Ministry of Foreign Affairs

HYDROGEN IN THE GCC

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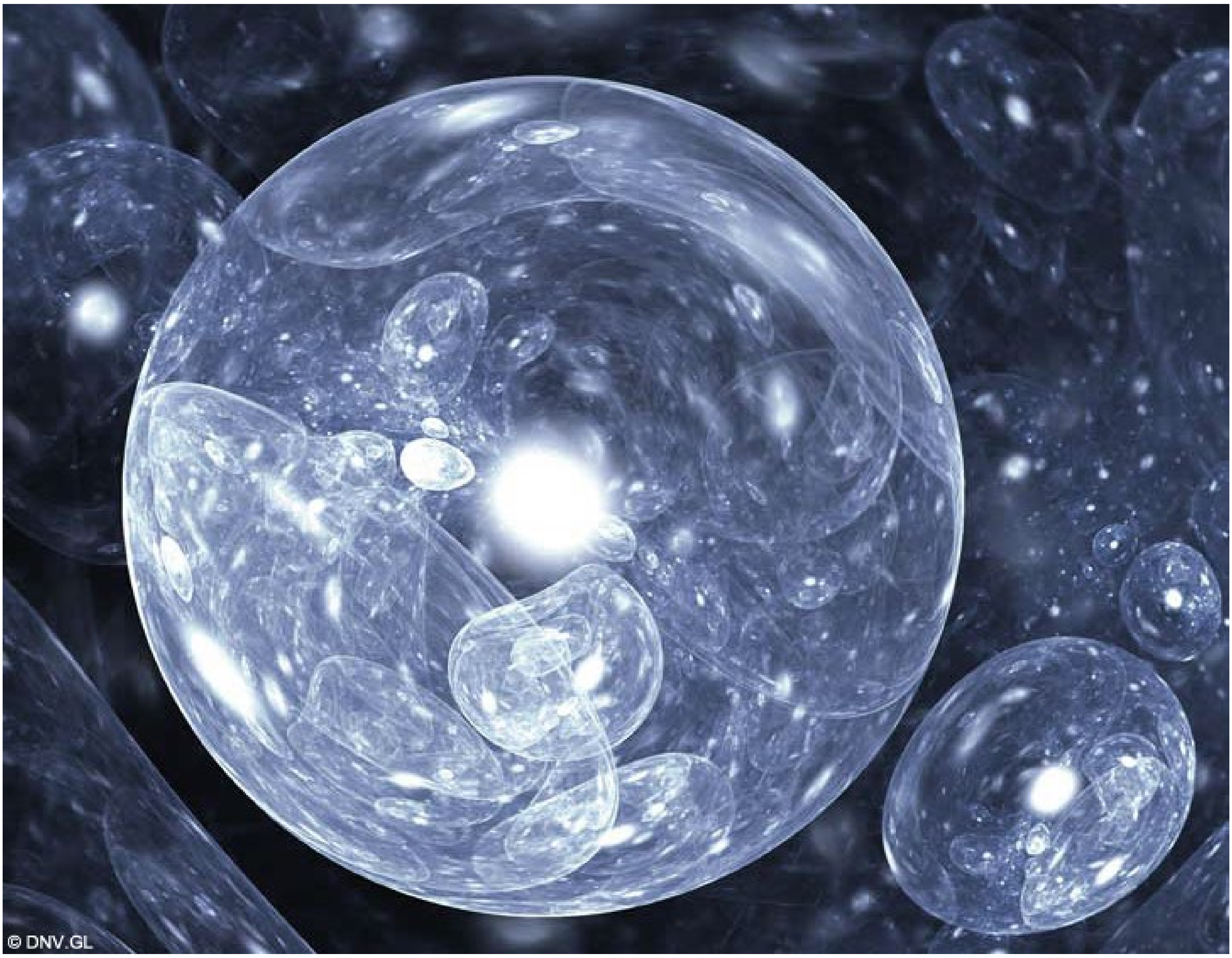

QAMAR ENERGY

HYDROGEN IN THE GCC

A REPORT FOR THE REGIONAL BUSINESS DEVELOPMENT TEAM GULF REGION

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1. EXECUTIVE SUMMARY

- GCC countries use large quantities of 'grey' hydrogen based on natural gas, about 8.4 Mt/year, or ~7% of the world total. Some of this may be suitable for retrofitting with carbon capture, use and storage (CCUS). Most hydrogen units exist as part of refineries, steel factories and petrochemical facilities. Gas-to-Liquids (GTL) represents an estimated 39% of H_2 consumption in the region, followed by oil refining (27%), ammonia production (21%), methanol production (9%) and steel manufacturing (4%).
- The GCC's ample low-cost land, low cost of capital, existing industrial capacity, excellent solar and (in places) wind resources, and geographical proximity to growth markets sets it in an excellent position to become a green hydrogen producer. Similarly its low-cost natural gas and ease of carbon capture, use and storage (CCUS) allow it to produce cost-competitive blue hydrogen.
- Currently, hydrogen production is not high on the agenda of oil and gas companies[1] in the region, but is rather the focus of utilities, power plant developers and industries. There is one advanced large-scale green hydrogen production project in the GCC, the US$5 billion, 237 000 tonne/year Neom Helios project in NW Saudi Arabia developed by Acwa Power and Air Products.
- Current costs of hydrogen production vary depending on the technology and region, which is projected to change in the long run. 'Green' hydrogen could become cheaper than 'blue' hydrogen as technology improves and carbon pricing is increasingly adopted. Green hydrogen costs are expected to fall from US$ 3.5-7.5/kg in 2020 to US$ 1.6-2.2/kg by 2030.
- Decarbonisation policies, particularly in Europe, pose a risk to the GCC's exports of hydrocarbons and energy-intensive materials. Hydrogen could be exported directly, and/or GCC states could export decarbonised materials made with blue or green hydrogen, such as ammonia, steel, glass, and fertilizers.
- The EU's potential carbon border tax could cut the profits from exports of oil, steel, and wood pulp by 10-65%, impacting both EU and non-EU producers of goods. GCC countries are considered amongst the most exposed and least resilient to an EU carbon pricing scheme. This could encourage increased production of H_2-derived materials to reduce the carbon footprint of energy-intensive materials exported to Europe.
- Global demand for green hydrogen is expected to grow rapidly in the medium term to 530 Mt, displacing 10.4 billion barrels of oil equivalent by 2050 or 37% of 2020's global oil production. This should urge Gulf countries to target low-carbon export products.
- Pipeline-transported H_2 is generally the most cost-effective method to transport large volumes over long distances, which can be done in pure form, or blended into natural gas, according to the local regulations or as contracted.
- However, while pipelines connect North Africa to southern Europe, there are no existing pipelines from the GCC to Europe. Liquid hydrogen transport is costly, while liquid organic hydrogen carrier's gravimetric density is low and the supply chain is complicated. The ammonia value chain appears the most practical and cost-effective approach to transporting GCC hydrogen over long distances, and this is the approach being pursued by NEOM.
- The GCC region has a number of suitably-located salt deposits in Kuwait, the Saudi-Kuwaiti Neutral Zone, UAE, and Oman, in which caverns could provide low-cost buffer storage of hydrogen.
- GCC countries have engaged in a number of R&D projects, including feasibility studies and pilot projects for blue and green hydrogen for different uses. However, more R&D investment needs to be allocated to strengthen technology expertise, drive cost reductions in electrolysis, create an infrastructure network and refine export business models.
- The GCC should (i) include the hydrogen economy in the revision of Nationally Determined Contributions (NDCs) for the Paris Agreement, due in late 2020, (ii) build EU-GCC collaboration on technologies and co-ordination on harmonising regulations and standards, (iii) develop carbon pricing mechanisms, and/or links to other carbon pricing schemes including the European ETS, to encourage hydrogen use and boost demand, hence creating business opportunities to expand the H_2 market.
- Given the early stage of the industry, EU companies interested in GCC hydrogen will have to initiate and develop projects themselves, most likely in partnership with large Gulf state energy companies and strategic investment vehicles. At the same time, they should promote supportive policies and awareness-building.
- Europe's hydrogen strategy mainly focusses on green hydrogen. However, to meet its goals practically, it will require large quantities of lower-cost blue hydrogen at least in the medium term. GCC National Oil Companies (NOCs) can target this European market, but need to engage to achieve supportive regulations and pricing for low-carbon material exports.
- On the side of green hydrogen, GCC governments and their state utilities and industries can propose the creation of a downstream project from generation plant (electrolyser) and create hydrogen-derived materials (likely ammonia and steel) for export, in which EU entities will be the exclusive off-taker (captive demand).

[1] Although ADNOC plans to invest in hydrogen to expand its clean energy portfolio, while Aramco sent the world's first shipment of blue ammonia to Japan in September 2020.

2. THE HYDROGEN VALUE CHAIN

2.1 H_2 IS A KEY CONTRIBUTOR TO THE ENERGY TRANSITION

The landmark Paris Agreement of December 2015, ratified by parties to the UN Framework Convention on Climate Change (UNFCCC), saw the emergence of broad, politically-backed climate mitigation policies to limit global temperature increase to below 1.5°C[2], and achieve net-zero greenhouse gas (GHG) emissions by 2050. Progress under the consequent 190 nationally-determined contributions (NDCs)[3], however, has been unequal, with some world players struggling to implement effective climate policy instruments with stringent, achievable targets. The US has exited the framework altogether. Europe has emerged as a frontrunner in measures to tackle climate change, with its political landscape now strongly backing tighter emission reduction targets for 2030 and 2050. The Gulf Cooperation Council[4] (GCC) countries' NDCs are not yet very specific or stringent.

Interest in an integrated, hydrogen economy is emerging, with hydrogen being recognised as a key contributor to the global energy transition. The EU established an ambitious hydrogen strategy which requires both substantial H_2 deployment and imports from regional and international markets to be able to achieve its 2050 net-zero carbon target and hydrogen strategy by 2030. This, however, comes with policy, cost and infrastructure-related issues.

According to EU policymakers, green hydrogen is considered an essential tool to decarbonize the industry and transport as Europe seeks to achieve a net-zero carbon economy by 2050. A cluster of European governments, including Germany, France, the Netherlands, Belgium, Switzerland, Austria and Luxembourg, prefer that green rather than blue hydrogen should be the predominant part of supply, certainly in the longer term. The EU hydrogen strategy was published in July 2020, setting a target of 40 GW of electrolysers installed within its borders by 2030 and another 40 GW of capacity imported from international producers, mainly North Africa. [5]

While achieving the EU hydrogen strategy might be a challenging task that needs scaling up on the production as well as the demand side simultaneously and requires an infrastructure in place, Europe's heavy industry already consumes millions of tonnes of H_2 per year, mostly produced from natural gas and coal. **Some of the challenges facing Europe's hydrogen target are the capital costs for production** which is estimated by Barclays to reach US$ 500 B for green and blue hydrogen. Therefore, governments need to introduce incentives to facilitate the transition to green hydrogen use. These include quotas for its use in industry, or mechanisms, like a carbon contract for difference. While laying out the EU hydrogen vision is one thing, implementing it at the national level is another, constituting the main barrier to the EU's emissions goal.

Yet, the major challenge is that of hydrogen infrastructure, which is currently almost non-existent and could double the last figure to US$ 1 trillion. According to Wood Mackenzie, European companies announced 9.4 GW of green hydrogen projects, mostly due onstream by 2030. However, analysts assume some projects will fail, implying that 2-3 times as many are needed to reach the EU's targeted 6 GW of capacity by 2024. Achieving the EU 2040 target would require 20-30 GW of projects to be in the pipeline by early 2021 taking into consideration the 20-30% typical success rate for large infrastructure development projects. Yet, hydrogen has the advantage of being a replacement that can use existing infrastructure as well. 11 EU gas infrastructure companies, including Spain's Engas, the Netherlands' Gasunie and Italy's Snam, have announced plans for a 6,800 km hydrogen pipeline network by 2030, rising to 23,000 km by 2040, 75% of which consist of converted gas pipeline.

In the Middle East, hydrogen is gradually gaining awareness as a way for leading hydrocarbon producers to continue utilising their resources in climate-friendly ways, and widen their export markets. Hydrogen production in the Middle East could potentially be more cost-competitive than in other regions, such as the EU, China, Japan, and Australia, due to available low-cost renewables and integration with lower-cost carbon capture technologies (CCUS[6]). Hydrogen began gaining momentum as a scalable alternative to fossil fuels over the last two years, attracting growing interest from both supply and demand sides.

[2] Over pre-industrial levels
[3] Nationally Determined Contributions (NDCs) are intended to meet the goals of the Paris Climate Agreement, December 2015
[4] Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and United Arab Emirates
[5] European Commission
[6] Carbon capture, use, and storage/sequestration (CCUS). Refers to the capture of carbon dioxide and its use (typically in industrial processes), conversion to solid minerals or permanent storage in geological formations underground, including for enhanced oil recovery (EOR).

Our research indicates that even though 2019 is the likely peak of worldwide carbon dioxide (CO_2) emissions, primarily due to pandemic-led lockdowns in 2020, global GHG emissions in 2020 shall reduce only by 4-7%[7], significantly lower than the UNFCCC's stipulated ~8% annual reduction in emissions to 2030. Renewable energy use has grown quickly in recent years, and gas has replaced coal in markets including the US, UK, and now increasingly India and China, reducing emissions from the power, heating and industrial sectors. In sectors such as industry and long-distance transport, renewable integration remains niche, and low-carbon technologies expensive and immature, meaning emissions from these continue to rise. Hydrogen is one of the few near-term viable technologies to decarbonise such sectors at scale and speed.

Regions with large energy sources typically also have large industrial sectors. Some, like Australia (coal and solar) and the Gulf Cooperation Council (natural gas and renewables) in the Middle East, are coming to see hydrogen as the link between economic growth and net-zero emissions. As decarbonised energy production grows, transferring it to meet rising primary energy demand, while maintaining the quality of energy services provided, will require a reliable energy carrier that can cross-cut across every energy sector. Hydrogen, including electricity-integrated hydrogen[8], can fill this gap. Estimates for how much of world energy demand the "hydrogen economy" can meet, vary. According to the International Renewable Energy Agency's (IRENA) Renewable Energy Roadmap (REmap), hydrogen shall make up 6% of total final energy consumption by 2050[9]. The Hydrogen Council, however, is more aggressive, and estimates hydrogen to supply 18% of world energy demand by 2050[10]. Current pure hydrogen demand, according to the IEA[11], is about 70 million tonnes (Mt), while global annual demand for hydrogen in all forms (mostly, hydrogen as a component of syngas along with carbon monoxide and other gases) is ~120 Mt (2018e).

