help in reducing the carbon footprint of the existing vehicle fleet[81].

Multiple initiatives have appeared, focusing on the development of a hydrogen refuelling infrastructure and ensuring vehicles' availability for pilot studies.



Saudi Arabia has been progressing fast on its ambition to enable a hydrogen-fuelled transport sector. On January 30th, 2022, the Ministry of Energy signed eight MoUs with several Saudi entities to develop and implement pilot projects introducing hydrogen and related low-carbon fuels as part of the Kingdom's transport infrastructure. These pilot projects extend across transport modes, including road, rail, and aviation, focusing on hydrogen FCEV cars, buses, trains, transport applications, and sustainable aviation fuels.[82] These pilot projects will be executed across several locations in the Kingdom and involve multiple stakeholders like NEOM and Red Sea Projects. The aim of these pilots is to enable stakeholders to partner and collaborate with local and international companies to introduce and incorporate the new technologies, provide a better understanding of the performance of the hydrogen-based transport applications, increase public awareness and help generate and acquire the technical and commercial expertise required for managing hydrogen as a transport fuel.[83]

In March 2022, as part of the regulatory environment required to help introduce hydrogen as a transport fuel the Saudi Standard, Metrology and Quality Organization (SASO) issued the technical regulations for hydrogen-fuelled cars.[84] These technical regulations (the draft was made available for public consultation earlier in December 2021) will help develop the safety criteria, permit conformity assessment for potential vehicle importers, and ensure compliance with local safety standards.[85]

6. Potential for cooperation between Saudi Arabia and Germany

The penetration of hydrogen as an energy vector in Saudi Arabia's energy mix relies as much on technology advancements and adaption as it does on political-economic incentives and financial support. Green hydrogen technology will most likely form the mainstay for hydrogen production in the long run. The most significant hurdles here remain the large-scale production and deployment of electrolysis and an abundant availability of solar and wind-generated electricity. So affordable technological advancements in renewables are directly tied up with green hydrogen availability.

The Kingdom also possesses the world's most abundant oil reserves and one of the lowest carbon intensities in crude oil production. Blue hydrogen is a natural fit under these conditions, further enabled by emerging technologies in cleaner reforming and heavy residue gasification with carbon capture and sequestration. With a mix of green and blue hydrogen production, the Kingdom can achieve frontrunner position in hydrogen export and maximise hydrogen utilisation and contribute to the decarbonisation of key economic sectors of the global economy.

Hydrogen as an energy carrier and a fuel has low volumetric density, which limits application in standalone utilisation systems like ships and aircrafts. Fuel cells may be a good fit for ground transportation, especially over long distances. Hydrogen combustion entails enormously high flame speeds that impede power generation applications like burning in gas turbines, ICEs, and steam boilers.

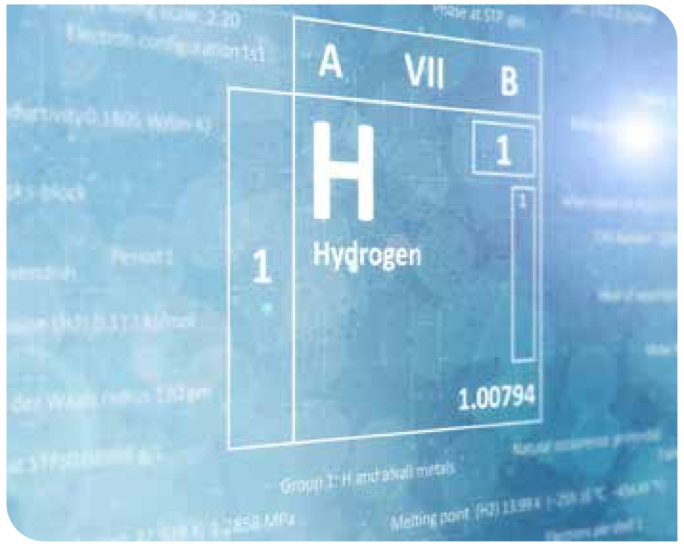
Several other sectors like steel, glass manufacturing, cement, and chemicals require high process temperatures where utilisation of hydrogen has not progressed so far. Operational safety is another critical area that needs attention when considering the penetration of hydrogen usage. Hydrogen can be readily converted to ammonia, a zero-carbon hydrogen carrier for long-distance or intercontinental transport and cracked back to hydrogen at the end user's site.

