THE UAE'S ROLE IN THE GLOBAL HYDROGEN ECONOMY

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ABOUT QAMAR ENERGY

Qamar Energy is an independent consultancy that specialises in Middle East & North Africa energy strategy, commercial and economic consulting, market intelligence, and international energy trading strategy across the energy spectrum. It has an in-house team of experts with over 40 years of combined experience, who contribute specialised market intel, building on a global network of industry and government links.

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ACKNOWLEDGEMENTS

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UNITED ARAB EMIRATES
MINISTRY OF ENERGY & INFRASTRUCTURE

KEY FINDINGS

1. **Hydrogen will be a competitive business, and the UAE is well-placed to take an early-mover advantage.**
   Though the addressable market is potentially very large – estimated at US$ 2.5 trillion[1] – several important world regions, including Australia, Chile, Russia, Canada, north-west Europe, North Africa and the southern USA, have particularly good conditions for the production of blue or green hydrogen. Not many have a combined competitive advantage like the UAE. This lends adaptability to the UAE's ambition of establishing profitable world-scale hydrogen businesses in both blue and green forms, above other players in the Middle East region, who have announced large-scale plans primarily for green hydrogen. This can allow for building scale in blue hydrogen while introducing green and balancing the output of the two forms to allow for a steadier supply. Given the competitive advantages and plans already underway, the UAE is well-placed to take an early-mover advantage in the global hydrogen business.

2. **The UAE has natural competitive advantages.**
   For blue hydrogen, these include reliable and cost-competitive hydrocarbons, existing large-scale hydrogen and ammonia production facilities, and large, well-characterised subsurface formations for carbon dioxide storage. For green hydrogen, these are the excellent solar generation conditions, and the very low levelized cost of solar electricity generation achieved. For all hydrogen projects, advantages include strong existing infrastructure such as port facilities, LNG export and import terminals (which could be modified/retrofitted to support hydrogen trade), and gas pipelines, salt domes for hydrogen storage, a central geographic location between key markets, and a stable, business-friendly and innovative approach. The country also enjoys a sophisticated, large-scale network of refining and petrochemical facilities, including the Ruwais ammonia plant, and future potential for methanol and synthetic fuels production.

3. **The UAE is pursuing a balanced strategy covering both 'blue' and 'green' hydrogen.**
   Blue hydrogen is currently lower-cost but the cost of producing green hydrogen is likely to fall significantly over time, it is lower-carbon, and enjoys more political support in Europe.

   Given uncertainties in the evolution of cost-competitiveness of the two production methods over time, and whether policy in some markets will favour green hydrogen explicitly, it is wise to cover both options currently, as the UAE can develop a competitive advantage in both forms. Blue hydrogen will be easier to scale-up initially[2] and is therefore important for creating a global market. Major projects announced to date are ADNOC's 1 Mtpa blue ammonia project at Ruwais, and a 0.2 Mtpa green ammonia project by Helios Industry, a private consortium, at the Khalifa Industrial Zone Abu Dhabi port (KIZAD).

4. **Low-carbon hydrogen has been identified early by the UAE as a critical part of the transition to low-carbon energy.**
   Grey hydrogen from fossil fuels is already widely used in the UAE and other major hydrocarbon and industrial centres, but is currently not a widely traded commodity. However, the flurry of activity in the hydrogen space in recent months speaks to the UAE's ambition of deploying hydrogen not only as a key pillar of decarbonisation but also creating new export markets. In 2020, the Abu Dhabi National Oil Company (ADNOC) announced an ambitious five-year US$ 122 billion capital investment program, including plans for transitioning to a low-carbon future. As part of this announcement, the Supreme Petroleum Council (now the Supreme Council for Financial and Economic Affairs), in charge of Abu Dhabi's energy decision making, approved the capex program, and mandated ADNOC to become a "hydrogen leader".

5. **Low-carbon hydrogen is an emerging business that has to address significant challenges in technology and economics.**
   Technology issues include improving the cost and technical efficiency and optimising the capacity factor of green hydrogen production; reducing the use of precious metals in electrolysers; lowering the cost of carbon capture and storage for blue hydrogen; advancing hydrogen conversion, storage and transport methods; and developing hydrogen infrastructure (including fuelling systems, pipelines, port upgrades, and ammonia and methanol synthesis and shipping systems). These are required for blue and green hydrogen to reach viability with grey hydrogen and fossil fuels when carbon costs are accounted for.

   In the UAE, specific actions to scale-up blue hydrogen initially could include adapting oil refining, methanol, direct reduced iron and fertiliser production. There is some opportunity for ground transport, but likely shipping offers a larger and readier market. Gas-fired power plants can be adapted to run on a blend of hydrogen or ammonia for aluminium smelting, cement, and other industry. Industrial and port clusters offer the potential for hydrogen hubs, particularly at Ruwais (port, gas processing, refining, petrochemicals, ammonia, nuclear power, and planned methanol production); Musaffah-Taweelah near Abu Dhabi city (port, petrochemicals, gas infrastructure, steel, aluminium); and the Jebel Ali-Dubai-Sharjah-Ras al Khaimah belt (ports, gas infrastructure refining, aluminium, chemicals, cement).

6. **The right policy will underpin a successful hydrogen strategy.**
   Policy requirements to create a market for low-carbon hydrogen and derived products (ammonia, fuels, plastics, steel, etc.), domestically and internationally, include accessing premia or credits for low-carbon products. In parallel, the physical infrastructure and regulation for hydrogen use in industry, transport and other sectors must be developed to serve key markets and industries.

7. **Partnerships and tangible projects are essential for progress.**
   The currently nascent market has to be developed. A sufficiently large market with consumers willing to pay appropriate prices will give producers the assurance of an acceptable risk-adjusted return on investment.

   Consumers need to be confident that heavy investment in midstream infrastructure and end-use applications will be supplied with hydrogen at competitive costs, allowing for carbon costs and any additional government support. Costs have to be brought down as project sizes and their associated financing requirements scale up. This requires partnerships at government-to-government level, between companies and research institutions, and with companies and end-users.

   The UAE has a strong track record of public-private partnerships with both domestic and international entities across the energy, industrial and other sectors and is regarded as a trusted and stable investment environment. The formation of the Abu Dhabi Hydrogen Alliance between ADNOC, Mubadala, ADQ and the Ministry of Energy and Infrastructure is an important step towards a coordinated effort combining the partners' distinct skills and assets. Several other key strategic areas, each with specific potential partners, can be identified to drive progress to meet other objectives of the UAE's low-carbon drive, including development of carbon accounting standards and protocols for hydrogen production, use and trade.

1. STRATEGIC OPPORTUNITY

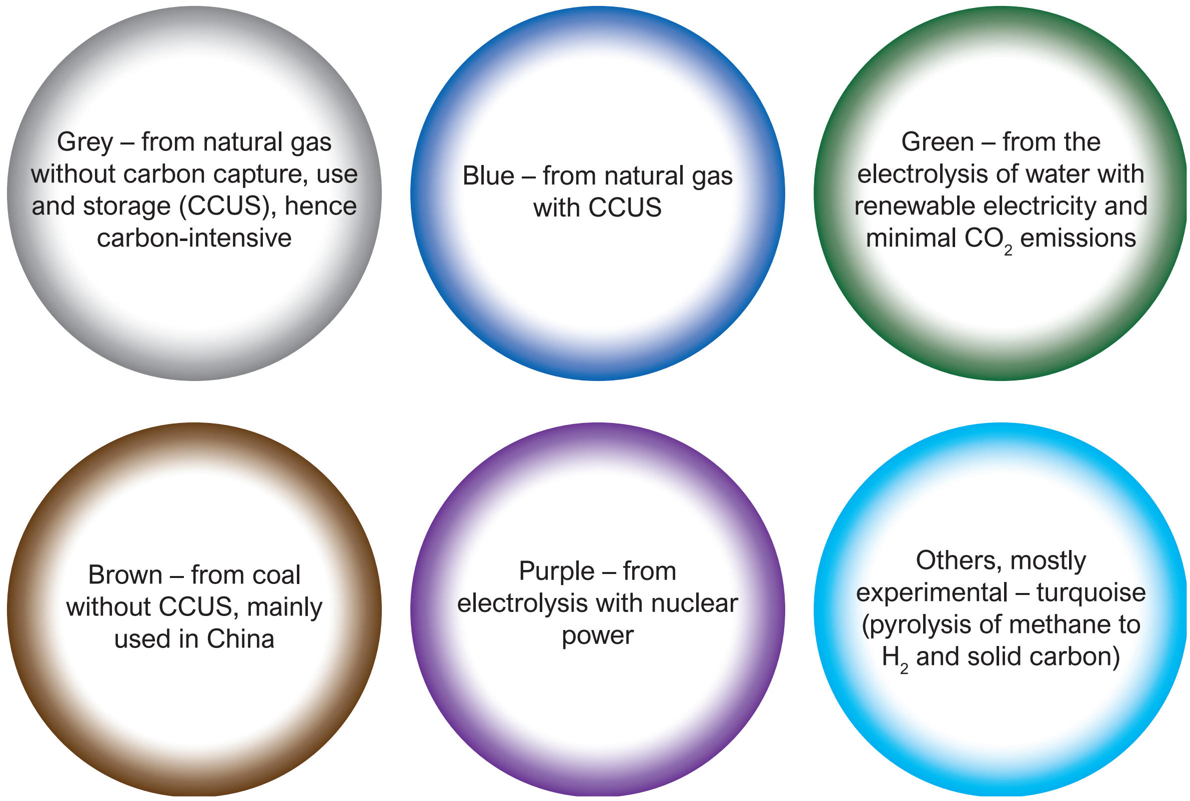
The role of hydrogen for an oil- and gas-exporting country such as the UAE revolves around three pillars: sustainability, economy, and innovation.