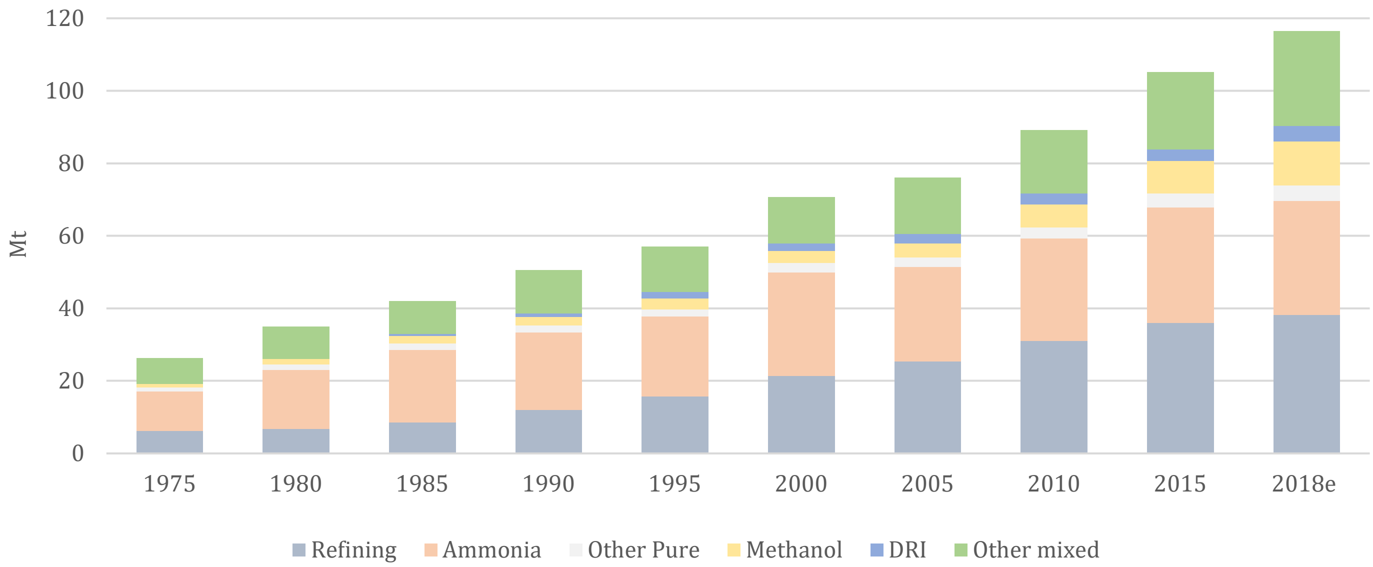


Figure 1 Global annual demand for hydrogen[12]

Current global demand for hydrogen:

- is equivalent in energy content to about 353 billion cubic metres (BCM) of natural gas;
- is ~9% of the size of the natural gas market in 2018;
- consists of 70 Mt of pure hydrogen consumption in 2018 from fossil fuels;
- is produced using 6% of global gas and 2% of global coal;
- results in emissions of around 830 MtCO_2e, about 2.7% of world energy-related CO_2 emissions (Figure 2). Other, low carbon footprint production routes exist, but these are immature or not yet commercially developed on a large-scale.

[7] Le Quéré et al., "Temporary Reduction in Daily Global CO2 Emissions during the CoVid-19 Forced Confinement", Nature Climate Change, 10, 647-653, 19 May (2020)
[8] Hydrogen generated from water electrolysis and used as a storage medium for electricity
[9] IRENA, "Hydrogen: A Renewable Energy Perspective", September (2019)
[10] Hydrogen Council (2017)
[11] International Energy Agency
[12] IEA, "The Future of Hydrogen", June (2019)

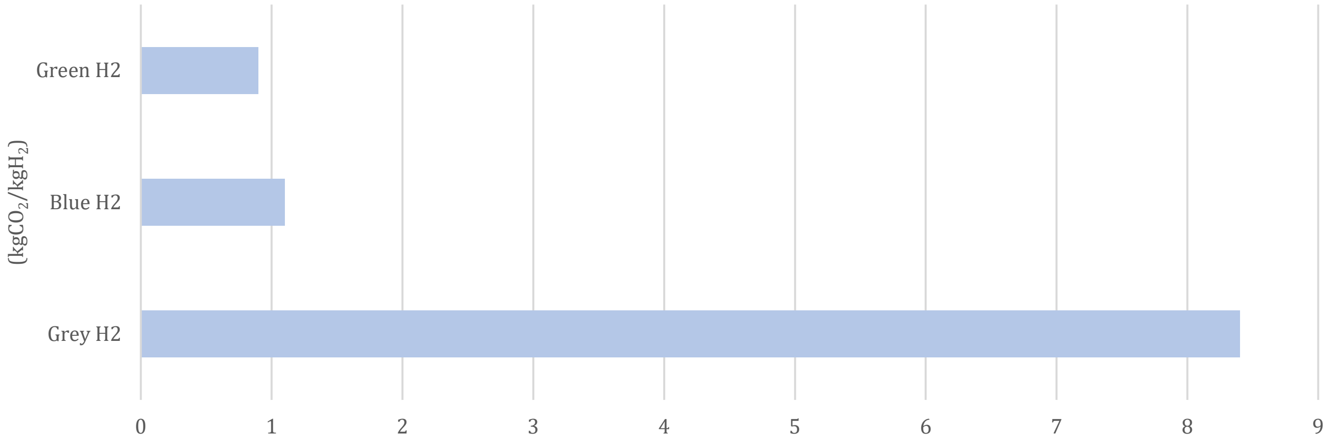


Figure 2 CO_2 emissions per technology[13]

Hydrogen has multiple production routes:

Globally, 95% of current hydrogen production is via steam methane reforming (SMR) with natural gas as a feedstock, or through the gasification of coal. The key challenge in scaling up hydrogen production to a level where it can fuel regional economies is the high level of 'clean' hydrogen production costs. SMR without CCUS (or 'grey' hydrogen) is the cheapest, and therefore the most used for hydrogen production. Demand for pure hydrogen, that is, for refining, ammonia, and transport, is typically supplied from dedicated hydrogen production facilities, meaning that hydrogen is their primary product. Therefore, production methods at such facilities are the simplest to replace with alternative sources of low-carbon hydrogen.

Current SMR or autothermal reforming (ATR, a combination of SMR and partial oxidation) can be combined with CCUS to produce 'blue' hydrogen, which drastically reduces emissions, only slightly higher than 'green' hydrogen produced via electrolysis with renewable energy sources (0.9 $kgCO_2e/kgH_2$)[14]. The future of the hydrogen economy is expected to concentrate on 'green' hydrogen, even though 'blue' hydrogen is a natural fit for large oil and gas producers worldwide, and especially in the Gulf region.

Feedstock	Route	Process	Product
Natural Gas	Reforming	Separation with CCUS	Fuel Cell Grade H_2
Coal	Gasification	Separation with CCUS, Purification	
Renewables	Electrolysis	Purification, Compression	
Nuclear	Electrolysis	Thermochemical pyrolysis	

Table 1 Routes for low-carbon hydrogen production[15]

Hydrogen has multiple advantages that support its production from low-carbon technologies. The fuel is light, storable, reactive, and has high energy content per unit mass (39.4 kWh/kg, three times that of traditional liquid hydrocarbons, 13.1 kWh/kg). This means it can be readily produced at industrial scale. It can also be stored for long periods of time with minor losses, making it a storage medium for renewable energy, which can balance the intermittency of renewable power generation. When combusted, it yields only water. However, its low density as a gas and small molecular size requires heavy containment methods.

[13] CE Delft, "Feasibility Study into Blue Hydrogen: Technical, Economic, & Sustainability Analysis", July (2018); ICIS.

[14] Depending on the nature of renewable energy used; renewables generally do not emit greenhouse gases during use, but they have life-cycle emissions, for instance from producing the input steel and cement. This will fall as the energy system generally is decarbonised.

[15] Qamar Energy Research

3. BLUE HYDROGEN IS A NATURAL FIT FOR GCC OIL PRODUCERS

Table 2 The GCC has advantageous factors to support the uptake of 'blue' hydrogen, but interest remains low

Factor	Advantage for 'Blue' Hydrogen
Large, low-cost natural gas	The GCC is one of the largest and lowest-cost producers of natural gas in the region. Qatar has 24.7 trillion cubic metres (TCM) of proved natural gas reserves, the third largest worldwide, while Saudi Arabia (6 TCM) and the UAE (5.9 TCM) hold the ninth and tenth largest, worldwide, respectively. Natural gas production costs in Qatar are around US$ 1.2/MMBtu, and in the UAE average ~US$ 2/MMBtu, due to higher hydrogen sulphide content.
H_2 Production Facilities	Energy-intensive industries, like ammonia and methanol production and steel manufacturing, including existing hydrogen production facilities, in the GCC are often already concentrated in clusters, typically coastal, along with power and desalination plants. These include fertilizers such as SABIC in Saudi Arabia, FERTIL in the UAE, QAFCO in Qatar, PIC[16] in Kuwait, and OMIFCO in Oman; steel manufacturers like UAE's Emirates Steel, Saudi Hadeed, Bahrain's SULB, Shadeed DRI in Oman, and Qatar Steel; and methanol plants including Saudi Methanol and Ar-Razi, Qatar's QAFAC, Oman Methanol and Salalah Methanol. These can be ideal centres to expand the use of CCUS to create hydrogen, with CO_2 sent to nearby oil fields for enhanced oil recovery or further industrial use.
CO_2 Storage	GCC hydrocarbon producers have significant CO_2 storage capacity. Considering voided spaces in oil and gas fields only, storage capacity is 33.4 $GtCO_2e$, half of which is concentrated in Saudi Arabia. Much larger additional storage space is available in deep saline formations. The Gulf's geology is well-understood and characterized through decades of hydrocarbon exploration, has short source-sink distances, and regionally-extensive high-injectivity reservoirs with effective seal rocks. CO_2 storage enjoys high public acceptability in the region. Emissions from point sources available for capture (2019-2050) are 35.8 $GtCO_2e$, meaning the region would still have spare storage capacity if 100% of point-source CO_2 were captured, including emissions from hydrogen SMR.
Existing Infrastructure	GCC producers have well-developed existing natural gas grids, which could be potentially be modified for transporting hydrogen (or other alternative fuels, like biomethane or synthetic methane) in-land for domestic purposes. This may be preferable to full electrification, which would likely require reinforcement of local distribution grids to meet peak loads.

Hydrogen costs vary from one region to another:

Current costs for SMR without CCUS vary widely. In the US and Middle East, costs at industrial scale are as low as US$ 0.9/kgH_2 produced. Costs in Europe are double, at around US$ 1.8/kgH_2 produced, mostly because of higher natural gas prices. Rising gas prices means that production costs for 'grey' hydrogen shall also increase. This is a problem in much of Asia, where liquefied natural gas (LNG) prices are mostly oil-linked, typically to average Brent crude prices of the previous three months.

The inclusion of CCUS raises the required natural gas input by about 10%, and the overall cost of the produced hydrogen by about 35-50%, or about US$ 0.5/kg. Therefore, 'blue' hydrogen can cost US$ 2.3/kgH_2 produced, equivalent to about US$ 18.2/MMBtu of natural gas, which is rather exorbitant in current terms (with spot LNG around US$ 4/ MMBtu in August 2020), but within the upper range of historic gas and LNG prices, particularly including a premium for its zero-carbon characteristic. With SMR emissions around 8.4 $kgCO_2e/kgH_2$, the cost premium for blue over grey hydrogen equates to a carbon price of about US$ 60/tonne, above current EU emissions trading system (ETS) levels of € 25/tonne (~US$ 29/tonne), but within the range of anticipated future carbon prices, which Reuters forecasts at about € 50/tonne (US$ 59/tonne) by 2030[17].

In the medium-term, regional oil and gas producers can take advantage of 'blue' hydrogen to kickstart their decarbonisation drives. However, interest in the Middle East for this type of hydrogen remains low, as can be seen in Figure 3 which suggests the majority of near-term growth in North America, then later Europe and Asia-Pacific, even though industry players acknowledge its pivotal role as a viable offramp from fossil fuels to zero-carbon energy.

[16] Petrochemical Industries Company K.S.C. (PIC)
[17] https://ec.europa.eu/clima/sites/clima/files/docs/0094/thomson_reuters_point_carbon_en.pdf

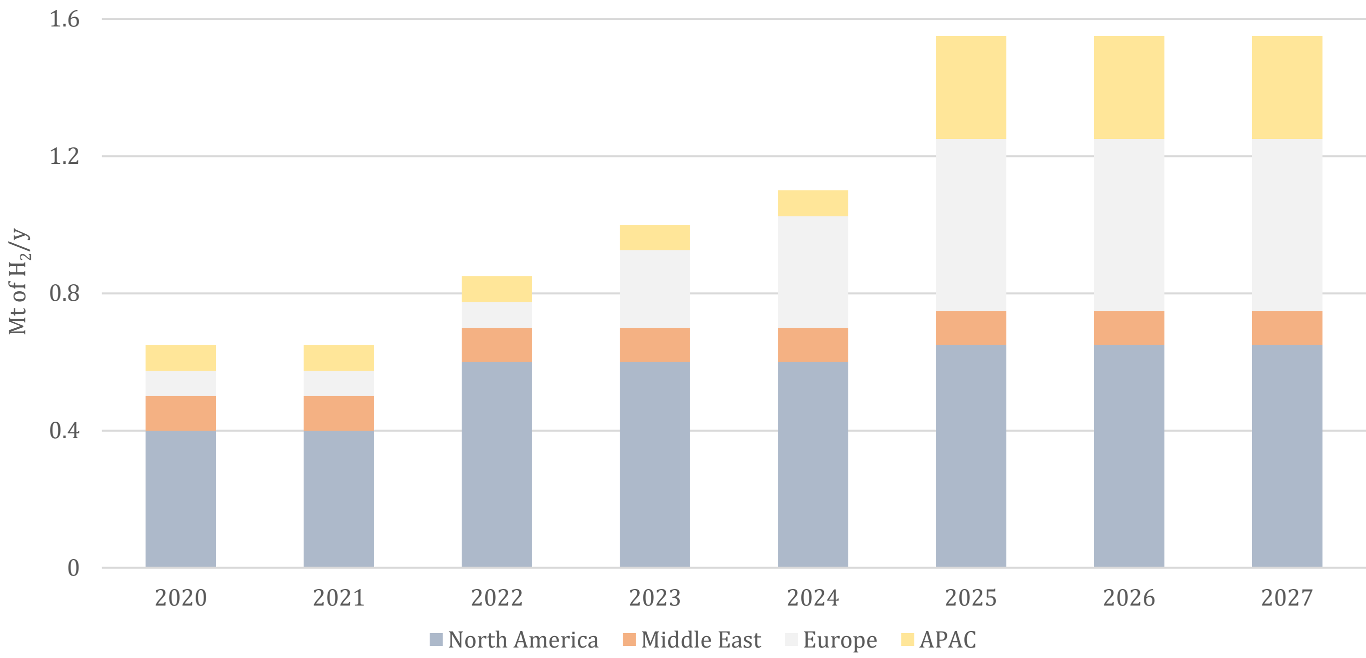


Figure 3 Medium-term 'blue' hydrogen production capacity by region[18]

Critics of 'blue' hydrogen in the region believe that CCUS is still expensive, due to the costs associated with expanding CO_2 pipeline and storage infrastructure, especially due to moderate-size demand for CO_2 in the long-term. For example, according to our research, industrial CO_2 demand in the GCC could reach 22.5 Mt by 2035, compared to EOR demand of ~48 Mt. Capture volumes, however, can range from 94 Mt in the medium-case to 148 Mt in the high-case, due to a large number of densely concentrated and large point emission sources. This means at least 23-78 $MtCO_2e$ per year requires sequestration, or export/alternative uses, which are currently lacking. Capture costs from hydrogen plants are likely to be relatively low and mostly related to drying and compression. Steel production's estimated capture costs are US$ 65/tonne and for fertilisers (ammonia) are US$ 24/tonne[19]. CO_2 transport by pipeline over short distances would be cheap, an estimated US$ 0.44/tonne[20]. Current CO_2 storage in geological subsurface costs between US$ 0.4-20/tCO_2e[21], depending on site-specific factors such as onshore versus offshore, reservoir depth, and geological characteristics.