In the transition period towards a possible widespread usage, hydrogen can be blended (or co-fired) with low-carbon intensity fuels like natural gas, ammonia, or methanol for combustion applications. Gas turbine, reciprocating engine, and steam boiler equipment manufacturers are making considerable technological strides in achieving 100% hydrogen-burning capability by 2030. The Saudi power generation and desalination sector, which is wholly dependent on oil and natural gas combustion as a primary energy source, can be transitioned to hydrogen- or ammonia-based burning in the short term. Hydrogen-derived synthetic e-fuels such as ammonia, methanol, gasoline, kerosene, and diesel have the potential to usher in the hydrogen era for aviation and shipping.

Hydrogen will need to ramp up rapidly to meet short-and long-term climate targets.

The Kingdom has made significant strides in R&D associated with hydrogen and CCUS-focused technologies. A few representative examples from ongoing research at KAUST, SABIC, and Aramco in hydrogen and energy carrier value chains include the following:

- Solar to hydrogen-photocatalytic splitting of water for hydrogen production.[86]
- Ammonia energy economy.[87]
- High-pressure ammonia/hydrogen combustion for gas turbine application.[88]
- Oxy-fuel combustion technology.[89]
- Metal-organic frameworks for direct air carbon capture.
- Cryogenic carbon capture technology.[90]
- Synthetic fuels.[91]



Many scientific and technology pieces need to be put together and move towards a high(er) TRL at affordable costs for a hydrogen-based transition to become a reality. Table 4 in the appendix enlists some mature and potentially disruptive technologies along several stages of the hydrogen value chain. The list overview covers the relevant technologies and research themes from the Saudi-German collaboration. However, this overview is not exhaustive. R&D in hydrogen-focused technologies should receive significant budgetary provisions and prioritised funding in the Kingdom. Pilot-scale, high TRL demonstration projects can pave the way for the industrial deployment of mature technologies at a faster rate.

As a leader in the market development of hydrogen, Germany can offer technology transfer across the entire value chain to speed up the development and deployment of R&D infrastructure in the Kingdom. Overall, an ecosystem of scientific advancements and innovation must encompass the Kingdom's foray into the hydrogen economy, with German collaborative exchanges and local development of new knowledge in this field.

7. Next steps

Saudi Arabia and Germany are committed to realising the full hydrogen cooperation potential in the context of the Saudi-German Energy Dialogue.

Stakeholders from both countries are therefore working together in three working groups: **business**, **technology**, and **regulatory**. These groups were agreed upon as part of the roadmap to implement the bilateral MoU on the hydrogen cooperation. The working group meet on a regular basis and are pursuing regularly and are pursuing the following overarching aims as mentioned in the MoU:

- Connecting relevant stakeholders from research institutions, the private sector, and public sector entities to implement bilateral activities.
- Promoting mutual knowledge sharing and transfer of technological know-how to Saudi stakeholders and the deployment of German technologies in the implementation and localisation of new technologies for new start-up projects in the Kingdom.
- Making efforts in implementing concrete projects for the production, processing, application, and transport of hydrogen, including NEOM Helios.
- Establishing a sustainable supply chain for hydrogen and its derivatives
- Contributing to the development of a hydrogen-based energy sector in Saudi Arabia, including localising value chains, and promoting the use of German technologies.
- Facilitating the development of a CO_2-neutral hydrogen sector in Germany.
- Preparing a Saudi-German innovation fund for the promotion of hydrogen.

To meet the overarching aims, each of the three working groups will hold regular meetings and work on the following objectives (Table 3).

Table 3: Saudi-German Hydrogen Cooperation Working Groups.