The UAE's climate plans and commitments include reducing greenhouse gas (GHG) emissions 23.5% below business-as-usual projections by 2030 (a cut of about 73 million tonnes), as committed in its December 2020 update of its Nationally Determined Contribution (NDC) under the Paris Agreement. Its NDC identifies hydrogen as "a fuel of the future"[3].

The country has introduced multiple national low-carbon energy initiatives, making it a regional leader. ADNOC was an early frontrunner in low-carbon hydrocarbon development in the Gulf region, with initiatives such as LNG exports in the 1970s and elimination of routine flaring in the 1990s, and has been recognised as one of the world's lowest-carbon footprint producers[4]. The UAE hosts the International Renewable Energy Agency (IRENA), the World Future Energy Summit as part of Abu Dhabi Sustainability Week, the low-carbon Masdar City, and is bidding to hold the 28th Conference of the Parties (COP28) on climate change in 2023[5]. Hosted annually by ADNOC, the 2021 ADIPEC conference in Abu Dhabi will be held in November, with a dedicated hydrogen focus for the first time, as will the prestigious GasTech conference to be held in Dubai earlier in September[6]. The UAE has been a leader on introducing civil nuclear power into the Middle East and globally in pioneering low-cost solar power and industrial carbon capture and storage. Environmental sustainability is a key theme of the UAE's national strategies and international diplomacy. The country has invested more than US$ 16.8 billion in renewable energy projects across 70 countries.

The future use of oil and gas will be constrained by climate limits. Some fossil fuels can be used to make long-lived materials such as plastics, and some can be combusted with carbon capture, use and storage (CCUS). But even if the pace of decarbonisation is not as fast as that outlined by some

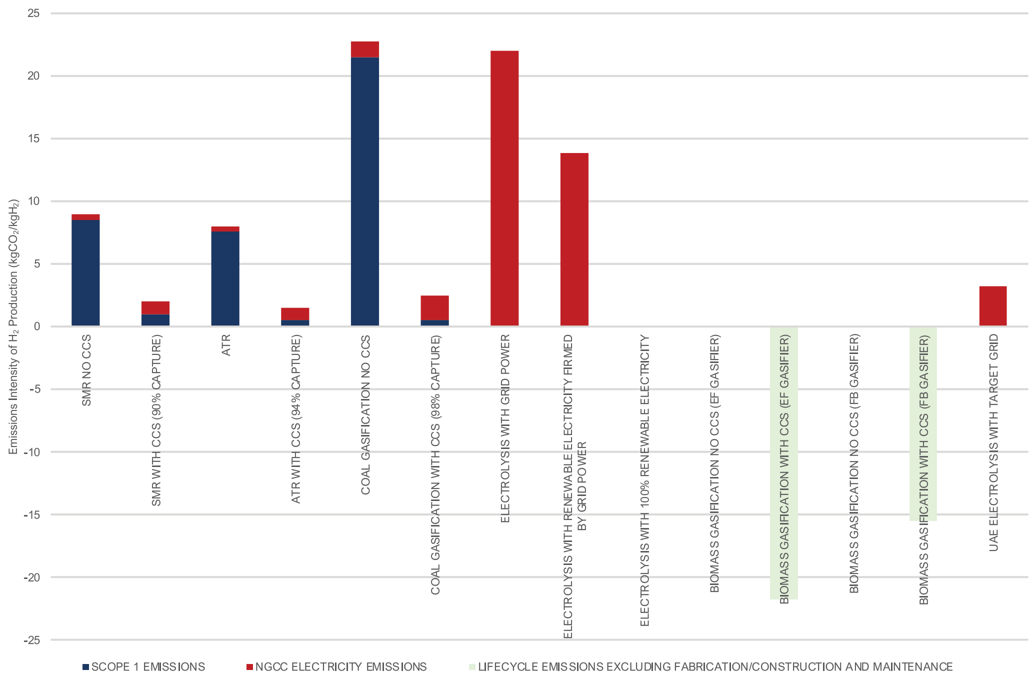
Figure 1: The different colours of hydrogen



agencies and analysts[7], world oil demand is expected to begin declining in the coming decades.

Oil and gas production and export, along with associated industries such as petrochemicals, remain core pillars of the UAE economy. Other vital businesses for the country include aviation and shipping, currently reliant on oil-based fuels. To maintain economic vitality, it is therefore essential that low-carbon ways are developed to use hydrocarbons, and new export industries are created. Hydrogen is a carbon-free fuel or feedstock. Low-carbon hydrogen represents a potential route to decarbonise domestic industry and to create new export streams, whether hydrogen directly, or hydrogen-derived industrial materials such as ammonia, plastics, synthetic fuels and steel.

Figure 2: Carbon intensity for various hydrogen production pathways, including projected UAE hydrogen from electrolysis carbon intensity with target grid[8]



According to the International Energy Agency (IEA), current pure hydrogen demand has grown approximately four-fold since 1975, reaching around 75-85 million tonnes (Mt) in 2018. Meanwhile, global demand for hydrogen in all forms[9] is nearing 120 Mt (Figure 3). Pure hydrogen is produced almost entirely from fossil fuels, using 6% of global gas production and 2% of global coal production, resulting in around 830 $MtCO_2e$ – 2.7% of world energy-related CO_2 emissions. Demand for low-carbon hydrogen is expected to grow significantly, making up 6% of the total final energy consumption by 2050, according to IRENA. The Hydrogen Council, however, is more aggressive, estimating hydrogen to supply 18% of world energy demand by 2050.

In 2019, GCC countries' consumption is estimated at around 7 Mt (Figure 4), with the UAE's H_2 demand standing at almost 0.5 Mt, driven mainly by industrial applications (fertilisers, steel and oil refining). GCC H_2 demand is expected to reach 25-50 Mt in the next 30 years, including direct use in industries such as steel-making, rising demand for cleaner oil refining, and the production of ammonia and methanol for industrial, power and transport applications (Figure 5).

The UAE priorities have to be defined. At the moment, a strong market pull for low-carbon hydrogen and related materials is emerging from Europe and Japan in particular. The UAE can avail of significant near-term opportunities in these export markets, while simultaneously

Figure 3: Global annual demand for hydrogen[10]