Saudi Arabia has large flat deserts, well-characterised by multiple giant storage formations, which means storage costs would fall on the lower end of the cost spectrum. Fields in Qatar are mostly offshore, with somewhat higher storage costs but no community issues; there may be available onshore saline formations. Reservoirs in Oman are geologically more complicated, but also in remote areas with little population. The UAE has a range of storage sites offshore and onshore in little-populated desert areas. Kuwait and Bahrain tend to have more complex geology or inhabited by urban/rural populations due to smaller geographical size, which could face community resistance and urban area loss. Storage at these sites would be costlier. At rough estimates, therefore, a 0.24 Mt/year blue hydrogen plant using natural gas (equivalent in size to the Neom green hydrogen plant) would produce about 1.3 Mt/year of CO_2, costing from US$ 0.13-0.36/kg of hydrogen for CO_2 capture, and US$ 0.007- US$ 0.03/kg of hydrogen for CO_2 storage and monitoring. Alternative uses of CO_2, meanwhile, are currently extremely limited in the GCC, but could include manufacture of synthetic fuels, CO_2-enhanced cement, soda ash, and various plastics and polymers to support high capture volumes in future. Inadequate progress on developing viable use/storage for captured CO_2, therefore, hinders the popularity of 'blue' hydrogen.

Retrofitting existing hydrogen production facilities with CCUS is also complex. For instance, in the EU, it is estimated that integrating H_2 plants with CCUS technology would require at least US$ 13 B[22]. Similar cost estimates for the GCC do not exist, because 'dedicated' hydrogen plants are few. Regardless, even with the lower cost of natural gas, the inclusion of CCUS into traditional SMR will raise required gas input by ~10%, and the overall cost of the produced hydrogen by 35-50%. Moreover, hydrogen production with CCUS units (either

[18] S&P Global Platts Analytics' Hydrogen Market Monitor
[19] https://www.globalccsinstitute.com/archive/hub/publications/201688/global-ccs-cost-updatev4.pdf
[20] https://kilthub.cmu.edu/articles/journal_contribution/Models_of_CO2_Transport_and_Storage_Costs_and_Their_Importance_in_CCS_Cost_Estimates/6073220/files/10942655.pdf
[21] ICF International, "Analysis of the Costs and Benefits of CO2 Sequestration", September (2012)
[22] Angeli Mehta, "Overcoming Hydrogen Hype", Royal Society of Chemistry, 18 August (2020)

solvent-based or membrane-based) consumes electricity, which could otherwise be exported to the grid. If 'blue' hydrogen can mitigate CO_2 emissions from traditional SMR processes, focus on developing a sophisticated renewable hydrogen infrastructure and introducing 'clean' hydrogen shall diminish. If 'blue' hydrogen doesn't pick up, valuable time to support the energy transition is lost. This can become a significant risk. EU and particularly German policy so far has expressed a strong preference for green hydrogen in the long-term, while Japan is more open to both blue and green.

4. GREEN HYDROGEN POTENTIAL IS YET TO BE UNLOCKED

Globally, less than 0.7% of current hydrogen production is from renewables or from fossil fuel plants equipped with CCUS. The key reason is unattractive economics. Estimates for producing hydrogen from renewable electricity vary widely. Costs depend on the process used, its own costs, the cost of input electricity, the lifetime of the electrolyser, and its load factor. Currently, water electrolysis is the only feasible method for large scale H_2 production without any CO_2 emissions. It consists of splitting the water molecule into hydrogen and oxygen through direct electric current ($2H_2O \rightarrow 4H_2 + O_2$). This technology is mature and well established, producing high purity H_2 needed for fuel cell applications, and has a high energy efficiency (above 70%). In recent years, installed electrolyser capacity has considerably increased from less than 1 MW in 2010 to more than 25 MW in 2019 (Figure 4). Project size has also increased significantly as most projects in early 2010 were below 0.5 MW, while between 2017 and 2019 the largest were 6 MW and others between 1-5 MW[23]. The installed capacity in the GCC currently is about 1.25 MW from the Siemens-DEWA pilot project in Dubai, discussed below,

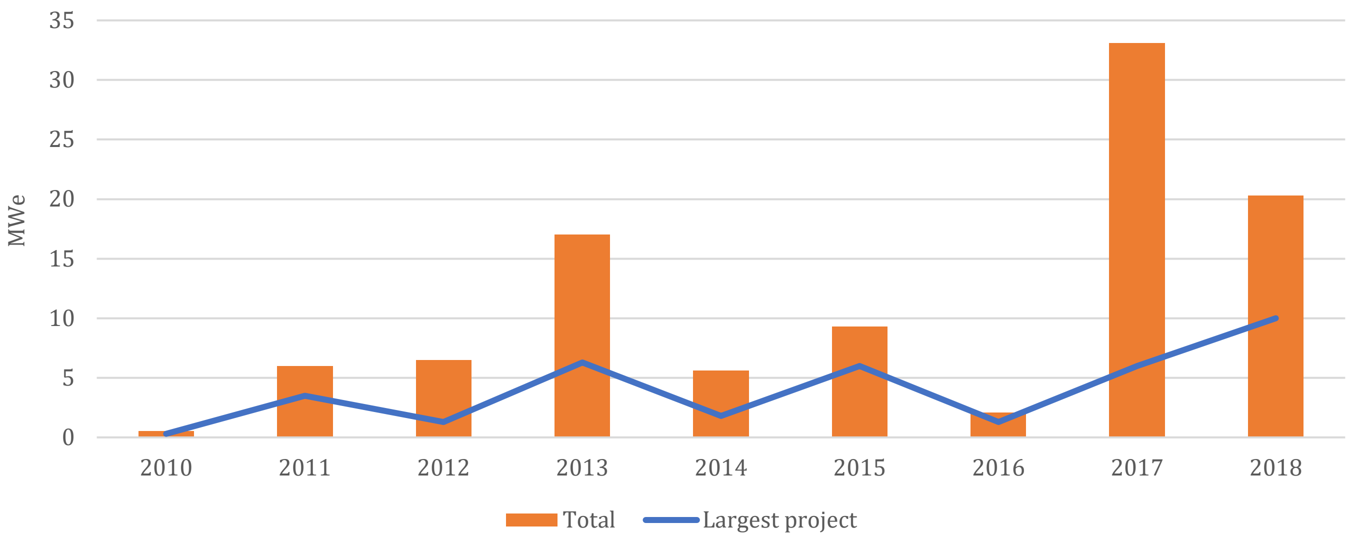


Figure 4 Global annual installation of electrolyser capacity, 2010-18

There are three main types of electrolyser: alkaline, polymer electrolyte membrane (PEM), and solid oxide (SOEC). Alkaline electrolysis is most mature, PEM is generally expected to be the main future system, while SOEC is still technologically immature but has the potential for high efficiencies. In general, a high load factor is required to offset the high capital cost of the electrolyser, though this would become less important as electrolyser costs fall with experience and technology improvements. On the other hand, cheap electricity is needed (and is more important for lower-efficiency electrolysers). But very cheap electricity from solar or wind in good locations is still intermittent, reducing the achievable load factor. At times of lower renewable generation, it may also be more profitable to sell electricity to the grid (in the case of grid-connected projects). This leads to a complex set of trade-offs, which may favour different systems in varying situations. Electrolyser systems used in water electrolysis currently have an efficiency of 60-81% and require around 9 litres of water to produce 1 kgH_2. Freshwater access can become an issue in water-scarce or water-stressed areas, meaning desalinated seawater will likely be required in the Gulf. Current electrolysers require desalinated water, though new generations are under development that could work with salt water.

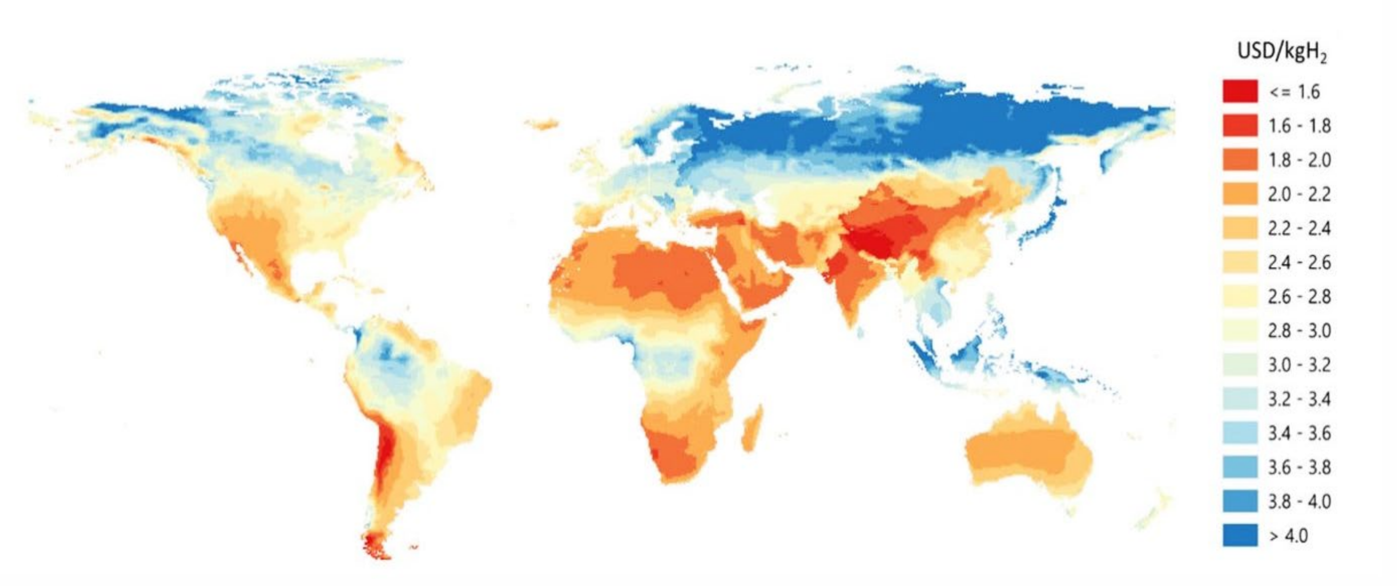
[23] IEA

Table 3 Green H_2 costs and potential reductions[24]

Technology	Cost (US$/kg$H_2$)	Load factor (%)	Potential cost convergence (US$/kg$H_2$)	Green H_2 Cost reduction factors
PEM	4.2-5.2	30	2-3> blue H_2 cost (US and Middle East)	- Large-scale deployment - Improvements in the scale of operation and load factors - Cheaper RE electricity inputs could reduce overall H_2 cost by US$ 0.5-0.7 kgH_2 by 2040. - Carbon policies or ETS schemes to make natural gas pricier, implying that blue could become more expensive than green H_2 - Elimination of energy subsidies - Extensive investment in green H_2 R&D
SOEC	18	30		

As Figure 5 shows, the GCC countries are projected to be among the lowest-cost regions in the world for green hydrogen production – particularly in NW Saudi Arabia and SE Oman, due to their very high direct normal irradiance and wind speed (>8 m/s). The GCC relies on desalinated water for its needs, which is relatively expensive, but water is only a small fraction of hydrogen production costs; in addition, certain electrolysers can run on saline water. There are other good locations though, including much of North Africa, SW Africa, Chile, the south-western US, Mexico, western China and NW India, indicating this could be a competitive market and the GCC does not have a unique advantage. Furthermore, the high transport costs of hydrogen will tend to offset low production costs for more distant markets.

Figure 5 Hydrogen costs from renewable energy (hybrid solar PV and onshore wind systems) in the long-term[25]



[24] Qamar Energy Research
[25] IEA, "The Future of Hydrogen", June (2019)

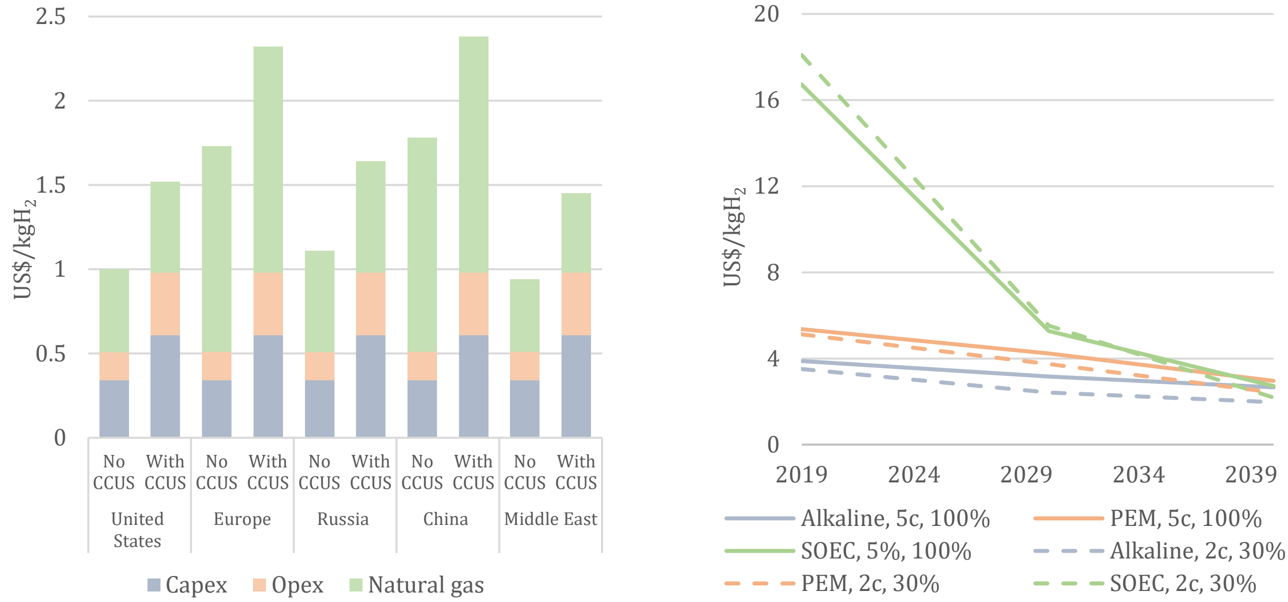


Figure 6 Hydrogen production costs using natural gas[26] versus hydrogen production costs using electrolysis[27]

5. HYDROGEN TRANSPORT OPTIONS IN THE GCC

Whether blue or green, the preferred option for transporting hydrogen depends mainly on the application, while the lowest-cost option depends on the state of hydrogen. H_2 can be transported and stored in pure form or as an intermediate energy carrier (Figure 7).