Working Group	Objective	Activities
Business	The role of the private sector is critical in the large-scale deployment of hydrogen projects. The cooperation welcomes the active participation of companies involved in the entire hydrogen value chain to unlock business opportunities. The business working group focuses on specific pilot projects for hydrogen production, use, and transportation and its derivatives (such as the green ammonia Helios project NEOM announced). Table 4 (Appendix) shows the cooperation potential between the two countries along the hydrogen value chain.	• Business-to-business collaboration, including joint ventures and pilots. • Expert workshops (e.g., hydrogen export potential) and business roundtables. • Delegation visits and study tours, bringing together business stakeholder from Saudi Arabia and Germany.
Technology	Technology maturity is a crucial success factor for the hydrogen industry. The working group aims to advance hydrogen research, development, and deployment in both countries for mutual benefit, including capacity building and access to innovative technologies.	• Joint studies to expand and exchange knowledge along the hydrogen value chain. • Workshops and roundtables discussing the latest insights in hydrogen technologies. • Delegation visits, study tours, and education programmes.
Regulatory	The regulatory working group aims to promote a regulatory architecture suitable to help the hydrogen industry. Such an architecture includes accounting and certification standards, frameworks necessary for consistency in international trade and supply chains, safety protocols for production, transportation, storage, and use, and fiscal instruments to support hydrogen. The working group is also reflecting on existing and expected regulations in Saudi Arabia, the European Union, and Germany.	• Expert workshops and roundtables focusing on topics such as sustainability of hydrogen and certification. • Delegation visits and study tours.

A main outcome of the working groups and the ongoing collaboration between Saudi Arabia and Germany should be the short-term implementation of concrete hydrogen projects that benefit both countries in emission reduction, knowledge exchange, and economic growth.

8. Appendix

Overview of technology solution providers

Germany and Saudi Arabia host many companies that provide critical components of the rapidly growing hydrogen economy. Saudi Arabia's companies working in oil & gas-related or renewable energy projects could contribute to the Kingdom's hydrogen ambitions. Companies that started in the construction and oil & gas sectors and developed skillsets to leverage and establish themselves in the renewable sector have the potential to replicate that success in relation to hydrogen. Over several decades, Saudi organisations have delivered complex projects, including raising the proper finance, finalising engineering, completing construction, and operation and maintenance. Policy support for hydrogen projects that allows for training and capacity building attracting employees can be of enormous help in removing barriers to labour-force development. Secondly, it could support the incremental growth of the Kingdom's economy. Due to its early advancements in the energy transition, Germany is home to companies along the entire hydrogen value chain. Table 4 summarises technology providers in Saudi Arabia and Germany.

Table 4: Overview of companies in Saudi Arabia and Germany active along the H_2 value chain (not exhaustive).

Value chain step	Companies in Saudi Arabia	Companies in Germany
Renewable electricity generation and water desalination	• ACWA Power • Alfanar Group • Safeer • Saudi Electricity Company • Saline Water Conversion	• Siemens Energy • Enercon • Vestas • Nordex
Asset (electrolyser) manufacturing		• AREVA H2Gen GmbH • Bilfinger SE • Enapter GmbH • H-TEC Systems GmbH • Siemens Energy • thyssenkrupp Industrial Solutions AG • Sunfire GmbH
Power-to-X O&M	• Alfanar Group • Desert Technologies • CEPCO • Zahid Group • Mowah Company • NESMA • Babtain Contracting Company • Al Gihaz Holding	• Siemens Energy • thyssenkrupp Industrial Solutions AG • Robert Bosch GmbH
Storage and distribution	• Air Liquide • Air Products Qudra • Saudi Aramco • Al Bagha Group	• Hydrogenious LOHC Technologies GmbH • Linde GmbH • VINCI Energies • Wenger Engineering GmbH
End use: Mobility	• Saudi Aramco and Air Products • Saudi Aramco and Hyundai Motor Company • Abdul Lateef Motors and Toyota Motor Company	• H2 MOBILITY Deutschland GmbH & Co KG • Linde GmbH • Wenger Engineering GmbH • Schaeffler AG • ZF Friedrichshafen AG
End use: Industry	• SABIC • Sadara Chemical Company	• BASF FZE • Evonik Industries AG • Linde GmbH • thyssenkrupp Industrial Solutions AG
Cross-cutting: Consulting	• Altaaqa Global Energy Services • ACWA Power Engineering	• AVL Schrick GmbH • FEV Group GmbH • Elia Grid International GmbH • ILF Consulting Engineers GmbH • Ludwig-Bölkow- Systemtechnik GmbH

Potential R&D areas for Saudi-German hydrogen collaboration

Table 5: Potential R&D Areas for German-Saudi Hydrogen Collaboration.