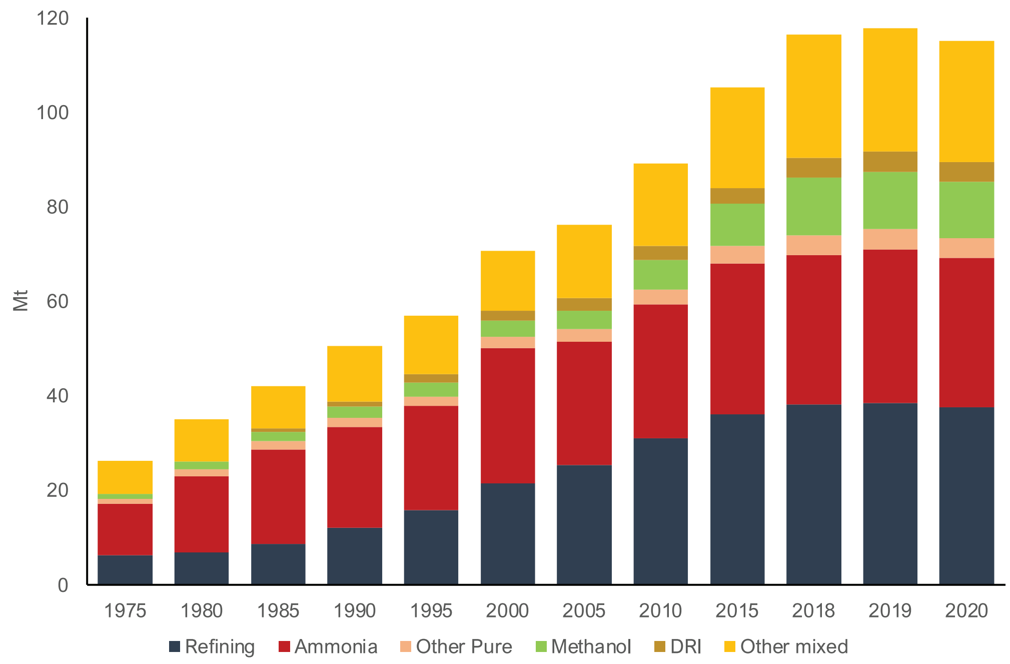
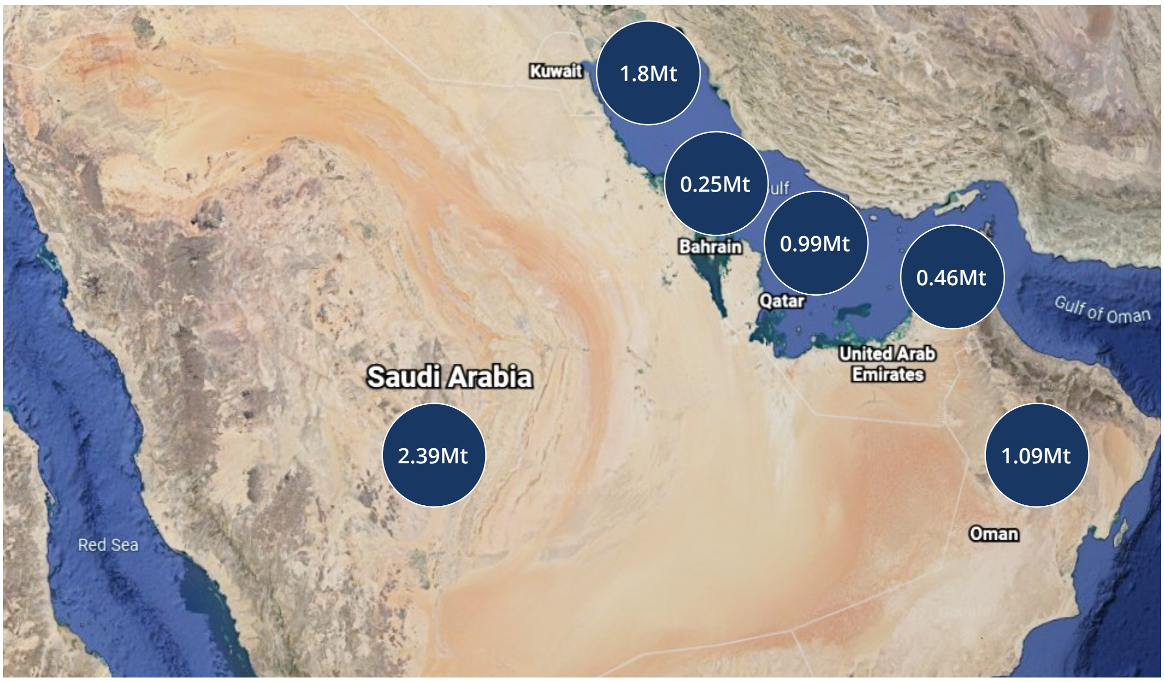
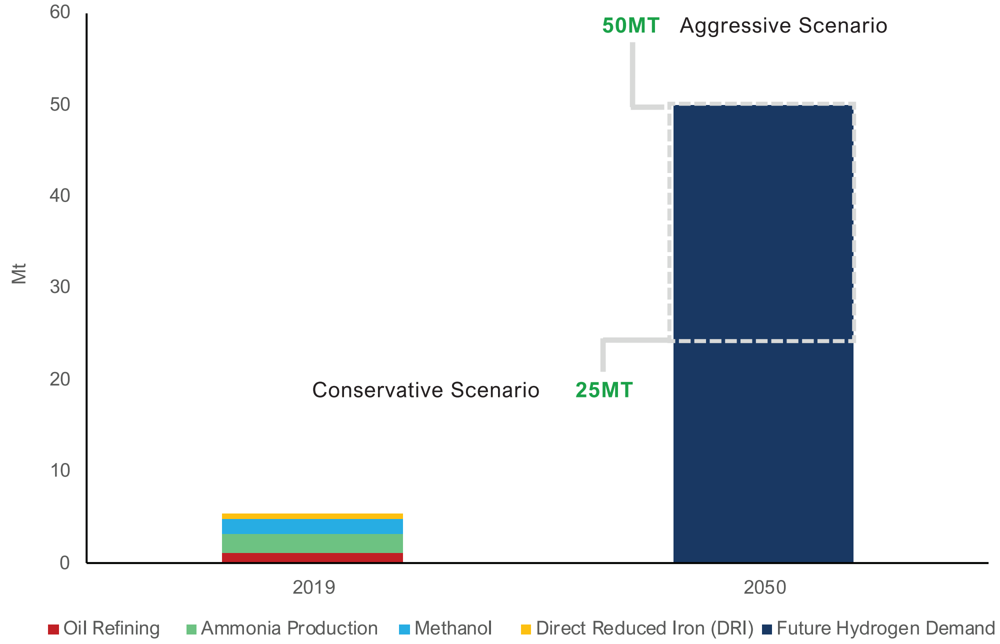


Figure 4: Hydrogen demand in the GCC countries, 2019



developing local applications of hydrogen such as transport and replacing grey hydrogen use domestically. However, these have to be assessed against two pre-requisites: the absence of low-carbon accounting standards and the current lack of a national carbon price or other incentives and requirements to use low-carbon hydrogen.

Figure 5: Current and future H_2 demand in the GCC countries[11]



Note: The Conservative and Aggressive Scenarios are defined based on the level of renewable deployment that can be achieved in GCC countries. Under the Conservative Scenario, the GCC countries continue their renewables deployment in line with 2030 targets (~100-140 GW per decade), enabling them to dedicate this capacity for ~150-210 GW of electrolysis capacity to produce 50-70 MT of hydrogen per year by 2050.

Under the Aggressive Scenario, GCC countries deploy a renewable capacity of 700-1,000 GW to power ~350-500 GW of electrolysis capacity, that can produce 80-100 MT of hydrogen per year by 2050. This scenario assumes that GCC countries can address a larger share of the market. Chile, for example, plans to deploy 300 GW for hydrogen production by 2050; since the GCC is ~3 times larger than Chile in surface area, it could deploy up to 3x Chile's capacity for hydrogen production.

The UAE's decarbonisation actions have historically focussed more on power generation and energy efficiency. To align with decarbonisation targets elsewhere, and measures such as an EU carbon border tariff, decarbonised materials (such as steel and ammonia) can be produced for export. As it already has with aluminium, the UAE could leverage competitive local low-carbon energy resources and preferred costs to become a leading international supplier of steel, chemicals and other hydrogen derivatives. These materials would be easier to transport globally than native hydrogen. An alternative approach, already explored by other players in the GCC, would be to export a fuel such as liquefied petroleum gas (LPG) or ammonia, which would be reformed into hydrogen in the destination market or used as blendstock, then receive back a shipment of carbon dioxide for storage.

In a conservative scenario[12], GCC countries could supply around 20 Mt of hydrogen and derivatives to European and East Asian markets by 2050 – equivalent to 10% of Europe and East Asia's market. This could generate US$ 30-40 B in annual export revenues. In an aggressive scenario[13], the volume would increase up to 50 Mt by 2050, 30% of Europe and East Asia's market, reaching US$ 80-100 B in annual revenues.

The strategies of the EU and some of its constituent member states, and of Japan, Singapore and South Korea, imply that despite domestic production, sizeable imports will be required to meet consumption targets. For instance, EU H_2 imports are forecast to reach 100 Mt by 2050 with Germany and Belgium importing 25 Mt each. Meanwhile, Japan is projected to import 85 Mt of ammonia[14].

The UAE is geographically placed to serve both European and Asian markets, but will still have to compete successfully with closer suppliers: North Africa and Russia in the case of Europe, Australia in the case of Asia, as well as with its GCC neighbours. Since these markets are paying a green premium on the basis of low-carbon life-cycle, competition in these markets will be a function of both carbon footprint and price.

The UAE's most attractive export market may lie in South Asia, which is geographically close and could even be connected by pipeline, if this proved a feasible economic option given the distance and water depths. The South Asian countries have not announced much by way of hydrogen use so far, but could be significant markets by 2050 given their huge populations, rapid projected economic growth, and decarbonisation imperative. This suggests the UAE could benefit from bilateral partnerships with South Asian governments and companies to develop supportive hydrogen policies and projects.