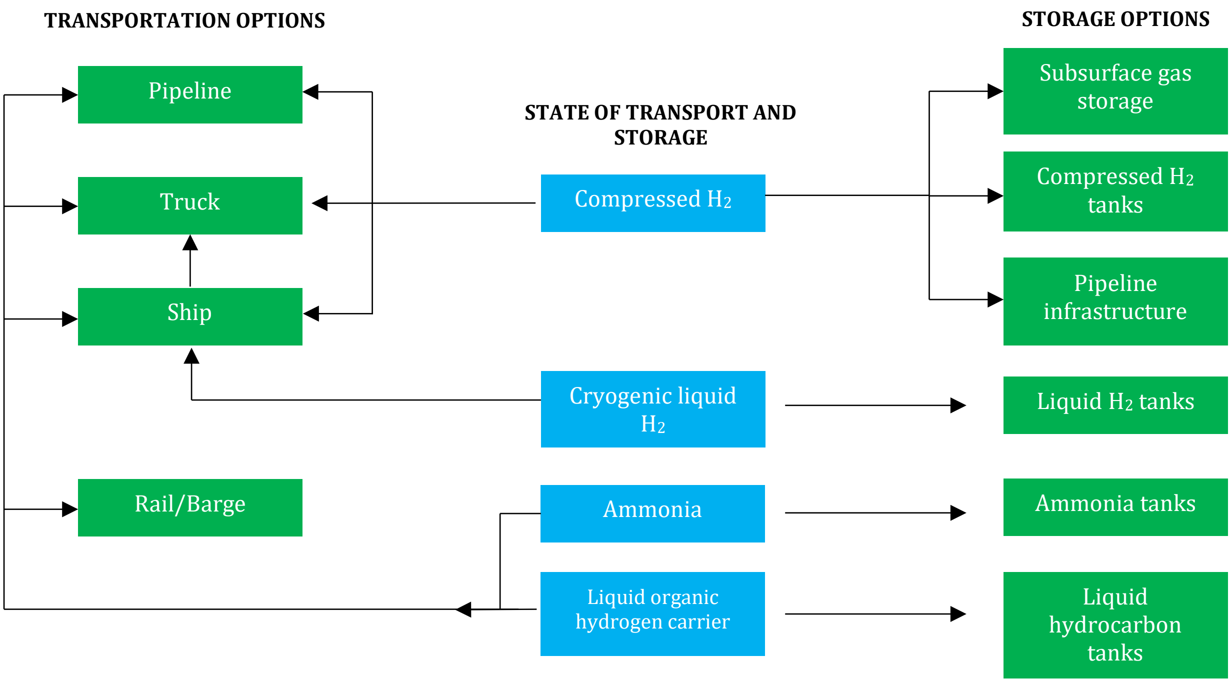


Figure 7 Main options for H_2 storage and transport[28]

[26] IEA, "The Future of Hydrogen", June (2019)
[27] Qamar Energy Research
[28] DNV

GCC countries can export hydrogen to Europe in a relatively low-cost way as ammonia, since pipelines to transport compressed gaseous hydrogen (CGH) between the two regions are currently non-existent and liquefied hydrogen (LH) transport is costly, while liquid organic hydrogen carriers (LOHC)'s gravimetric density is low.[29] In 2017, the GCC countries produced 30 Mt of ammonia and urea, 90% of which was exported. The Netherlands' study of Power-to-Ammonia (2017) confirmed that if cost-effective renewable energy (RE) is available, ammonia produced with electrolysers and air separation units would cost € 270-370 / tonne, compared to the traditional SMR process to produce ammonia at € 300-350 / tonne. Due to the low solar electricity cost in the GCC, green ammonia could be produced in a cost-competitive way.[30] A professor at a Netherlands university suggested a hydrogen pipeline from Saudi Arabia/Egypt to Greece, but this would still be expensive and politically complicated. Pipelines have the disadvantage of requiring large scale to be economic, while hydrogen will initially be a small business with an uncertain future that will have to build up sequentially.

LH's transport and storage are found to have a high cost partly due to high energy losses from liquefaction and high cost of hydrogen ships (Figure 8). CGH's and ammonia's transport and storage costs are similar, but the cost components vary. For ammonia, the major cost components are synthesis and reforming, whereas the main cost components in the CGH value chain are the hydrogen pipelines and storage tanks. Transportation of ammonia is relatively easy because it becomes a liquid at -33°C or moderate pressure of 862 kPa (about 8.5 atmospheres) and can be shipped in a standard refrigerated gas carrier, a much less demanding requirement than for liquefied hydrogen (-253°C temperature or 25 MPa / 250 atmospheres pressure) or liquefied natural gas (-160°C). Ammonia is also regularly transported by pipeline. However, if the desired end-product is hydrogen, not ammonia, the ammonia has to be decomposed to hydrogen at high temperatures, adding significant costs.

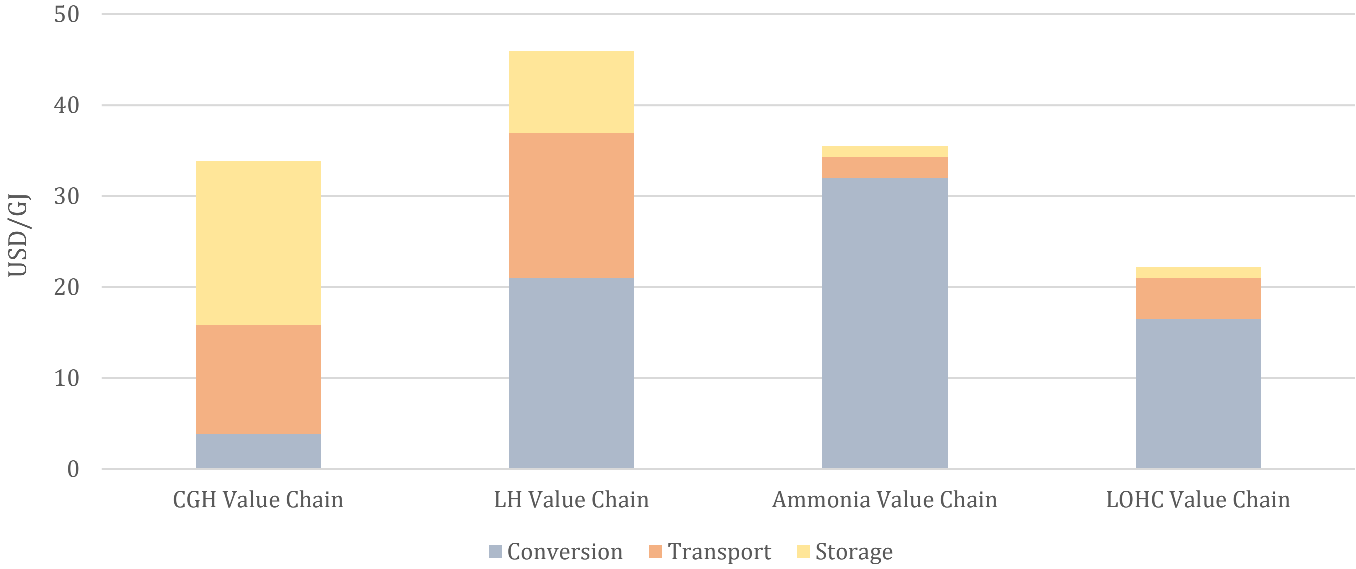


Figure 8 Global cost of energy penalty from four hydrogen value chains

[29] LH's transport and storage are found to have a high cost partly due to high energy losses from liquefaction and high cost of hydrogen ships. Compressed gaseous hydrogen (CGH) and ammonia's transport and storage costs are similar, but the cost components vary. For ammonia, the major cost components are synthesis and reforming, whereas the main cost components in the CGH value chain are the hydrogen pipelines and storage tanks.

[30] Revolve Media

6. HYDROGEN STORAGE OPTIONS IN THE GCC

In terms of storage, subsurface salt caverns can provide low-cost buffer storage of hydrogen. The GCC region has a number of evaporite deposits including flat bedded and relatively deep Gotnia (Jurassic) salt in Kuwait and the Saudi-Kuwaiti Neutral Zone, the Hormuz salt of Eocambrian age in deposits in the UAE and Oman, and Miocene salt in Kuwait and the UAE. Oman has three Hormuz salt basins, the South Oman Salt Basin, the Ghaba Salt Basin and the Fahud Salt Basin, all bordered to the north by the thrust front of the Oman Mountains. The area of the northern salt domes is linked by gas and oil pipelines to the northern shore next to Muscat, where there are an oil refinery and an LNG terminal. However, the potential for storage is low given the long-distance of terminals/refining capacities. The UAE's Jebel Dhanna structure is covered by residues of the salt sequence several hundred metres thick due to dissolution. The structures are partially commercially used and provide raw material for infrastructure, chemistry and agriculture. They are already being used for storage purposes and would make an excellent buffer for hydrogen. Jebel Dhanna is close to the Ruwais refinery and petrochemical centre and also hosts Abu Dhabi's main oil export terminal (Figure 9) which is being upgraded to allow new range of crudes to the refinery and will be completed in 2023, increasing pipeline capacity by 30%. This indicates excellent infrastructure that can be used as a hydrogen buffer storage, which can make the CGH value chain less expensive for the GCC region.

7. HYDROGEN APPLICATIONS

While hydrogen is mostly used for carbon-intensive industrial applications such as refining, ammonia and methanol production, the gas is expected to play a role in transport applications where electrification is most difficult, which can pave the way for aviation and maritime synthetic fuels manufacturing. In 2018, the GCC consumed the energy equivalent of 8.1 Mt of hydrogen in marine bunkers and 5.5 Mt of hydrogen in international aviation.

Hydrogen use in the GCC's transport sector is likely to grow as the UAE and Saudi Arabia have shown interest in hydrogen mobility by testing fuel cell electric vehicles and building a few fuelling stations. International initiatives towards reducing CO_2 and sulphur emissions will also push heavy fuel oil and marine gas fuel out from the shipping industry to allow cleaner alternatives like LNG, ammonia and maybe hydrogen. This is likely to take place in the UAE, home to the world's second-largest bunkering port, Fujairah Terminal, the storage of which will be expanded by 42 million barrels by 2022. The UAE also plans to invest a new 250 kb/d Fujairah refining complex to produce low sulphur fuel oil that complies with the IMO's 0.5% rule. Decarbonised air travel will be increasingly important for the region's air hubs in Dubai, Abu Dhabi and Doha, and for the GCC's travel and tourism industry, but hydrogen aircraft are a long-term prospect. Synthetic kerosene made from captured carbon dioxide with hydrogen may be a medium-term option.

H_2's industrial applications include metalworking, flat glass production, electronics, and applications in electricity generation. According to DNV, demand for H_2 as an industrial feedstock will keep growing from about 55 Mt/y today to 69-114 Mt/y in 2050, with the iron and steel industry expected to begin using the gas in direct iron reduction adding 4-11 Mt/y of H_2 consumption by 2050. H_2-fuelled heating is expected to be established in industries like cement and aluminium by 2050. The GCC will take a major part in the future industrial use of hydrogen given its diversification plans, which are likely to be accelerated as a result of CoVid-19's oil demand and price destruction. Hydrogen could be used in ammonia, methanol, steel, food and glass production, and possibly cement and aluminium. Since other decarbonization options are more mature and simpler, hydrogen might not see large-scale use for industrial process heating by 2030. Space heating and cooking could be the major applications of hydrogen in regards to residential end-use, but not in the GCC as electrification is more cost-effective at the moment, with H_2 residential demand expected to grow in the US, Western Europe, China and Russia at 2.6 Mt, 4.1 Mt, 0.9 Mt, and 0.7 Mt, respectively by 2030.[31]

Figure 9 Jebel Dhanna salt dome (dotted line) with infrastructure (tank farm, refinery, export terminal)

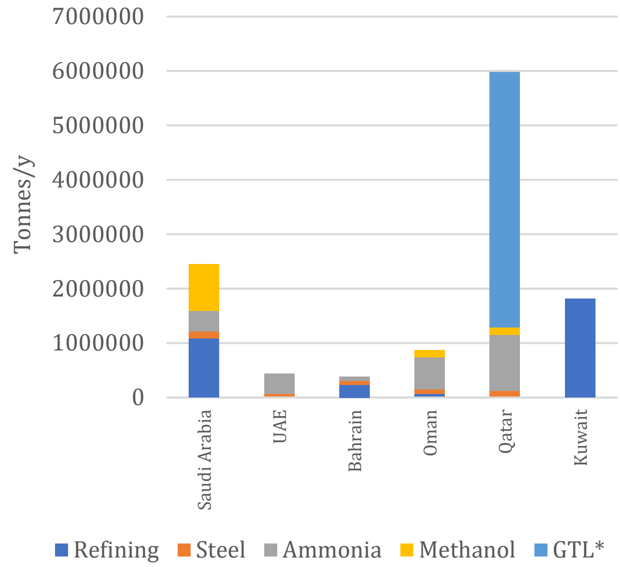
Hydrogen as a long-term seasonal electricity storage may not be required in the GCC as solar and batteries fit well with seasonal demand patterns, which have high summer consumption for air-conditioning. The region has almost no use of pipeline natural

[31] IEA

gas for residential and commercial distribution, and therefore does not have the option of hydrogen blending being explored in Europe.

8. OVERVIEW OF HYDROGEN DEVELOPMENTS IN THE GCC REGION

GCC countries already use large quantities of grey hydrogen based natural gas, about 8.4 Mt/year, or ~7% of the world total. Most hydrogen units exist as part of refineries, steel factories and petrochemical facilities (see Appendix).[32] Pearl Gas-to-Liquids (GTL) plant, the world's largest GTL plant, makes Qatar the largest H_2 consumer in the region, taking the country's H_2 consumption to nearly 6 Mt/y (Figure 10). Gas-to-Liquids (GTL) represents an estimated 39% of H_2 consumption in the region, followed by oil refining (27%), ammonia production (21%), methanol production (9%) and steel manufacturing (4%).



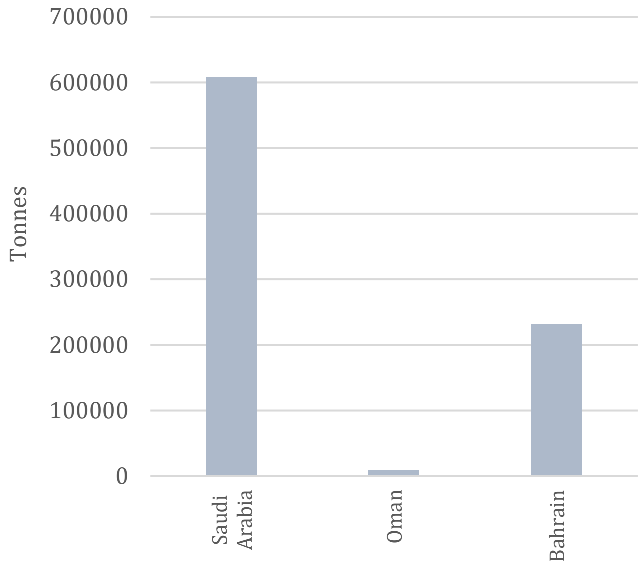


Figure 10 Hydrogen consumption by country and industry (2019)

Figure 11 Planned grey hydrogen capacity for oil refining by 2023

Although making a slow start, the GCC countries' renewable energy projects are on the rise (Figure 12). Between 2008 and 2018, the total financing needs of completed and announced renewable projects in the GCC countries stood at US$ 155 B. The GCC countries' potential for hydrogen production depends on a number of factors including their policies, location, solar radiation, level of renewable energy deployment, renewables' levelized cost of Energy (LCoE), availability and price of natural gas, infrastructure availability, financing costs, and cost of carbon capture, utilization, and storage (CCUS).

[32] Note that in most of these uses, the hydrogen is generated within the plant for its own use, and not transported or traded between facilities.