Hydrogen value chain	Central themes	Potential R&D areas
Production technologies	**Green hydrogen**	Efficiency improvement for solar PV and wind; Improving capacity factors, digitisation for variability and grid stability; system integration for hybrids and decentralisation.
		GW-scale alkaline water electrolysis (AWE); advancements in Proton-exchange membrane (PEM); solid oxide electrolyser cell; anion exchange membrane; seawater electrolysis; materials for electrodes and separators; novel catalysts.
		Seawater reverse osmosis (SWRO), renewable driven water desalination. Brine treatment; membrane technologies.
	Blue hydrogen	Advance reforming technologies; autothermal reforming (ATR); partial oxidation (POX); reforming of liquefied petroleum gas; chemical looping; utilisation of oxygen from electrolysis in reforming (combined blue and green).
	Synthetic fuels	Gasification of petroleum residues and biomass; municipal waste; underground gasification; carbon negative technologies.
		CCUS technologies (advanced solvents, cryogenic carbon capture); oxy-combustion; advanced thermodynamics cycles (e.g. Allam, supercritical CO_2 cycle); geological storage of CO_2; CO_2 leakage prevention.
		DAC technologies and services.
	Turquoise hydrogen	Natural gas pyrolysis; sour gas sweetening; solid carbon utilisation.
	Other routes	Scaling up photochemical and microbial process-based hydrogen; microwave/plasma enabled the conversion of natural gas to hydrogen.
	Hydrogen valorisation	Technologies for reduced use of hydrogen in industry, e.g., hydrogen-less oxidative desulfurisation of distillate and heavy fuels. Process improvements for hydrogen from refinery and industry by-products (e.g., Chlor-Alkali processes); waste heat recovery technologies.
Energy carriers; conversion, storage, transportation, and distribution	**Physical conditioning**	Gas separation and purification, e.g., pressure swing adsorption improvement and alternatives; efficient compression, liquefaction, and boil-off loss reduction in hydrogen transport; ultrasonics, cryogenics, and heat exchanger technologies; last-mile delivery loss prevention.
	Chemical conditioning	Ammonia-alternatives to Haber-Bosch process; electrochemical synthesis. Air-separation; ammonia cracking, catalysts; integration of renewables (e.g., solar-ammonia cracking); technologies for other carriers like methanol, dimethyl ether (DME), formic acid.
		Metal hydrides.
		LOHC.
		Battery for hybrids.
	Storage	Technologies for geological storage of hydrogen; saline aquifers, basaltic formations, ocean storage; round-trip efficiency.
	Transport	Trucks; pipelines; hydrogen embrittlement abatement: Advance materials.
		Carbon-neutral shipping with fuel cells; ammonia, methanol, e-fuels.
Power to X and Sector coupling (electrification)	**Chemicals and fuels**	Synthetic or e-methane, ammonia, and methanol; process (e.g., Fischer Tropsch) efficiency and carbon footprint improvements for e-fuels: e-methanol; e-gasoline; e-kerosene; e-diesel; fertilisers.
	Gas and Power	Synthetic natural gas for power; methanation process.
	Heat and Feedstock	Process heating; hydrogen for refineries.
	Grid balance	Integration of heat pump technology.

Hydrogen value chain	Central themes	Potential R&D areas
End-use application	**Power**	Hydrogen/ammonia fired gas turbines; ammonia co-firing in boilers.
	Mobility	Advanced fuel cells for mobility; fuel cells for heavy duty transport.
		Low-purity hydrogen use: solid oxide fuel cells (SOFC); direct ammonia fuel cells; hydrogen-fired ICE; ammonia ICE for shipping.
	Heavy industries	Hydrogen as a heat source for heavy industries; hydrogen integration in cement; aluminium, glass, mining; steel-direct Iron reduction (DRI).
	Residential	Building heating with hydrogen burners; heat pumps for cooling and heating.
Hydrogen system and grid integration; hubs	**Digitisation**	High-speed computing; AI; Industry 4.0 technologies. Smart grids.
	Hubs	Knowledge sharing and partnerships on industrial-scale hydrogen hubs.
End-of-life (EoL) technologies; Stranded assets	**Circular economy**	EoL of fuel cells and hydrogen products: AWE, SOFC, and PEM water electrolysis material and mineral retrieval/disposal; strategies for valorisation stranded assets.

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