Finally, hydrogen offers support to the UAE's innovation agenda. This encompasses the technology and skills in scaling up hydrogen production, reducing its costs and establishing markets and business models. The availability of hydrogen then allows for decarbonisation of many industrial processes and the creation of entirely new industries, supporting initiatives including the Ministry of Industry and Advanced Technology's 'Make It in the Emirates'[15]. As a stable and business-friendly location, the UAE is a natural centre for the hydrogen industrial ecosystem, including research and training, technology development, manufacturing, logistics, trade, finance and supporting activities.

Table 1: UAE environmental and climate-change commitments

Clean Energy/ Efficiency Targets	**2021**	The UAE set a clean energy target of 27%, targeting nuclear and solar energy. The country's current installed electricity capacity stands at around 40 GW.
	2024	The UAE expects 20% of its power generation capacity to come from clean energy sources. The country will have around 50 GW of generating capacity by 2024, with more than 11 GW coming from renewables and nuclear.
	2030	The UAE plans to reduce greenhouse gas (GHG) emissions 23.5% below BAU (310 Mt). This absolute, economy-wide target covers sectors including Energy, Industry Processes and Product Use, Waste, Agriculture, Land Use Change & Forestry. It covers all the major GHGs including carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and perfluorocarbons (PFCs). The Abu Dhabi National Oil Company (ADNOC) announced a 25% GHG emissions intensity reduction target. The Emirate of Dubai aims to reduce electricity consumption by 30% below BAU. The Dubai Green Mobility Strategy targets a 2% share of electric and hybrid cars and a 30% share in Dubai's government-procured vehicles.
	2036	The UAE's Water Security Strategy aims to reduce potable water consumption by 20% and increase reuse of treated water to 95%. The country targets over 50% increase in the share of reverse-osmosis (RO) based desalinated water in potable water supply.
	2050	The UAE's National Energy Strategy 2050 aims to increase the share of clean energy, including renewables and nuclear, to 50% of the installed power capacity mix by 2050 and reduce final energy consumption by 40% versus business-as-usual. The Ministry of Energy and Infrastructure renewed its commitment to cut the country's CO_2 emissions by 70% by 2050.

The UAE government is working on a National Hydrogen Plan, which is still in the initial stages. The Ministry of Energy & Infrastructure has completed a position paper which includes the elements required to understand the existing resources, stakeholders, and key players. The Plan aligns with the Supreme Council for Financial & Economic Affairs' mandate for ADNOC to become a "hydrogen leader", which will also underpin the National Roadmap for hydrogen.

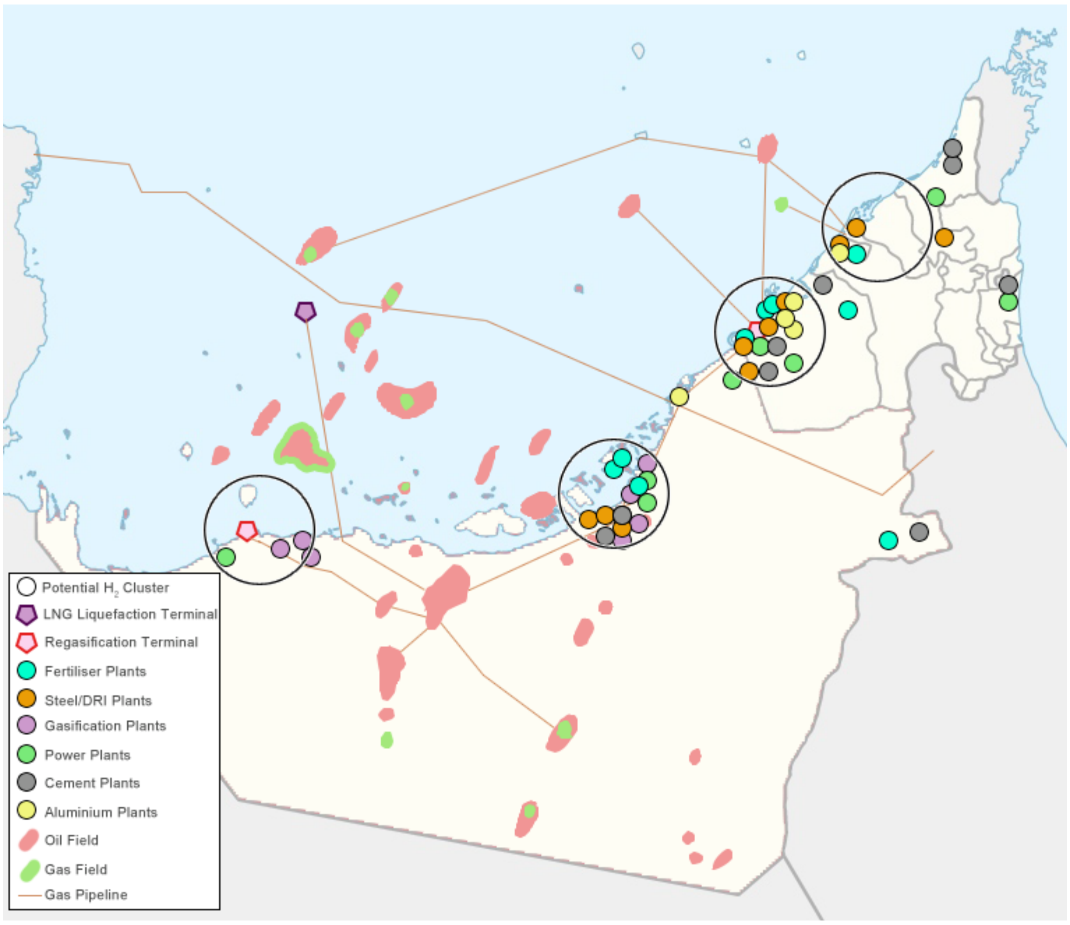
2. UAE'S COMPETITIVE ADVANTAGES

The UAE's competitive advantage in hydrogen can be divided into three categories: those relating to blue, those to green, and those to hydrogen in general.

For **blue hydrogen**[16], key hydrocarbon-related infrastructure is already available (Figure 6), and includes natural gas production, storage, pipeline transport and liquefied natural gas (LNG) export and import; gas-fired power plants; hydrogen-producing and -using facilities (ammonia plants, refineries, petrochemical plants, direct reduced iron); and CO_2 storage sites (the Rumaitha and North-East Bab enhanced oil recovery locations). Major field development projects are underway to achieve national gas self-sufficiency by 2030, by developing unconventional resources, sour gas, particularly offshore, and the gas caps of oil-fields.

As noted, the UAE is already a major producer and user of hydrogen, though this is consumed within company facilities rather than being sold as a commodity. Embodied blue hydrogen (i.e., products made from blue hydrogen) is already used and exported in the form of steel made with syngas, containing hydrogen, from the direct reduced iron (DRI) process with CCUS. With a relatively moderate investment, it may be possible to capture additional amounts of by-product H_2 and waste CO_2 to increase the output of blue hydrogen, which can then be used in the domestic economy or converted to exportable products such as ammonia.

Figure 6: Abu Dhabi and UAE's major natural gas infrastructure, including industry for potential hydrogen use, and major CO_2 emitters for capture to expand gas production, and consequently blue hydrogen production[17]



The most promising existing blue hydrogen opportunities in the UAE (Table 2) are for steel/DRI, oil refining and fertilisers. Gas-fired power plants, which dominate the current UAE generation fleet and are used for aluminium smelting, can be adapted to run on hydrogen or ammonia, for seasonal energy storage and load balancing. Hydrogen can also produce high-temperature heat for cement and other industry, but this is less of an immediate priority due to high costs. Industrial and port clusters offer the potential for hubs[18], as in the popular European concept of 'hydrogen valleys'. The emerging centres in the UAE, shown in Figure 6, would be Ruwais (port, gas processing, refining, petrochemicals, ammonia, nuclear power); Musaffah-Taweelah near Abu Dhabi city (port, petrochemicals, gas infrastructure, refining, steel, aluminium); and the Jebel Ali-Dubai-Sharjah-Ras Al Khaimah belt (ports, gas infrastructure, refining, aluminium, chemicals, cement).