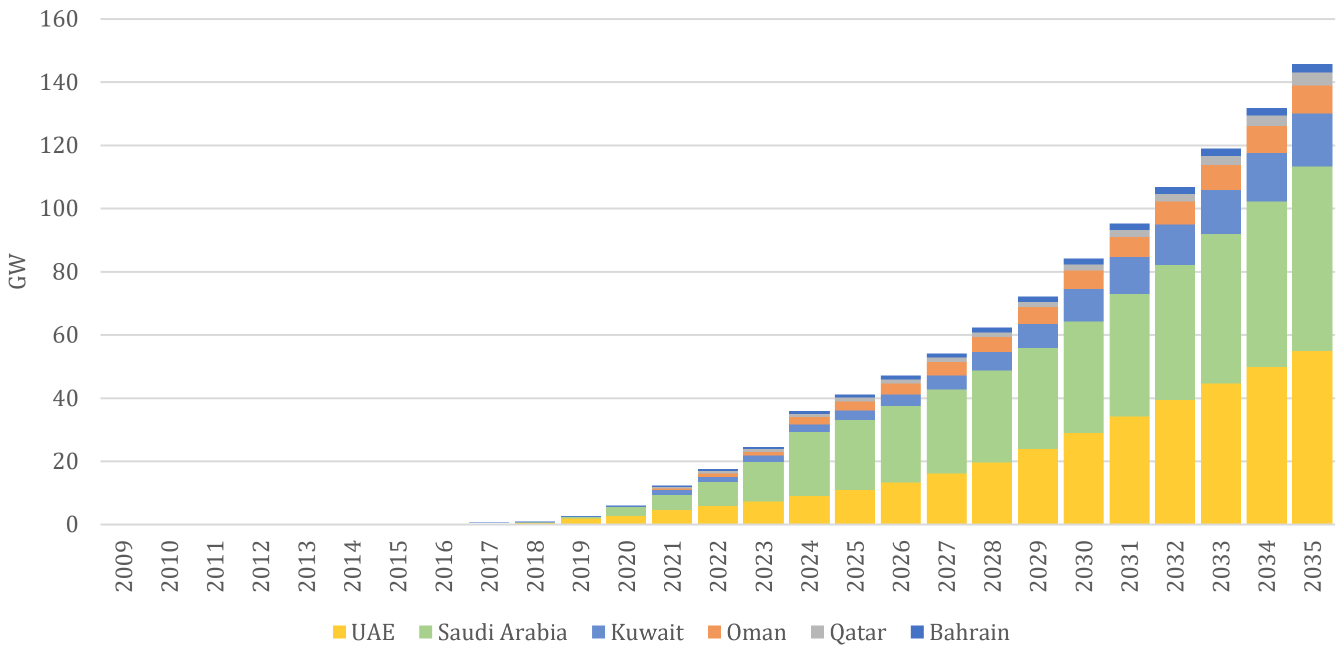


Figure 12 Installed and planned solar (Photovoltaic + Concentrated Solar) Power capacity in the GCC

Table 4 Hydrogen production potential per country

Country	Solar and Wind Resources		Installed RE capacity 2019 (MW)	RE/Efficiency targets	Comparative Advantage	Weakness
	DNI (kWh/m²/d)	Wind Speed (m/s)				
United Arab Emirates	6.0	5.3	1885	2020: Abu Dhabi 7% of capacity; Dubai 7% of electricity generation 2021: 27% clean energy capacity 2030: Dubai's electricity consumption 30% below business-as-usual 2040: Ras Al Khaimah 25-30% clean energy 2050: 44% clean energy capacity. electricity consumption down 40% below business-as-usual	- Highest regional RE installed capacity - Very low LCoE - 5.9 trillion cubic metres (TCM) of proved natural gas resources - Regional markets proximity	- Lack of hydrogen s - trategy - No carbon pricing mechanism - Limited of energy mix diversification - Dependency on fossil fuels - Energy subsidies (except in the UAE)
Saudi Arabia	6.5	>8	397	2020: 3.45 GW 2021: Electricity consumption and	- Very high solar and wind resources	

				peak demand down 8% and 14% respectively 2030: 9.5 GW (10% of capacity); 30% of generation from renewables and others (mainly nuclear)	- 6 TCM of proven natural gas resources - Lowest LCoE in the world (Sakaka plant)
Qatar	5.6	5.7	43	2020: 200-500 MW of solar 2022: Per capita elec. and consumption and water consumption down 8% and 15% respectively	- 24.7 TCM of proven natural gas reserves - High solar resources
Oman	6.2	>8	8	2025: 10% of elec. generation 2030: emissions down 2%	- High solar and wind resources - Strategic export location (Port of Duqm) - Hydrogen strategy underway
Kuwait	6.5	5.5	106	2020: Generation efficiency up 5% 2030: 15% of elec. generation; Generation efficiency up 15%: Energy consumption -30%	- High solar resources - 63 trillion cubic feet (Tcf) of proven gas reserves
Bahrain	6.5	>5.2	7	2025: 5% elec. generation; Elec. consumption -6% 2035: 10% of elec. generation	- High solar resources - 325 Tcf of proven natural gas resources

High; Low; Very low

Global demand for green hydrogen is estimated at 530 million tons (Mt) by 2050 and annual global export market for hydrogen is projected at US$ 300 billion by 2050. With the GCC's high export potential, given its strategic location, high solar radiation, hydrocarbon production, carbon capture potential, and very low levelized cost of renewable energy (LCoE), Gulf countries may be able to export much of their green and blue hydrogen while still having ample, low-cost volumes for domestic use (Figure 13).

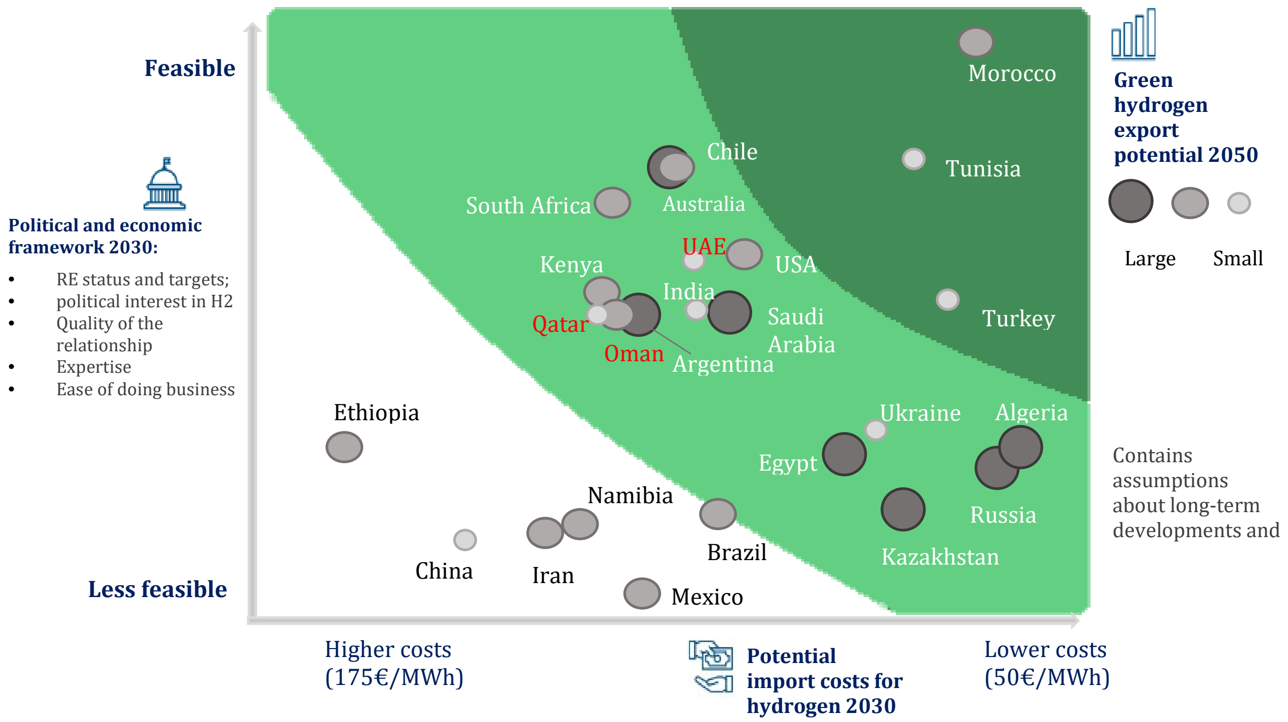
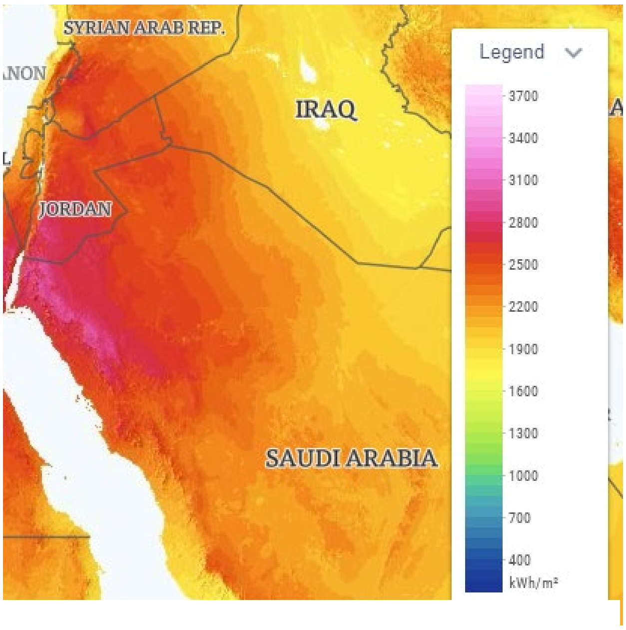


Figure 13 H_2 Export potential per country

Table 5 Green H_2 projects are yet to take off in the GCC, with Saudi Arabia, UAE and Oman leading the main developments

Saudi Arabia is leading the region's green H_2 uptake
In September 2020, Saudi Arabia sent the world's first ever blue ammonia shipment to Japan to be used to produce emissions-free electricity. In the first shipment, Japan will receive 40 tons of blue ammonia, which will be blended into coal-fired power plants at a rate of 20% up to 50%. Japan is taking blue ammonia for a price of US$ 400-500/tonne, compared to grey ammonia at US$ 200-399/tonne. According to the Japanese National Academy, ammonia is considered the highest energy-density low-carbon fuel, with the advantage of an existing supply chain and markets. Waste heat from the gas-fired turbine could also be used to dissociate ammonia to H_2, then add H_2 into the turbine (up to 30%) with minor modifications.

In July 2020, Saudi Arabia's ACWA Power signed a US$ 5 B agreement with US Air Products to develop the world's largest green hydrogen-to-ammonia project, Neom Helios, powered by 4 GW of wind, solar, and storage capacity (Figure 14). The giant hydrogen production facility, planned to be installed in the new city of Neom , will use Germany's ThyssenKrupp's electrolysis technology which will be capable of producing 650 tonnes of hydrogen per day (237,250 t/year). This will be converted into ammonia using an air separation unit (ASU) from Haldor Topsøe of Denmark, with output estimated at 1.2 Mt/year, which will be exclusively bought by Air Products and distributed by sea or road.



While ammonia will be the mean of transporting hydrogen, Air Products will not be selling green ammonia but rather green hydrogen, with the cost of the ASU and ammonia production likely included in the US$ 5 B figure. The project is targeting the commercial vehicles' market, which is indicated in an Air Products schematic (Figure 15).

After export, the hydrogen will be dissociated from the ammonia at a hydrogen refueling station and then compressed for fueling trucks and coaches. 250,000 commercial hydrogen vehicles operate worldwide as of 2018, but the number in Saudi Arabia is negligible and such vehicles would need to be introduced, along with fueling stations. This joint venture is the first international partnership for Neom and is intended to set the foundation for its strategy to become a global centre for renewable energy and hydrogen – in line with the country's Vision 2030 and the Crown Prince Mohammed bin Salman's plan to diversify the economy by reducing the dependency on oil revenues. Neom would make ACWA and Saudi Arabia the lead producers of green H_2 and ammonia globally, which can bring a revolutionization of the transport sector, as a charging stations' feedstock, or a bunkering fuel for ships and other large industrial engines.

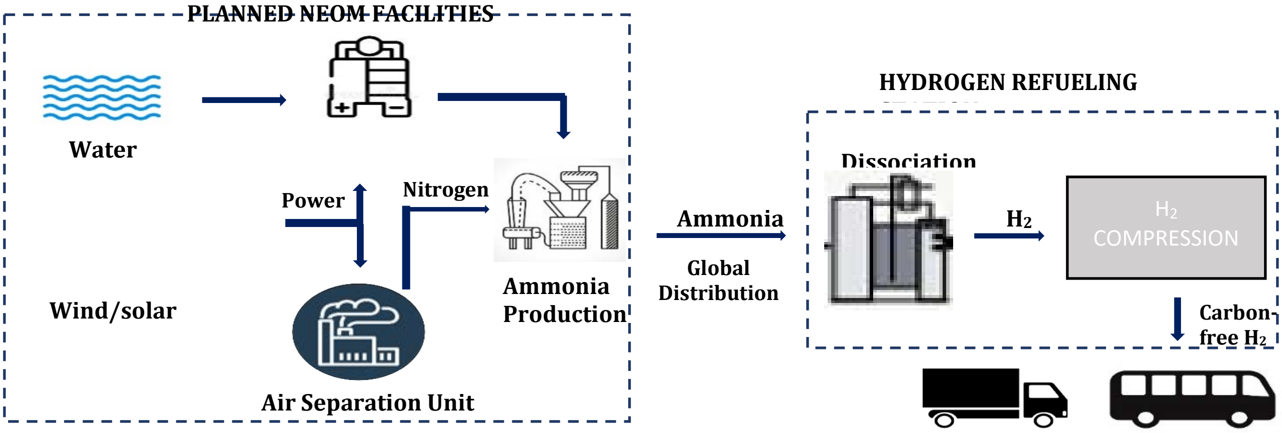


Figure 15 Neom planned H_2 production, transport and application

The location on the Gulf of Aqaba is ideal for renewable energy, available 70% of the time, with considerable sunshine during the day and regular winds at night. This allows the electrolyser to run at a high load factor and improves its economics. However, due to the nascent state of renewable energy in the Kingdom and the project's tight schedule, Neom's green hydrogen facility will be a challenging task. Green electricity will be required for desalination as well as hydrogen and ammonia production. The required 4 GW of renewable energy is about half ACWA's current capacity and represents double the world's largest single-site solar PV plant – more than three times larger than the largest solar plant in the region. Even at around record low pricing, the 4 GW of renewable generation capacity would account for up to US$ 2 B of the project costs. Analysts question ACWA's financial strength for the project, suggesting a lack of financial transparency, which might hamper its attempt to attract investors to fund the development of the project, although it is backed by the Public Investment Fund (PIF) of Saudi Arabia.

In February 2020, Air Products Qudra, a joint venture of Air Products (US) and Qudra Energy, a subsidiary of Vision Invest, a Saudi firm, began constructing a 150,000 tonne/year SMR to produce hydrogen at Jubail Industrial City on the Gulf coast of Saudi Arabia. Vision Invest is also a shareholder of Acwa Power. A hydrogen fuelling station will be constructed at the site, and a pipeline network to distribute hydrogen to refining and chemical customers in the area. This is grey hydrogen, i.e. not combined with CCUS.

In January 2020, operations began on the US$ 400 million hydrogen production site and 16 km pipeline in Yanbu', an industrial city on the west coast of Saudi Arabia. Air Liquide Arabia (ALAR) supplies hydrogen from a dedicated production facility on the location of the YASREF refinery, a joint venture between Saudi Aramco and Sinopec of China. The hydrogen is supplied to SAMREF, a joint-venture refiinery between Saudi Aramco and ExxonMobil, and will later be provided also to three industrial complexes within Yanbu'. ALAR is a joint venture between Air Liquide of France and TAQA, owned by the Public Investment Fund of Saudi Arabia. The facility currently provides 200,000 Nm^3 per hour of hydrogen, about 156,000 tonnes per year.

Meanwhile, the UAE is commissioning the region's first solar powered hydrogen plant

In February 2018, the UAE's Dubai Electricity and Water Authority (DEWA), Siemens, and Expo 2020 Dubai launched a pilot project to build the Middle East and North Africa's (MENA) first solar-based hydrogen electrolysis facility at Mohammed bin Rashid Al Maktoum (MBR) Solar Park. The MW-scale hydrogen production facility, using a Proton Exchange Membrane (PEM) electrolyser, is intended to supply fuel-cell vehicles showcased by Expo 2020 Dubai. If the facility uses only daylight solar power from the park, each unit will be able to produce up to 240 kg of hydrogen per day (1 average fuel cell electric vehicle needs 1 kg of hydrogen per 100 km of range, depending on the model and other factors). In January 2020, Manuel Kuehn, senior vice president at Siemens Middle East, announced that the project is currently in its commissioning phase and would be ready before Q3 2020, which is unlikely given CoVid-19's impact on overall project completion and the postponement of the Expo by one year. In July 2019, German manufacturer of gas-driven combined heat and power (CHP) system, 2G Energy AG, won a deal to supply green hydrogen-driven CHP system to the pilot project.