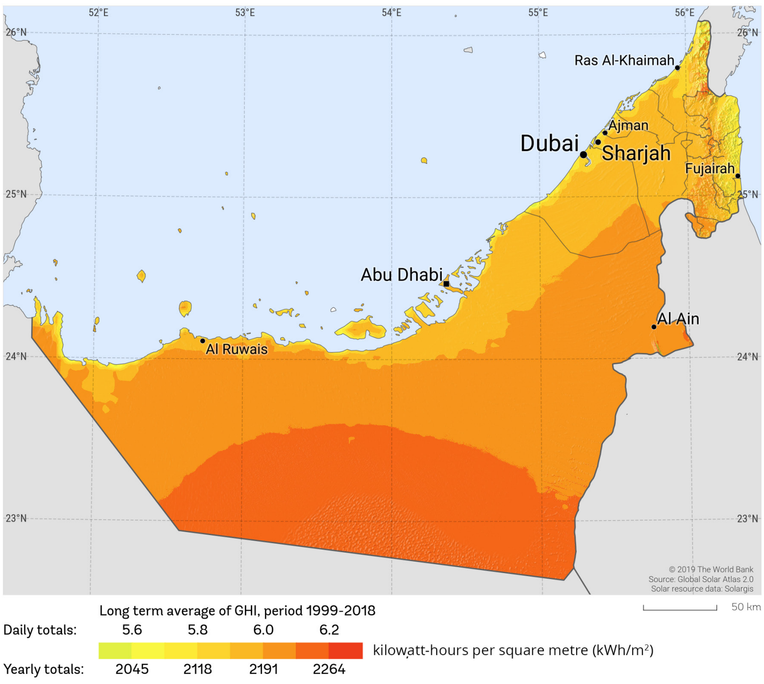
Table 2: Existing UAE industry is well-placed to support blue H_2 as a transitional or complementary track to green[19]

Sector	Can Produce H_2	Can Utilise H_2	Typical world benchmark emissions	Can Support CCUS	Best Configured for H_2 produced through
Steel / direct reduced iron (DRI)	Currently only a small amount of residual H_2 is produced	Yes; H_2 can be used as an auxiliary or sole reducing agent	1.9 tCO_2 per tonne of steel	Yes; can either have a dedicated CCUS facility for own emissions, or, by design modification to utilise H_2 instead of fossil fuels, can indirectly support capture of CO_2 due to demand for (blue) H_2; captured CO_2 can be used for EOR and more natural gas for blue H_2	Blue H_2; in future, green H_2
Refining	Yes; refinery crackers and gasification units produce H_2 as syngas; naphtha reformers produce excess hydrogen	Yes; refineries use hydrogen for desulphurisation	~ Varied ~	Yes; can have a dedicated CCUS facility for CO and CO_2 syngas; H_2 can be used for fuel cells for electricity	Can support both blue and green H_2
Fertilisers		Yes; fertiliser plants reform methane to H_2 and combine it with nitrogen taken from the air to make ammonia	2.9 tCO_2 per tonne of ammonia	Yes; easily configurable to support CCUS of emissions	Blue H_2; in future green H_2 for production of ammonia
Power Plants		Yes; can replace natural gas or other fossil fuels for generation	0.33 tCO_2 per kWh for high-efficiency gas power	Yes; can either have a dedicated CCUS facility for own emissions, or, by design modification to utilise H_2 instead of fossil fuels, can indirectly support capture of CO_2 due to demand for (blue) H_2; captured CO_2 can be used for EOR and more natural gas for blue H_2	Green H_2 or ammonia, or renewables and nuclear
Aluminium		Yes; can be used as fuel for power generation to allow continuous operation	11.5 tCO_2 per tonne of aluminium	Yes; can either have a dedicated CCUS facility for own emissions, or, by design modification to utilise H_2 instead of fossil fuels, can indirectly support capture of CO_2 due to demand for (blue) H_2; captured CO_2 can be used for EOR and more natural gas for blue H_2	Blue H_2; in future, green H_2 or electrification of production
Cement		Yes; can generate sufficient heat, displacing currently used natural gas, fuel oil or coal	0.5-0.7 tCO_2/ tonne cement of which about 40% from fossil fuel combustion	Yes; can either have a dedicated CCUS facility for own emissions, or, by design modification to utilise H_2 instead of fossil fuels, can indirectly support capture of CO_2 due to demand for (blue) H_2; captured CO_2 can be used for EOR and more natural gas for blue H_2	Blue H_2; in future, green H_2

For **green hydrogen**, the key is the availability of low-cost renewable energy. The UAE is better than on track to reach 14 GW of clean energy capacity by 2030 from just above 100 MW in 2015 and 2.4 GW in 2020 (Figure 9), 91% of which consisted of solar PV. Qamar Energy expects solar PV capacity to reach 9.2 GW in the UAE by end-2025. **The country's 2020 target of 7% renewable energy share in the power generation mix has already been achieved**, suggesting that the 2030 and 2050 targets are well within reach. Abu Dhabi and Dubai house the majority of renewable capacity, together making up 90% (8.3 GW) of the total by 2025[20]. The 2 GW Al Dhafra PV plant, the 1.5 GW Abu Dhabi PV3, and the 950 MW Mohammed bin Rashid Al Maktoum (MBR) Phase V are expected to drive the growth in solar capacity, while the remaining 0.9 GW will come mostly from Umm Al Quwain, Ras Al Khaimah and Sharjah emirates. So far, out of the US$ 163 billion that the UAE has allocated for clean energy projects until 2050, the country has invested over US$ 40 billion in clean energy in the UAE and more than US$ 16.8 billion across 70 countries.

The UAE sits in a very convenient location on the Sunbelt, enjoying amongst the highest yearly solar energy input out of 207 regions. The country gets 10-15 hours of sunshine almost every day, which is adequate for energy storage technologies to operate around the clock[21]. Dubai receives around 2,200 kilowatts per square metre (kW/m^2) of Global Horizontal Irradiance (GHI), with a Direct Normal Irradiance (DNI) at 1,900 kW/m^2 per year (Figure 7).

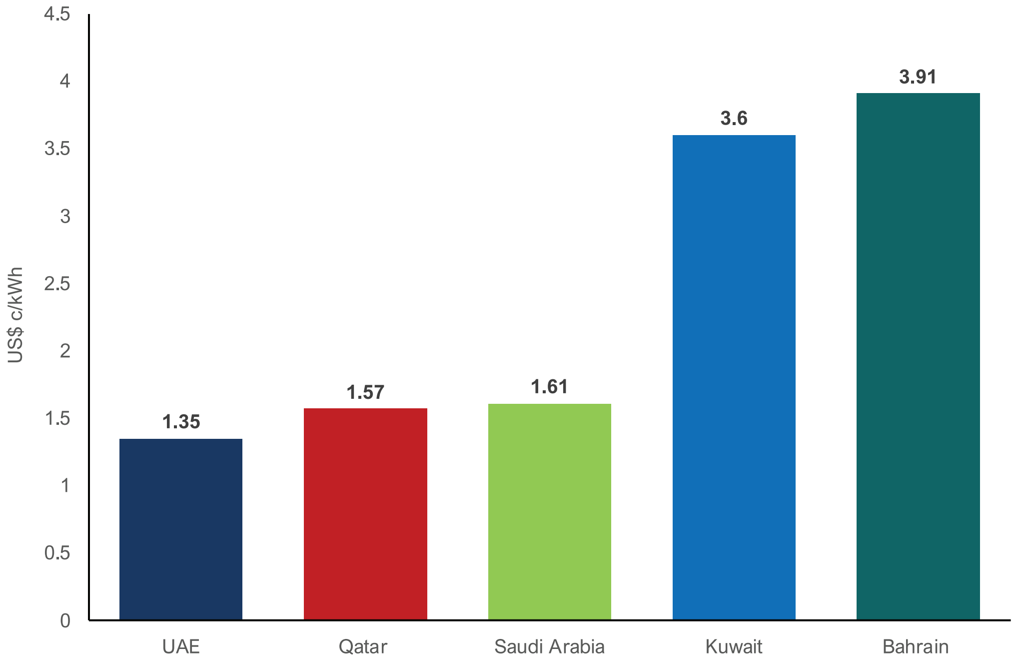
Figure 7: Global horizontal irradiance (GHI) in the UAE



Credit: World Bank Group, ESMAP, Solargis

UAE is home to one of the lowest tariffs in the world, with a 76% drop in prices in the past four years. In 2014, the region's largest utility-scale solar plant was the 200 MW project of Dubai's Sheikh Mohammed bin Rashid (MBR) solar park, selling electricity at 5.84 ¢/ kWh, a record at the time. In mid-2020, Emirates Water and Electricity Company (EWEC) awarded the 2 GW Al Dhafra PV plant to the lowest bid of 1.35 ¢/kWh in mid-2020, one of the lowest solar power purchase agreement (PPA) prices in the world (Figure 8). Dubai also achieved what was then a record-low

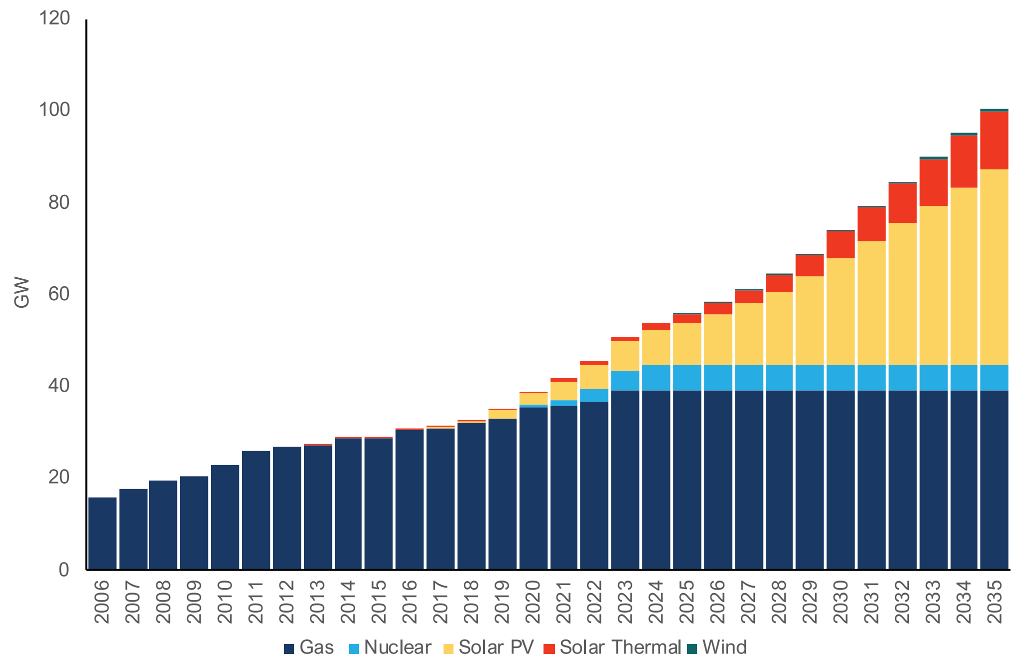
Figure 8: Renewable Power Purchase Agreement Prices in the Gulf Cooperation Council Countries[22]



price for concentrated solar power, 7.3 ¢/kWh for the 700 MW project awarded in September 2017.

Based on these low achieved costs, the UAE's installed renewable capacity is set to grow strongly (Figure 9). This provides a strong base to develop renewable-powered electrolysis. In addition, the

Figure 9: UAE historic and forecast installed power generation[23]

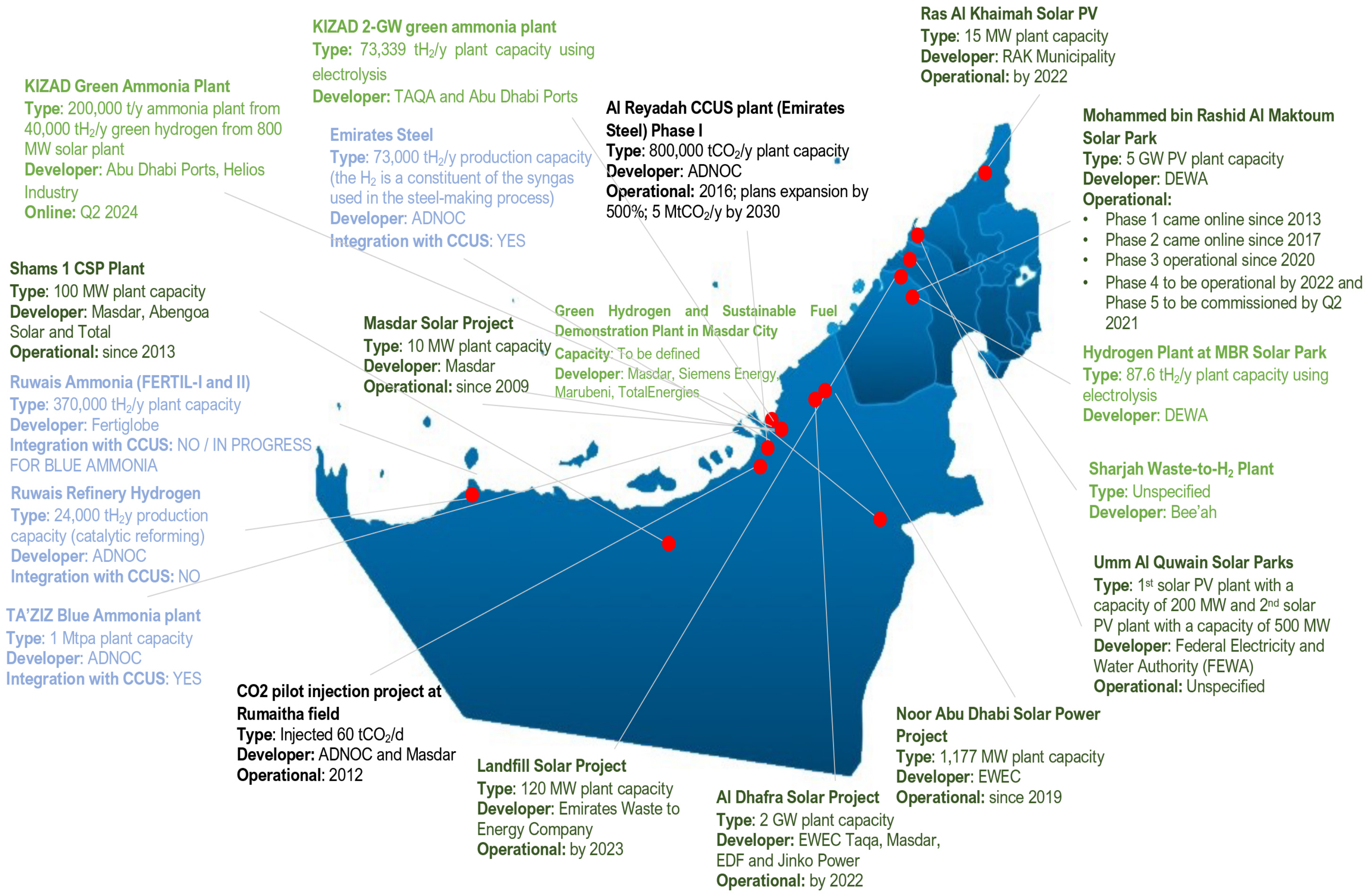


installed base of nuclear power in low-demand periods can provide electricity at very low variable costs.

Finally, general advantages for hydrogen include the UAE's established status as an energy and international business hub. The country has built relationships with energy customers, notably in Asia, over many decades and established a relationship as a reliable supplier. Most of the world's leading international oil companies, including Shell, Total, BP, ExxonMobil, ENI, Occidental, CNPC, CNOOC, ONGC, INPEX, Mitsui, PTTEP, GS Energy, KNOC, Lukoil and others, have an equity presence in the oil and gas sector, primarily in Abu Dhabi as partners to ADNOC. Mubadala and Taqa (majority-owned by ADQ) also have international energy businesses in oil, gas and power.

Existing infrastructure is of high quality, and most multinational businesses choose the country as their regional centre. The country's strong financial resources are underpinned by a high credit rating (Fitch assesses the UAE at AA- and Abu Dhabi at AA), and the substantial assets of sovereign wealth entities Abu Dhabi Investment Authority (ADIA), Mubadala, ADQ, and Investment Corporation of Dubai, as well as private funds. A strong push for technology-led growth is combined with specific policies, including incentives for innovative businesses to set up, and recent reforms of laws on foreign ownership and residence. Such attractions are important for complementing the UAE's inherited competitive advantages in hydrogen, which may be shared by some regional peers.

Figure 10: RE, CCUS and H_2 projects in the UAE[24]



3. THE UAE’S BALANCED APPROACH

Blue and green hydrogen are complementary pathways

Blue hydrogen is an important and necessary step towards the UAE's overall hydrogen ambitions. It will play a critical role in realising the country's second and new NDC under the 2015 Paris Agreement. Carbon capture, use and storage (CCUS) is recognised as a key facilitator of the transition to a low-carbon future in the UAE[25]. The country has reiterated its commitment to trialling all possible options in its fight against climate change, and maintains that CCUS, alongside all other mitigation measures, is essential to achieve its hydrogen, and by extension, climate targets.

One of the key aims of ADNOC's US$ 122 billion budget over 2021-25 is to make the UAE self-sufficient in gas and also cover the development of low-carbon hydrogen. ADNOC has been among the first in the region to recognise the shift in customer preferences toward lower carbon fuels, particularly in Europe and OECD Asia Pacific. This has informed the development of core competencies in blue hydrogen, particularly through international partnerships and joint ventures, and the firm's recent entry into the Hydrogen Council, the international initiative of energy, transport, industry and investment companies to develop the global hydrogen economy[26].