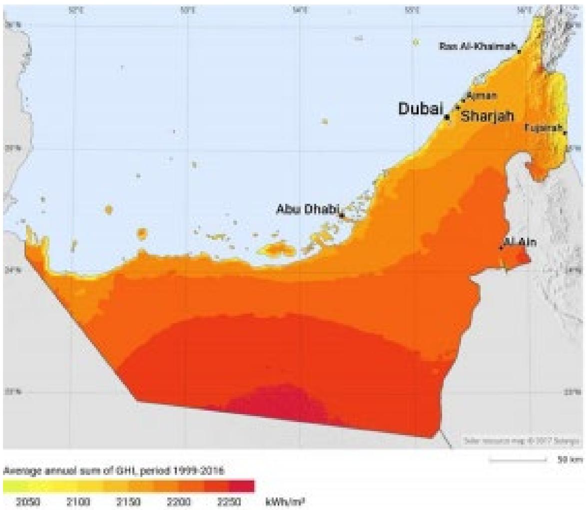


Figure 16 The UAE global horizontal irradiation

Sources of hydrogen are available locally, either as by-product of refining processes or through SMR. Blue hydrogen could also be produced especially as the country has already developed a large-scale CCUS plant in 2016, led by Al Reyadah, originally a JV between ADNOC and Masdar (now 100% ADNOC). The project is aimed at enhanced oil recovery in ADNOC's oil fields in Rumaitha and Bab using CO_2 captured at Emirates Steel Factory. H_2 can also be produced from the thermal decomposition of hydrogen sulphide (H_2S)[33], which exists in substantial amounts in the country – Shah gas field has 23% H_2S. Biomass could be another source for hydrogen production in the UAE, especially as daily per capita municipal solid waste stands at over 1.9 kg/day, the highest in the world[34], though this route to hydrogen is technologically immature.

Oman is showing enormous interest in green hydrogen after announcing its HyPort Green H_2 project

In March 2020, the Belgian firm DEME Concessions announced the development of a 500 MW green hydrogen plant in the port of Duqm, Oman. The plant is designed to have an electrolyser capacity between 250 MW and 500 MW in the first phase, which could be upscaled

[33] e.g. https://pubs.rsc.org/en/content/articlelanding/2020/ee/c9ee03231b#!divAbstract
[34] Air Liquide

in the following stage. The intention is to export green hydrogen and/or derivatives such as green ammonia and methanol. The location of the plant is an advantage given the availability of cheap renewables along with large, accessible on- and offshore sites at Duqm and a new port and industrial hub.[35] The feasibility study, coordinated by consulting firm Roland Berger, will cover customer offtake choices, technology options, electricity feed-in options, shipping options and will define the scope of the commercial scale demonstration project. The final investment decision for the commercial scale demonstration project is expected by 2021. However, this should be regarded with some scepticism given the novel nature of the project for both DEME and Oman, and the Sultanate's limited financing capability.

Along with Port of Antwerp International, DEME Concessions are active in Duqm already through their participation in the Port of Duqm Company SAOC. The company is present in more than 90 countries and is diversifying its portfolio from core dredging business to solutions for offshore energy market, land reclamation, infrastructure marine solutions – DEME's marine solutions provider "DIMCO" designs and constructs jetties, quay walls, bridges, trestles, locks, weirs, barriers, dams, among others – and environmental solutions.[36]

In February 2020, EJAAD (an Omani membership-based collaborative platform backed by the Ministry of Oil and Gas (MOG) and Petroleum Development Oman) has initiated a coordinating effort to create a national strategy for hydrogen. The platform organized a workshop in which 40 stakeholders discussed hydrogen as a business opportunity and are planning to identify strategic partnerships and create the necessary policy and regulatory frameworks to build the foundations of the hydrogen economy. These include the MOG, local and international industries, technology providers, academic institutions and investment organizations. However, the Sultanate will require external financing to develop additional green hydrogen projects due to the current fiscal deficit.

9. HYDROGEN RESEARCH & DEVELOPMENT IN THE GCC COUNTRIES

GCC countries have engaged in a number of R&D projects (Table 6), including feasibility studies and pilot projects for blue and green hydrogen for different uses. It can be seen that there was a pick-up in activity around 2010, which then went quiet until 2019-20 when there has been renewed interest. More R&D investment needs to be allocated to strengthen technology expertise, drive cost reductions in electrolysis, create an infrastructure network and refine export business models.

Table 6 H_2 R&D in GCC countries

Country	Entity	Project Type	Description	Year	Status
UAE	BP	Blue hydrogen	Masdar was planning a partnership with BP for a hydrogen power project, but it was cancelled. The plant would have used natural gas as feedstock and would send captured CO_2 (1.7 Mtpa) underground into storage or for EOR.	2009	Cancelled
	Marubeni Corporation	Green hydrogen feasibility	Japan's Marubeni Corp. signed an MoU with the Abu Dhabi Department of Energy to establish a hydrogen-based society targeting the water and electricity sector. The agreement will also include a feasibility study to evaluate the technical and commercial viability of green hydrogen production. Both parties will jointly explore the research, development, and proofs of concept related to the study, by sharing their expertise in renewable energy, hydrogen production, supply, and distribution. Temporary hydrogen storage is also considered as a reasonable solution for regions with a climate like Abu Dhabi.	2020	Ongoing

[35] https://renewablesnow.com/news/deme-to-set-up-large-scale-green-hydrogen-production-in-oman-689566/
[36] https://fuelcellsworks.com/news/deme-concessions-and-omani-partners-announce-partnership-to-develop-green-hydrogen-plant-in-oman/

	RTA & Hyundai/Toyota	Study/Pilot green hydrogen for mobility	Dubai's Roads and Transport Authority (RTA) discussed their engagement with Hyundai to deliver a hydrogen bus pilot for Expo 2020. Although the project did not materialize due to the lack of coordination from Dubai's side, Toyota is still interested, especially as it already delivered and tested Toyota Mirai, the region's first hydrogen fuel-cell electric vehicle, in Dubai Taxi fleet in coordination with Al Futtaim Motors in 2017.	2020	Ongoing
	Air Liquide, Khalifa university, Al Futtaim Motors	Joint study of H_2 mobility	Testing the Toyota Mirai, a zero-emission hydrogen-run fuel cell electric vehicles (FCEVs); Air Liquide opened 1 hydrogen station and working with ADNOC, Al Futtaim, & Masdar on the pilot. Al Futtaim will be leasing a fleet of FCEVs to key government and private institutions on a short-term basis as part of the pilot to promote better understanding of FCEVs and hydrogen-based societies.	2019	Ongoing
Saudi Arabia	HYSOLAR	Green H_2 Pilot Project	A solar hydrogen demonstration plant was developed in Riyadh's Solar Village within the scope of the joint program HYSOLAR. The plant started up in August 1993, producing 463 Nm3/d of hydrogen.	1993	Unknown
	Energy Research Institute & KACST	Pilot Project	Phosphoric acid fuel cell (PAFC) stack was fabricated and assembled with in-house developed components at Energy Research Institute (ERI) and King Abdulaziz City for Science and Technology (KACST).	1993	Unknown
	Ministry of Higher Education (MoHE)	Center of Research Excellence in Renewable Energy	MoHE established the Centre of Research Excellence in Renewable Energy (CoRE-RE) as part of the research institute at King Fahd University of Minerals and Petroleum. The amin research areas of CoRE-RE are hydrogen, methanol, fuel cells, advanced energy storage, electrical and control systems for wind and solar energies and economics of solar and wind energies.	2007	Ongoing
Qatar	QSTP	R&D – Green hydrogen	Joint research program between Qatar's Science and Technology Park (QSTP). Texas A&M University in Qatar and Germany's Fraunhofer to produce hydrogen from solar energy, the research project was dubbed "Solar Carbon Black Project." The agreement was signed by Dr. Tidu Maini, at the time Science and Technology Advisor to Her Highness and Executive Chairman at QSTP.	2010	Unknown
		Training lab	Heliocentris Group won a tender from Qatar University (QU) to establish a lab to share knowledge on clean energy including hydrogen technology	2011	Unknown
	Qatar Petroleum	Study	QP and Japan Cooperation Centre Petroleum (JCCP), with Kawasaki Heavy Industries, conducted a joint study on the potential for hydrogen liquefaction in Qatar and export to Japan	2012	Decided not to progress

Bahrain	BAPCO	R&D - Green hydrogen	BAPCO launched R&D program with German Heliocentris where it installed a fully integrated autonomous energy system receiving input from a 4 kW PV array and 1.7 kW wind generator. The system stores energy by generating hydrogen. The hydrogen is then converted to electricity (5 kW)	2011	Operational: small-scale
Oman	Ministry of Higher Education	Oman Hydrogen Centre	The German University of Technology in Oman in coordination with Hydrogen Rise AG launched the Oman Hydrogen Centre. The latter will be focused on achieving cooperative research and international exchange of knowledge and experience, network building, academic and industrial training consulting for institutions, applied research and exploring innovations in the hydrogen market.[37]	2020	Ongoing
Kuwait	Kuwait Institute for Scientific Research (KISR)	Global Patent in H_2 storage	KISR announced that the Nanotechnology Program of the Institute of Energy and Building Research in the Institute has obtained a global patent in the H_2 storage in nanoscale metals. The patent was earned from the US Patent and Trademark office.[38]	2019	Ongoing

10. GCC-EU HYDROGEN PARTNERSHIPS

As noted earlier, the EU plans to import the hydrogen equivalent of 40 GW of electrolysers by 2030, mainly from North Africa. Russia is another potential hydrogen supplier because of its existing gas pipelines to the EU; Russia has only recently begun exploring hydrogen seriously.[39] However, there is a significant potential to be unlocked in the GCC region which could complement the EU's efforts to achieve its target faster and cheaper. The recent large-scale Saudi Green Hydrogen project, Neom Helios, developed by US Air Products using German manufacturer ThyssenKrupp's electrolyser, shows the international recognition of the GCC as a potential green hydrogen hub.

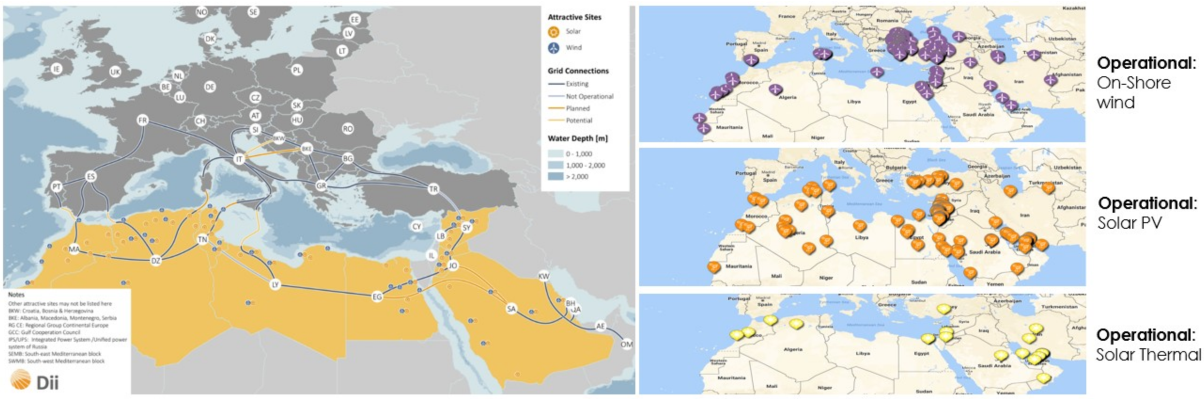


Figure 17 Simulated RE projects' locations vs. actual operational projects' location[40]

[37] https://fuelcellsworks.com/news/oman-hydrogen-centre-opens-at-gutech/
[38] https://fuelcellsworks.com/news/kisr-earns-global-patent-for-hydrogen-storage/
[39] https://www.petroleum-economist.com/articles/low-carbon-energy/energy-transition/2020/letter-from-moscow-russia-reluctantly-explores-hydrogen
[40] Dii Desert Energy

The EU revived Desertec[41] after failing twice due to the issue of transportation and cost-efficiency. Acwa Power of Saudi Arabia was a member of the 20 shareholders of the Dii industrial initiative, which was intended to begin reference projects to support Desertec (the others were mostly German and southern European power companies and financial institutions). Desertec 3.0 is more likely to have an impact now due to the falling LCoE of solar PV in MENA, currently standing at 1.7 USc/kWh and is soon approaching the one-cent mark. The EU's green hydrogen will be primarily produced by green electricity plants in Europe over and beyond the 2,000 GW solar and 650 GW wind capacity required to decarbonise the power sector, along with blue hydrogen. However, 50% of the 6,000 TWh/y of H_2 demand will be imported from North Africa and the Middle East where green hydrogen can be produced cheaply, if it can be transported in a cost-effective way.

North Africa is already well-connected by gas pipelines to Europe, namely Maghreb-Europe from Algeria to Spain via Morocco, Medgaz from Algeria directly to Spain, and TransMed from Algeria to Italy via Tunisia, and Green Stream from Libya to Italy. These could possibly carry increasing quantities of hydrogen blended into natural gas. There are no gas pipelines from the Middle East to Europe, and getting from the GCC countries to Europe requires crossing geopolitically-difficult borders. H_2 export via pipeline from the GCC might more plausibly be directed to South Asia.

Germany has already shown keen interest in the Middle East and GCC for potential green hydrogen production. The country set a target of up to 5 GW of new renewable energy capacity by 2030 to produce up to 14 TWh of hydrogen, with demand in Germany expected to reach 90-110 TWh of H_2 in 2030. Germany developed energy partnerships in both Jordan and the UAE. It carried a number of workshops in Abu Dhabi in January and February 2020, focused on hydrogen and synthetic fuels, in which Ambassador Ernest Peter Fischer, UAE Ministry of Environment (MOEI) Undersecretary Dr. Matar Al Neyadi and Assistant Undersecretary Fatima Al Foora Al Shamsi, ThyssenKrupp, Siemens, ILF, ADNOC, TenneT, IRENA, and Neumann & Esser discussed H_2 activities within the scope of the energy partnership between the two countries. Additionally, in June/July 2020, Germany and the UAE have been conducting a study on hydrogen potential in the UAE, in which they are mapping out and evaluating company profiles.

The country is also creating a brochure on the energy transition for the Gulf region including technology solutions. A study tour will be hosted either virtually or to Germany to introduce use cases for power-to-X technologies (converting electricity into an energy carrier, heat, or raw material) in either transport or industry. The EU country has also participated in energy dialogues with Saudi Arabia, Bahrain, Qatar, and Oman. Hydrogen Rise AG, a German firm, has in January 2020 formed a joint venture with Oman Educational Services LLC to support the development and commercialisation of hydrogen[42]. The German University of Technology in Oman formed in the same month the Oman Hydrogen Centre, intended to be the centre of hydrogen knowledge in Oman and the GCC[43].