> *"With the recently announced Hydrogen Alliance, ADNOC is leading the emirate's efforts to develop this promising sector for internal consumption, while also exploring the potential to export to countries where generation costs might be significantly higher."*
>
> **H.E. Eng. Awaidha Murshed Ali Al Marar, chairman of the Abu Dhabi Department of Energy (DoE)**

H.E. Dr Sultan Al Jaber, UAE Minister of Industry and Advanced Technology and ADNOC Managing Director and Group CEO, stated his firm's ambition of becoming "one of the lowest cost and largest producers of blue hydrogen in the world". The UAE has a strong foundation on which to build to realise this ambition. Through ADNOC and Emirates Steel, it already has sophisticated, mature CCUS capabilities responsible for capture, compression and transportation of 0.8 Mtpa CO_2 for injection into ADNOC's onshore oilfields for enhanced oil recovery (EOR). The firm is planning to expand CCUS further[27], and it is an integral aspect of the firm's 2030 strategy which aims to reduce greenhouse gas intensity by 25%.

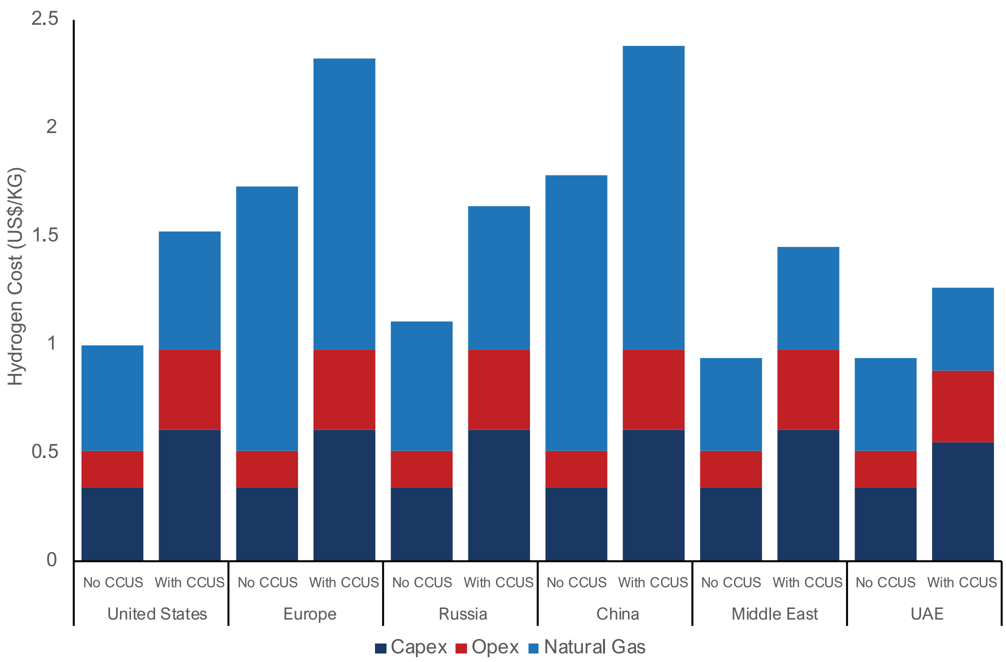
> *"The UAE is well positioned to assume a leadership role in the emerging global hydrogen economy as nations around the world begin to embrace new sources of low carbon energy. ADNOC aims to further the UAE's energy leadership by becoming one of the lowest cost and largest producers of blue hydrogen in the world."*
>
> **H.E. Dr Sultan Al Jaber, UAE Minister of Industry and Advanced Technology and ADNOC Managing Director and Group CEO**

All hydrogen currently produced in the UAE is made from fossil fuels without CCUS, and is therefore categorised as grey. ADNOC produces 0.3 Mtpa of hydrogen (excluding hydrogen produced at joint venture ADNOC Fertilisers (Fertil), with 1.2 Mtpa ammonia capacity) from its existing facilities for use in its downstream operations, which is planned to increase to 0.5 Mtpa. It is currently assessing its existing facilities, including refineries and petrochemical plants, to assess how much surplus hydrogen may be available, and how much CO_2 can be captured relatively straightforwardly to convert grey to blue hydrogen production.

The ambition has resulted in concrete investment plans. ADNOC is planning to build a 1 Mtpa blue ammonia production plant in the industrial hub of Ruwais as part of the Ta'ziz Industrial ecosystem, a sophisticated new industrial hub for the country's chemical and manufacturing sector. The plant will come into action in 2025, and is part of a US$ 5 billion Phase-1 investment plan, launched as a joint venture between ADNOC and ADQ.

New CO_2 capture technologies are in development to further drive down operational costs, including chemical looping processes, new adsorption methodologies, and new physical and chemical solvents for use in absorption processes, as well as novel membranes for the separation of CO_2 from other gases. These can support the development of large blue hydrogen hubs, benefiting from the economies of scale in CCUS capabilities that reduce the total unit cost.

Figure 11: Cost of hydrogen production using natural gas[28]



For example, ADNOC's plans to significantly expand its CO_2 capture by 2030 can enable the creation of sophisticated, larger industrial-level CCUS infrastructure, where multiple facilities, including hydrogen, can utilise common CO_2 transport and storage infrastructure, reducing risks and costs of capital. Even though average feedstock costs (natural gas) in the UAE are among the lowest in the world, reducing the capital intensity will further lower the unit cost of production.

Current blue hydrogen production costs vary depending on the cost of the feedstock, i.e. natural gas. The inclusion of CCUS raises the required gas input by about 10%, and the overall cost of the produced hydrogen by about 35-50% depending on the CO_2 capture rate. The cost of low-carbon hydrogen (with CCUS) is in the range of US$ 1-2.3 per kg, equivalent to US$ 7.9-18.2/MMBtu of natural gas, expensive in current terms, but within the range of historic gas/LNG prices[29].

The Middle East has the lowest cost of hydrogen production, unsurprisingly, due to the low cost of domestic natural gas. According to external sources including the International Gas Union, PwC and KAPSARC, current natural gas prices to industry are within the range of US$ 2.15-3/MMBtu[30], among the lowest in the region. Even though the inclusion of CCUS would increase the cost of production for an industrial-level hydrogen facility by a factor of 1.5, the UAE could still boast one of the lowest costs for blue hydrogen production in the world. Adjusting the IEA's estimates to allow for gas prices, CCUS costs and reasonable cost reductions for economies of scale suggest an achievable production cost of ~ US$ 1.3/kg – almost the same cost of grey hydrogen production in some markets (e.g., U.S.) and cheaper than other key markets (EU, China, India). Existing well-established natural gas supply chains can contribute to further cost savings. Achievable sales prices to domestic or international customers would depend on the market structure and competition.

The UAE's effective CO_2 storage costs are likely to be lower than most locations. Storage sites are formed by giant, well-characterised and high-quality reservoirs, with very effective overlying seals, in shallow water or open desert, and in close proximity to the sites of CO_2 production. Where CO_2 is used for EOR, it replaces valuable natural gas currently being reinjected, thus realising a double benefit.

"With Abu Dhabi's largest portfolio of energy and utilities investments, ADQ will play an important role in the transition to cleaner energy while shaping the future of this economic cluster leading to Abu Dhabi's longer-term sustainability. Additionally, as ADQ continues to develop key clusters in the local economy, including mobility and logistics, we are well-placed to drive local adoption in sectors with high energy demand."

H.E. Mohamed Hassan Alsuwaidi, CEO of ADQ

In terms of underground hydrogen storage, the UAE houses deposits in the Hormuz salt of Eocambrian age and Miocene salt. The Jebel Dhanna structure, near the Ruwais industrial hub and hydrocarbon port, is covered by residues of the salt sequence, which is hundreds of metres thick, due to dissolution. Such storage sites can be used as buffers allowing for seasonal balancing of output, and to smooth export logistics. In January 2018, Dubai Electricity and Water Authority (DEWA) signed an MoU with Belgium's Dredging, Environmental & Marine Engineering Group (DEME) and the GCC Interconnection Authority (GCCIA) to assess the potential for a large-scale hydrogen energy storage site[31].

"With the exceedingly low cost of solar PV, the declining costs of electrolyzers, and readily available natural gas, the UAE is well positioned to tap into numerous opportunities across the hydrogen value chain. As a responsible investor and an active player in the energy transition, Mubadala will continue to partner with leading entities to develop the UAE's clean hydrogen ecosystem and advance the role of hydrogen in meeting future energy demand globally."

Musabbeh Al Kaabi, CEO of UAE Investments at Mubadala

For such sectors, particularly refineries and fertilisers, hydrogen is not only an energy carrier, but a key feedstock.