Table 7 GCC-EU H_2 Strategic opportunities

H_2 trade	• Hydrogen could be liquefied at existing (retrofitted) liquefaction facilities, and shipped either on ultra-large carriers (since hydrogen's density is much lower than LNG's, requiring more or larger ships), or as ammonia (NH_3) to support an export market. If sent through existing gas pipelines, the delivered energy capacity of hydrogen would be only about as third as much for natural gas. • Shipping ammonia could be cheaper but incurs a further cost for reconversion on arrival.
GCC EU Trade	• The GCC's main market is Asian countries (China, India, Japan and others), but it is an important energy trade partner for Europe. In 2019, the main GCC exporters (Saudi Arabia, Kuwait and the UAE) sold 44.9 million tonnes of crude oil (9% of European imports) and 25 Mt of refined oil products (12% of European imports) to Europe, while Qatar exported 32.2 Mt of liquefied natural gas (LNG), 27% of European (including UK) imports. • Currently, the GCC represents the EU's fourth-largest export market while the EU is the largest trading partner of the GCC, with a significant trade documented in 2019 amounting to € 146.1 B; of this € 50.9 B are EU imports from the GCC[44]. However, talks for a EU-GCC free trade agreement, initiated in 1990, halted in 2008 and have not resumed.[45]

[41] An initiative to explore the potential of renewables in the desert areas of North Africa and the Middle East, improve market conditions and examine the synergies to be captured by connecting European and MENA power markets.
[42] https://www.zawya.com/uae/en/business/story/OmaniGerman_joint_venture_to_support_hydrogen_investments-SNG_165651712/
[43] https://fuelcellsworks.com/news/oman-hydrogen-centre-opens-at-gutech/#:~:text=The%20OMAN%20Hydrogen%20Centre%20is,the%20changing%20global%20energy%20industry.
[44] Data from https://madb.europa.eu/madb/statistical_form.htm
[45] https://ec.europa.eu/trade/policy/countries-and-regions/regions/gulf-region/

Decarbonisation	• Decarbonization policies, particularly in Europe, pose a risk to the GCC's exports of hydrocarbons and energy-intensive materials. Policies such as 'border carbon tariffs' would present a barrier to high-carbon footprint exports. Hydrogen can be a decarbonized export, and/or GCC states could export decarbonized materials made with blue or green hydrogen, such as ammonia, steel, glass, and fertilizers.
Employment	• PwC suggests that the green hydrogen export market can create up to 400,000 operations and maintenance jobs, 300,000 in renewable power generation and 100,000 at electrolysis facilities. They estimate a required investment of US$ 2.1 trillion to meet green hydrogen export demand by 2050 – US$ 1 trillion needed to build the renewable energy capacity, US$ 900 billion to set up the hydrogen conversion and export facilities, and US$ 200 billion to develop water electrolysis facilities.[46] • Establishing partnerships with the GCC can create an opportunity for European manufacturers to expand their market into the GCC, creating jobs, enhancing economic bilateral relations and assisting in recovery from the Covid-19 pandemic.
Achieving UNFCCC Goals	• H_2 imported from the GCC could enable Europe to realize its goal of becoming a hydrogen economy[47] and climate-neutral by 2050 in a cheaper and faster way. • Forming GCC-EU hydrogen partnerships can also contribute to the United Nations Framework Convention on Climate Change's (UNFCCC) goals, reducing emissions by 20% between now and 2050, according to a McKinsey report for the Hydrogen Council.[48]

Table 8 shows the main EU-GCC network organizations and other stakeholders which could facilitate European market entry into the different GCC countries.

Table 8 Main stakeholders for EU-GCC H_2 collaboration

Entity	Collaborations	Activities	Details	GCC Office
Desertec 3.0	Partnered with the Gulf Cooperation Council Interconnection Authority (GCCIA), the Energy Division of the Arab League, Masdar, and ACWA Power	Networking platform between GCC-EU political organizations, research institutes and companies, utilities, development banks	• Network meetings • Workshops • Expert collaborations	Dubai, UAE
EU-GCC Clean Energy Technology Network	Supported by Masdar, KASCT, Kuwait Institute of Scientific Research, Qatar Environment and Energy Research Institute	Networking platform between EU-GCC companies in clean energy	• Network meetings • Training seminars • Workshops • Expert collaborations	Masdar, Abu Dhabi, UAE
Carbon Sequestration Leadership Forum (CSLF)	Saudi Arabia and the UAE are member countries; Saudi Arabia is one of the policy group vice-chairs to identify	• Workshops & meetings • Promotes collaborative research, development, and	• Held Middle East and South Africa regional stakeholder engagement workshop in Riyadh (Oct 2017) with Saudi Arabia's Ministry of Energy	No

46 PwC
47 The Hydrogen Council stresses the potential contribution of the 'Hydrogen Economy' to the global economy, suggesting that an investment of US$ 280 billion by 2030 could supply 18% of world energy demand, generate US$ 2.5 trillion in revenues, create 30 million jobs, and reduce over 6.5 gigatonnes of carbon dioxide-equivalent ($GtCO_2e$). This presents an investment opportunity for both the GCC and EU to diversify, decarbonize and enhance their economic growth.
48 Derwent et al. "Global Modelling Studies of Hydrogen and its Isotompers using STOCHEM-CRI: Likely Radiative Forcing Consequences of a Future Hydrogen Economy," International Journal of Hydrogen Energy, Volume 45, issue 15 (March 2020), https://doi.org/10.1016/j.ijhydene.2020.01.125

	policies for advancing CCUS	demonstration projects that reflect members' priorities	and SABIC to discuss CCUS challenges • Held the 7th Ministerial Meeting in Abu Dhabi (Dec 2017) focused on advancing the business case for CCUS • Saudi Arabia is responsible for supporting enhanced communication of key CCS messages directly in other Ministerial-level meetings, with support from the IEA and the GCCSI	
IEA GHG	Abu Dhabi signed partnership with IEA on promoting attractiveness of clean energy including reducing greenhouse gas emissions	• Research evaluating technologies to reduce greenhouse gas emissions from fossil fuels, with a focus on CCS • Conferences • Technical publications, webinars, training	• Abu Dhabi hosted the 1st post combustion capture conference in 2011 • The services are not specific to GCC applications, but expert membership acceptance is global	No
Neom City	Air Products, Acwa Power	• Development of the world's largest green hydrogen plant		Neom, Saudi Arabia
Saudi Aramco	Air Products, hydrogen fuelling station in Dhahran IEEJ (Japan) on hydrogen and ammonia trade Hyundai, fuel cells		• R&D financing • Pilot projects • Training seminars • International collaborations (air Products)	Dhahran, Saudi Arabia
Royal Commission for Jubail and Yanbu'			• Oversees the two industrial cities which are installing industrial hydrogen networks	Riyadh, Saudi Arabia
Abu Dhabi National Oil Company (ADNOC)	Installing hydrogen filling stations with Air Liquide, Al Futtaim Motors and Masdar Partnership with ENI on CCUS Discussions on hydrogen with Japan-Abu Dhabi Economic Council		• Parent of Borouge, producing hydrogen off-gas • Operates Al Reyadah carbon capture project on Emirates Steel	Abu Dhabi, UAE
Masdar (subsidiary of Mubadala; Abu Dhabi government strategic investment company)	Partnered with UK, Spain, Portugal, and Central and Eastern Europe on renewable energy projects and infrastructure	Developing and operating utility-scale renewable energy projects around the globe and especially the GCC countries	• Renewable investment • Energy services consultancy • Training seminars • R&D financing • Government policy advisory	Masdar, Abu Dhabi, UAE

UAE's Ministry of Energy & Industry	Partnered with IEEJ on hydrogen R&D; supported ADIPEC's Blue and Green H_2 Dialogue	Develops plans and strategies, following up on their implementation and preparing specialized studies	• Workshops • R&D financing • Government policy	Abu Dhabi, UAE
Al Futtaim Motors	Collaborated with Air Liquide for the construction and supply of hydrogen stations in Dubai, in Festival City	Leading sustainable mobility in the UAE with the aim to drastically lower CO_2 emissions, in line with the UAE Vision 2021	• Feasibility studies • Pilot projects	Dubai, UAE
Khalifa University	Merged with Masdar Institute		• Research on hydrogen, CCUS, other clean energy • Testing of hydrogen-powered Toyota Mirai	Abu Dhabi, UAE
King Fahd University	Inaugurated the first H_2 fuelling station in Saudi Arabia as it owns the Technology Center in the Dhahran techno Valley Science Park; development of new nanomaterials and semiconductors to produce H_2 using solar energy	The University conducts a number of research projects focused on H_2 production from clean energy	• Pilot projects • Workshops	Dhahran, Saudi Arabia
Emirates Steel	ADNOC, Masdar on CCUS	collaborated with Hyundai hydrogen bus pilot for the Dubai Expo	• Operates Emirates Steel DRI plant, fitted with CCUS	Musaffah, Abu Dhabi, UAE
Dubai Electricity and Water Authority (DEWA)	Collaboration with international companies for clean energy and renewables	DEWA and Siemens collaborated to develop the region's first solar-powered hydrogen power plant	• Funding technology & assessments • Funding pilot projects • Collaboration on R&D	Dubai, UAE
Roads and Transport Authority (RTA), Dubai		collaborated with Hyundai hydrogen bus pilot for the Dubai Expo		Dubai, UAE
Qatar National Research Fund (QNRF)	QNRF hosted high-level workshop in partnership with the EC[49] on CSP use for H_2 production		• Hosting sustainable energy conferences and events • Conducting research studies • Research sponsorship	Doha, Qatar
Qatar Environment and Energy Research Institute (QEERI) and Hamad Bin Khalifa University (HBKU)	Organized an international workshop on "the hydrogen energy opportunity for Qatar." This attracted 50 delegates from eight countries including Japan, US, UK, Germany, France,	Supports Qatar's environmental and energy research and development	• Hosting conferences and interviews • Training sessions • Debates and workshops	Doha, Qatar

[49] The European Commission

	Australia, and Switzerland			
Qatar University and the Ministry of Municipality and Environment	Co-operated a joint research on hydrogen production using wastewater and solar energy	Provides research support to QEERI	• Research Studies • Workshops • Training	Doha, Qatar
Al-Attiyah Foundation for Energy and Sustainability	Conducts research reports on hydrogen; provides recommendations for hydrogen production and use in the GCC	Launched the sustainable development work program based on the Paris Agreement on climate change and the 2030 UN agenda for sustainable development.	• Publishing reports and publications	Doha, Qatar

Taking into consideration the inevitability of the clean energy transition, oil and gas companies should adopt a sustainable strategy that includes hydrogen development in their portfolio. GCC oil and gas companies, although showed interest in the H_2 market, haven't yet made material effort towards a dedicated H_2 facility. The below projects planned by international oil and gas companies should encourage GCC companies to contribute and even lead the transition.

Table 9 Planned H_2 projects by IOCs

Company	Project Description
Shell & ITM Power	The two companies will build the world's largest PEM H_2 electrolysis plant, Refhyne, at the 325 kb/d integrated Rheinland refinery in Wesseling, Germany. The 10 MW electrolysis plant will be used primarily for oil refining, but more testing is being done for possible use in other sectors. The project's total investment stands at around US$ 24.44 M and is supported by the Fuel Cells and Hydrogen 2 Joint Undertaking. The plant is set to be operational by 2020.[50]
BP and Edison Mission Group	The two companies will build the US' first blue H_2-fuelled power plant at the cost of US$ 1 B in California, with minimal CO_2 emissions. Located alongside BP's Carson refinery, the plant will be capable of producing 500 MW of low-carbon generation and capturing 4 Mtpa of CO_2 emissions, which will be transported and stored in deep underground oil reservoirs, for enhanced oil recovery. The plant will be using recycled and treated city water for its needs.[51]
Equinor	The company tends to favour blue hydrogen over green. It is leading a project to develop the UK and world's first "at-scale" facilities for blue H_2 production at the Saltend Chemicals Park northeast England. The project is targeting a final investment decision around 2023 with potential first production by 2026. The initial phase would comprise a 600 MW auto thermal reformer with CC, largest plant of its kind to convert gas to H_2, with an H_2 production capacity of 125,000 t/y.[52]

11. GCC HYDROGEN AND EUROPEAN BUSINESS

The GCC's ample low-cost land, low cost of capital, existing industrial capacity, excellent solar and wind resources, and geographical proximity to growth markets sets it in an excellent position to become a hydrogen exporter. Demand for green hydrogen is expected to grow rapidly in the medium term to 530 Mt, displacing 10.4 billion barrels of oil equivalent by 2050 or 37% of 2020's global oil production. This should urge Gulf countries to accelerate their diversification plans and produce more low-carbon export products to maintain their economic position. Based on PwC's supply and demand analysis, hydrogen exporting countries can capture a market of around 200 Mt of green hydrogen by 2050, worth US$ 300 B per year. The green H_2 export market is able to create up to 400,000 operations and maintenance jobs, 300,000 of which are in renewable power generation and 100,000 at electrolysis facilities. An estimated investment of US$ 2.1 trillion is needed to meet green hydrogen demand by 2050, US$ 1 trillion of which is required to build the RE capacity, US$ 900 B

[50] https://www.fuelsandlubes.com/shell-to-build-worlds-largest-pem-hydrogen-electrolysis-plant-in-germany/
[51] https://www.greencarcongress.com/2006/02/bp_and_edison_p.html
[52] https://www.spglobal.com/platts/en/market-insights/latest-news/electric-power/072420-norways-equinor-favors-blue-hydrogen-developments-over-green-cfo

to establish the hydrogen conversion and export facilities and US$ 200 B to develop water electrolysis facilities.[53] This represents an opportunity for EU businesses to expand technical expertise in the region and take part of a potential hydrogen economy. Giant hydrogen project developers like Air Products and Air Liquide have already established their presence in the region and are working extensively on different hydrogen projects (Table 10).

Table 10 Main H_2 project developers in the region

Project developer		Type	Focus Industry	Expertise
1	Air Products	Public (USA)	Industry leader in hydrogen supply for clean transportation applications	Developing, engineering, building owning and operating mega industrial gas facilities including syngas and carbon-free hydrogen[54]
2	Air Liquide	Public (France)	World leader in gases, technologies and services for industry and health	Engineering, construction, equipment supply, sub-contracting, logistics, and inspection, with a H_2 portfolio comprising pressure swing adsorption, zero steam H_2 production, and SMR[55]
3	Deme Concessions	Private (Belgium)	Dredging and land reclamation, offshore wind energy, wave, tidal energy and offshore mineral resources	Equity, project finance, equipment supply, including Alkaline and Proton Exchange Membrane electrolysers; product integration; engineering[56]
4	ACWA Power	Private (Saudi Arabia)	Global leader in water desalination and power industry	Developing, financing, co-owning, and operating power generation and desalinated water production plants

To fully utilize their potential of power-to-gas, the GCC countries need to accelerate the implementation of large-scale technology to drive down costs. For this, several barriers need to be overcome. Table 11 shows a number of challenges and the actionable items to address them.

Table 11 H_2 challenges and potential required action[57]

	Challenges	Required Action
Technology	• Lack of hydrogen transportation infrastructure and equipment (CGH tanks, pipelines and LH tanks) • Electrolysers need to become quickly available on multi-MW scale • Low installed renewable energy capacity • Dominance of conventional technology	• Better understand the potential to re-use/build gas pipeline systems for hydrogen transport – assess materials, end-use and storage issues • Encourage development of hydrogen infrastructure while diminishing green H_2 supply cost through R&D • Increase and accelerate renewable energy deployment
Economics	• Specific capital requirement for electrolysers is still high • Need high capacity factors for economic operation – requires combining different renewables and/or energy storage • CCUS costs need to be reduced to shrink cost penalty of blue vs grey hydrogen • Lack of understanding of hydrogen production, transport and storage costs	• Improve the understanding of the cost-reduction potential for electrolysers • Additions to electrolysis capacity to create larger economies of scale and a reduction in project capital costs • Repeatable experience of CCUS projects and construction of CO_2 pipeline and storage clusters

[53] PwC
[54] US-Saudi Business Council
[55] Air Liquide
[56] Hydrogen Europe
[57] Qamar Energy Research

Regulations	• Currently there is no carbon pricing mechanism in place • No established hydrogen strategy to set a H_2 policy roadmap • Energy subsidies in a number of GCC countries deincentivise H_2 uptake	• Include the hydrogen economy in the revision of Nationally Determined Contributions (NDCs) for the Paris Agreement, due in 2020 • Develop carbon pricing mechanisms to encourage hydrogen use and boost demand, hence, create business opportunities to expand the H_2 market • Use carbon pricing to encourage retrofitting of existing grey to blue hydrogen production • EU-GCC collaboration on technologies and co-ordination on harmonising regulations and standards
Application	• Industrial, residential, transport and power sectors dependent on fossil fuels	• Create demand for H_2 in each of the sectors by introducing incentives

The EU's potential carbon border tax could slash the profits generated by exporters of oil, steel, and wood pulp by a range of 10-65%, impacting both EU and non-EU producers of goods such as chemicals and machinery. GCC countries are considered the most exposed and less resilient to an EU carbon pricing scheme, which could encourage increased uptake of H_2 as a way of reducing the carbon footprint of exports of energy-intensive materials to Europe.

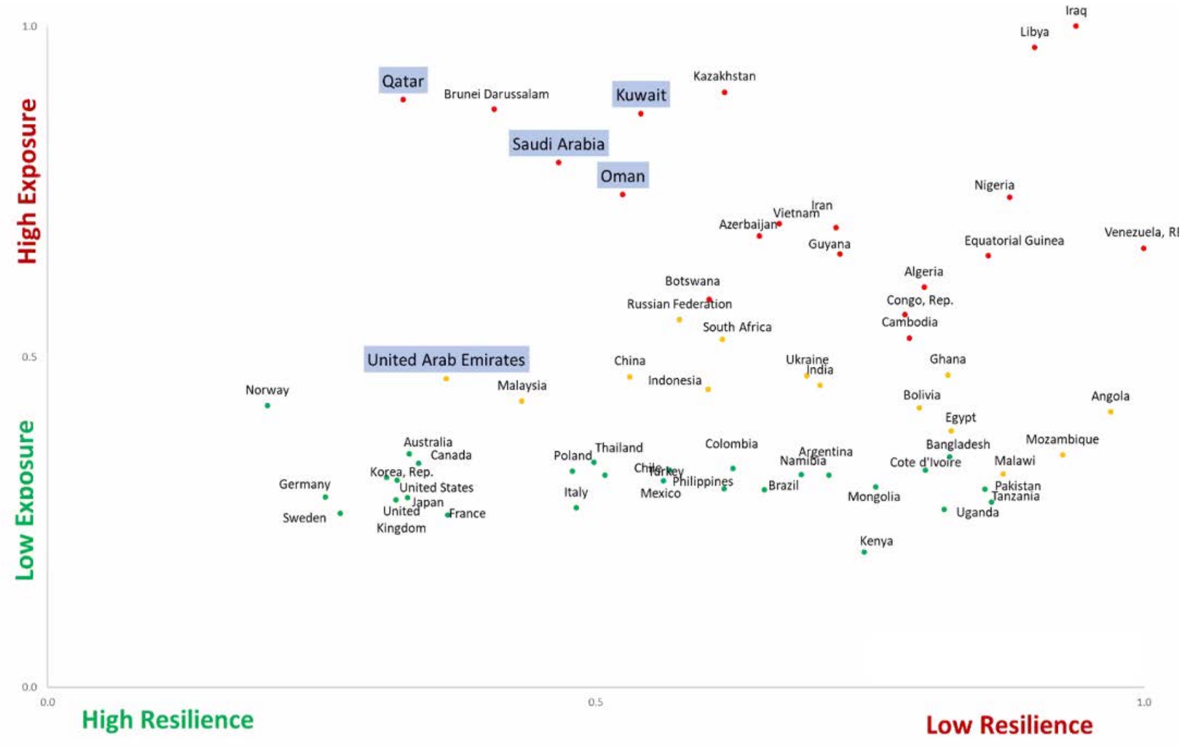


Figure 18 Countries' exposure and resilience to a foreign carbon pricing scheme[58]

European companies have a range of potential roles to play in a GCC hydrogen industry:

- Project developer of hydrogen production (green or blue)
- Equipment supplier: SMRs, air separation units, electrolysers, desalination equipment, renewable energy generation (particularly wind), fuel cells and other related equipment
- Technology development: improvement of electrolysers, CCUS and hydrogen transport systems
- Hydrogen storage: development and operation of tanks and salt caverns
- Hydrogen offtaker (for use within the GCC or import to Europe)
- Hydrogen mobility: hydrogen filling stations and road vehicles; hydrogen bunkering for shipping (longer-term prospect)

[58] EU-GCC Clean Energy Technology Network

- Hydrogen transport: pipelines (unlikely to Europe, but could include domestic pipelines); liquefied or compressed hydrogen tankers; ammonia tankers; road tankers
- Hydrogen conversion and reconversion: to and from ammonia or LOHC
- Trade, including hydrogen and potentially carbon offsets
- Finance: hydrogen value chain, including project finance, including backed by offtake, and potentially trade finance
- Support services: specialist law, training, certification, consultancy, price assessment, human resources provision

As noted, projects in Saudi Arabia have taken the form of joint ventures with Saudi companies, usually state-backed (Neom, Acwa Power, TAQA, Vision Invest). Masdar and ADNOC have been the main players so far in Abu Dhabi, and DEWA in Dubai. There are few active hydrogen projects currently, other than captive grey hydrogen projects as noted. Therefore, European companies interested in the sector will have to engage directly with the GCC national oil companies or major utilities and industrial players. At the same time, they can support building awareness and the development of supportive policies towards the sector.

The below opportunity map (Figure 19) shows the hydrogen manufacturing industry in the Netherlands, indicating a significant potential for electrolysers manufacturing. However, more concrete development plans are needed to capitalize these opportunities. This includes (1) setting up a Dutch Production Pilot for Electrolysis, as to facilitate technology development knowledge among Dutch companies active in the chain, (2) creating a manufacturing platform for Dutch companies to exchange knowledge and expertise in the electrolyser manufacturing industry, and (3) creating initial market demand by introducing policy that stimulates innovation through a collaboration between ptential system integrators and electrolyser customers.

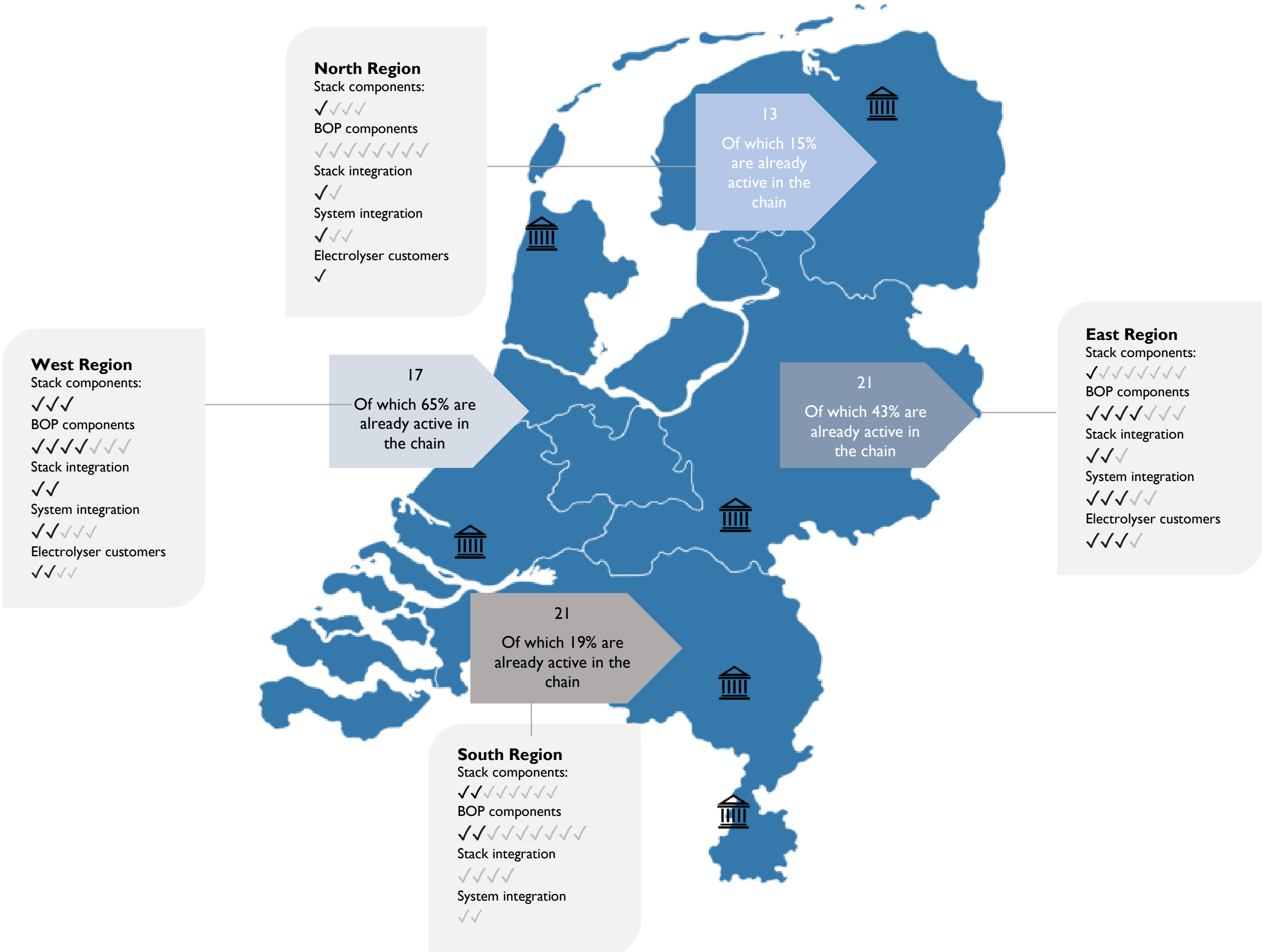


Figure 19 Opportunity map for Netherlands companies in electrolyser manufacturing (✓ = currently active company; ✓ = company with relevant knowledge / ambition for electrolyser manufacturing)

12. CONCLUSIONS

While the GCC has already begun diversifying into non-hydrocarbon forms of energy generation, more efforts are needed to achieve their energy transition targets. To be able to maintain and improve their economic growth, GCC governments and industry leaders need to establish a policy roadmap that would enable them to take part in the hydrogen economy at an early stage. This regulatory step is essential to attracting investors and realise the market soon. For this to materialise, GCC countries need to build collaborations with EU governments, research bodies and businesses for a combination of R&D, pilot projects and commercial-scale H_2 production. EU companies interested in the hydrogen sector will have to initiate projects, most likely in partnership with GCC state energy companies (ADNOC, Masdar, Saudi Aramco, QP, OQ, Petroleum Development Oman), utilities (DEWA, EWEC, SEC, Kahramaa) and strategic investment vehicles (PIF, Mubadala).

Currently, hydrogen production is not high on the agenda of oil and gas companies in the region, but rather the focus of utilities, power plant developers and industries. However, some other countries, notably Japan, are already showing interest in the region's hydrogen potential. GCC countries' H_2 production will feed mainly into their industrial and transport energy needs. Decarbonizing the steel industry will contribute to their GHG reduction targets, which would allow them a greater export market share to the EU (in the case of a carbon border tax). Hydrogen in the GCC will take some time before penetrating the transport and power sectors. This means that most H_2 volumes will be exported in some form to international markets, mainly EU, Japan, South Korea and potentially India. Exporting significant amounts of hydrogen to the EU depends on accelerated deployment of both renewables and electrolysers or CCUS-integrated SMR units as well as establishing a policy roadmap to ensure implementation. The most realistic and cost-effective H_2 transportation route currently would be that of ammonia conversion. Hydrogen pipeline networks from the GCC to the EU are unlikely to develop because of the cost and geopolitical complexity; it is more likely that existing gas pipelines from North Africa and perhaps Russia will be repurposed.

13. APPENDIX

13.1 HYDROGEN FACILITIES IN THE GCC

	Masdar / BP	Hydrogen Power Abu Dhabi	Natural Gas	155 000	Yes	Cancelled (2011)
	Borouge	Ruwais Ammonia (FERTIL-I and II)	Natural Gas	370 000	No	Operational
	Emirates Steel	Emirates Steel	Natural Gas	73,000	Yes	Operational
	Aramco	Jeddah Refinery Hydrogen Plant	Natural Gas	12 600	No	Operational
	Aramco	Luberef Hydrogen Plant	Natural Gas	7 000	No	Operational
	BAPCO	Sitra Refinery Hydrogen Plant	Natural Gas	232 000	No	2022
	MOGA	Sohar Refinery Hydrogen Plant	Natural Gas	62 000	No	Operational
	Shell	Pearl GTL Hydrogen Plan	Natural Gas	3 780 000	No	Operational
	QP	Laffan Refinery Hydrogen Plant	Natural Gas	176 000	No	Operational
	KP	Mina Ahmadi Refinery Hydrogen	Natural Gas	NA	No	Operational

13.2 POTENTIAL ROLES AND COMPANIES FOR GCC-EU H_2 TRADE

Note that, by citing the below, we are not making recommendations, but showing examples of companies potentially active in these roles. Also some companies may play multiple roles, for instance equipment suppliers taking equity stakes in projects.

Role	Companies
Project developer	• Siemens • ITM Power • ACWA Power • Air Products

	• Air Liquide • Power House Energy • Deme • Snam • Iberdrola • Fertiberia • Engie • BASF • rsted • Vattenfall • Enel/Endesa • Polenergia • Fortum • E.OM • RWE • PGNiG • EDF (Hynamics)
quipment supplier	• ThyssenKrupp • Haldor Topsøe • Fuel Cell Systems • Mitsubishi • Nel Hydrogen • Pretzel • Enapter
Hydrogen transport	• Deme • Engie • Exmar • Fluxys • WaterstoofNet • Gas Networks Ireland • Lotos
Hydrogen for mobility	• Linde • Hyundai • Air Liquide • BMW • Daimler • TESLA • Bosch Group • Renault • Peugeot • Audi • FIat
Industry Bodies	• Hydrogen Europe • The Oil and Gas Climate Initiative (OGCI) • The European Industrial Gases Association • The European Clean Hydrogen Alliance • The Hydrogen Council
Oil & Gas companies	• OMV • Total • Shell • Total • Repsol

- ENI
- MOL
- Wintershall
- Uniper
- Galp

13.3 GCC CO_2 STORAGE BY COUNTRY[59]

Country	Population (Million)	GDP (US$ Billion)	2018 CO_2 Emissions (Mt)*	2018 Large Point Emissions (Mt)**	CO_2 Storage Potential (Mt)***
Bahrain	1.6	34.9	38.0	15.8	NA
Kuwait	4.2	105.8	98.2	57.7	4600
Oman	4.8	73.2	71.4	41.4	1400
Qatar	2.7	149.6	101.2	31.5	2000
Saudi Arabia	33.6	698	571.0	269.1	19300
UAE	9.5	383.4	277.0	100.8	6100
Total	**56.4 million**	**US$ 1445 billion**	**1156.8 Mt**	**516.3 Mt**	**33 400 Mt**

* Emissions from fuel combustion only

** Estimate; excludes limestone decomposition from cement

*** Storage capacity in depleted oil & gas fields only; excludes saline aquifers or other storage options

[59] BP Statistical Review of World Energy 2019, CIA Factbook (CO2); ADNOC; Regional Profile: MENA, CCS TLM, ltd. 2010

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