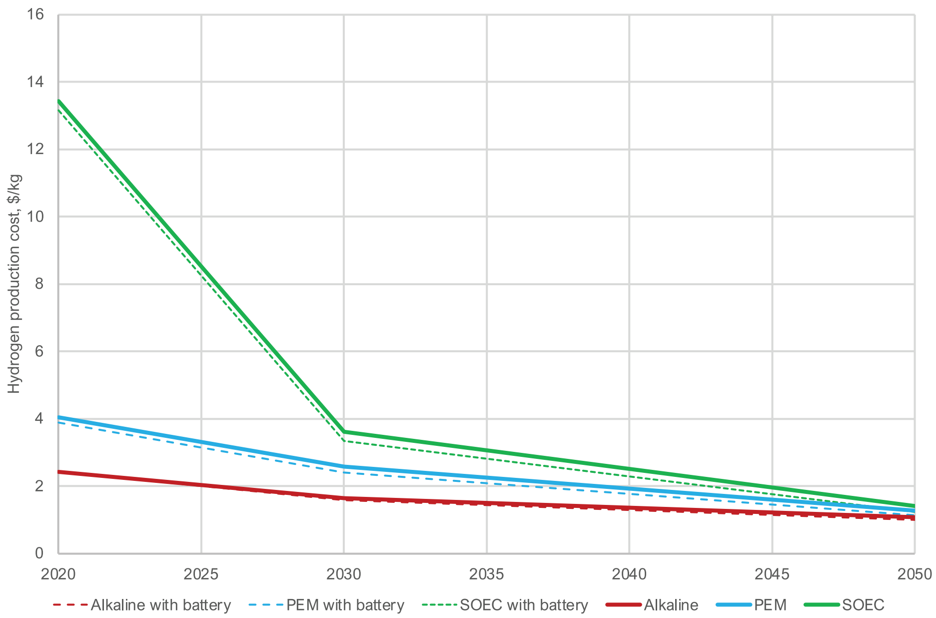
Table 3: Hydrogen production costs using electrolysis[32]

Method	Process	Cost (US$/kg$H_2$)
Electrolysis (Renewables)	Alkaline 5c, 100% load	3.5
Electrolysis (Renewables)	Polymer electrolyte membrane, 100% load	5.4
Electrolysis (Renewables)	Solid Oxide Electrolyser Cell, 100% load	16.7

On an international level, the cost of clean, green hydrogen is still 3-10 times higher than that of grey, while blue hydrogen is twice that of grey. In the UAE, the Abu Dhabi Hydrogen Alliance between ADNOC, Mubadala and ADQ expects the country's recent partnerships on competencies to result in technology improvements that can drive the cost of electrolysers for green hydrogen production down. The cost of hydrogen from electrolysis depends on the technology used and its efficiency, its costs (primarily capital, with operating costs less important), the cost of input electricity, the lifetime of the electrolyser, and its load factor (how much is used relative to maximum capacity).

Hydrogen from electrolysis in the table above assumes 100% load factors for the electrolysers. Using cheap off-peak renewable energy, the electricity cost for electrolysis can be reduced, but with lower load factors leading to higher overall production costs. Figure 12 shows the estimated costs achievable under UAE conditions from electrolysis using solar PV, with or without battery storage, for the three main technology options (alkaline, polymer electrolyte membrane (PEM) and solid oxide electrolytic cell (SOEC)). Given the uncertainties, by 2050 the cost of hydrogen production from each option is very comparable and the choice will depend on the local situation, technological progress, and operational issues such as the ability to ramp up and down easily, and the potential use of waste heat by the solid oxide system.

Figure 12: Cost of hydrogen production from electrolysis[33]



Therefore low-carbon electrolytic hydrogen needs to be produced from renewables and/or other clean energy with high availability and low costs, possibly a combination of solar PV, off-peak nuclear, concentrated solar thermal power (CSP) and batteries. These play to the UAE's strengths. On the other hand, the UAE has a relatively limited wind resource, while other locations in Oman, Saudi Arabia and Morocco have strong combinations of wind and solar resources. This suggests that the UAE's situation would be more favoured by electrolysers with low capital costs even if less efficient.

4. BUILDING THE EMERGING HYDROGEN BUSINESS

As mentioned, blue hydrogen produced from gas with CCUS is the lowest-cost method for clean hydrogen production today, and will likely remain so this decade. Actual costs for production of both blue and green hydrogen depend not only on site and project specifics, but technology requirements for production, conversion, storage, and transport, as well as usage of precious metals in electrolysers. The cost of transport and storage of CO_2 from blue hydrogen production has an impact on the overall cost of hydrogen production. For example, producing 1 kgH_2 (blue) yields 8 kgCO_2, which needs to be transported and stored, or utilised by a suitable industrial offtaker.

In the UAE, existing industry is well-established with potential offtakers in close proximity to emitters and hydrogen production units. Demand centres, such as cement plants, steel manufacturing units, smelters, and fertiliser plants are mostly concentrated in the Musaffah – Taweelah / Kizad – Dubai – Sharjah – Ras al Khaimah belt in a linear fashion, with an existing gas transmission network making the logistics, and therefore cost, of transporting blue hydrogen from production facilities to these centres significantly cheaper.

Current CO_2 capture technology for hydrogen production can be modified economically to output CO_2 in all forms (dry, liquid, and gas), making it more advantageous to the local UAE market, which also has a sizeable small-scale demand in the form of agricultural greenhouses, the food and beverage industry, and medical equipment manufacturers. If existing capture technology can be modified to decrease CO_2 capture costs from the current range of US$ 60-80/tonne to a range of US$ 40-50/tonne, it can result in further cost savings per unit of blue hydrogen. Capture technology costs have dropped dramatically over the past decade, and several important technology pathways should achieve those price targets this decade[34]. Also, since most of the plant components required to capture CO_2 are already required to produce hydrogen, the increment in the cost of hydrogen owing to modified CO_2 capture technology should be moderate.

ADNOC's sophisticated institutional and technical capabilities lend themselves well to the creation of a national low-carbon champion through partnerships with innovative, lower-cost carbon capture technology providers, which can aid in the transition towards low-cost clean hydrogen. During production, when both CO_2 and H_2 are under pressure, low-cost retrofitting could enable the extraction of the CO_2 at a high purity and elevated pressure, well-matched to CCUS. This leaves behind a less-than-pure form of hydrogen, but is concentrated enough to be commercially useful, sometimes also called refinery hydrogen. Existing technology for the extraction of hydrogen at high purity, also known as fuel-cell-grade hydrogen, is limited, and runs into a problem when burning off residual hydrogen, as the exhaust stream contains the CO_2 from the conversion process, but in a diluted form, making it harder to capture than the previous option. This demands new and innovative capture technology, to meet the joint goals of high purity hydrogen and low-cost CCUS. There are potential synergies between blue and green hydrogen, for example, the use of by-product oxygen from electrolysis as input to an autothermal reformer to produce hydrogen from natural gas.

Post-2030, green hydrogen will benefit from reliable supply of low-carbon electricity and improving electrolyser technologies. The expected continued decrease in the cost of renewable electricity in the region, led particularly by the UAE, through economies of scale, improved manufacturing, technological innovations and low financing costs, could result in the current levelised cost of green hydrogen production dropping by 30%-50% in the GCC[35]. Scale-up of manufacturing activities (such as electrolysers and other equipment in the hydrogen value chain) could result in significant cost reductions, enabling potential upgrade of new electrolysis systems to synthetic fuels, transport, storage, and other innovative demand-side processes. Improvements of cost and performance for both blue- and green-hydrogen technologies is also growing as the focus of national innovation programs[36]. Such improvements are required for both blue and green hydrogen to reach viability with currently-produced grey hydrogen and fossil fuels when carbon costs are accounted for.

In addition, electrolysis requires water of drinking water quality, which might not exist in adequate supply, especially in arid regions. The requirement for desalination moderately raises the cost of hydrogen production via electrolysis, and increases its carbon footprint unless carried out with reverse osmosis using low-carbon electricity. The UAE could benefit from electrolysis of seawater, which researchers globally are trying to develop, rather than requiring fresh (desalinated) water as an input.

Engineering and design activities for CCUS and electrolysis systems could be localized in the medium and long-term. In fact, clean hydrogen is a specific new focus of the multi-national Mission Innovation program, launched during the 2021 Clean Energy Ministerial[37]. Innovation focus can be cross-cutting, and include novel materials (notably catalysts), improved system integration, component improvement, and efficiency gains[38]. R&D activities like these are currently being promoted by Mubadala to gain technological leadership along the hydrogen value chain, for instance the replacement of costly platinum-group metals in electrolysers with cheaper alternatives. These activities can target opportunities that arise from the specific requirements for hydrogen production, as well as transportation and transportation vectors.

The UAE could be an advantaged hydrogen exporter of the near-future due to its proximity to major demand centres. This allows for two transport options: pipelines or shipping. The UAE's strategic coastal location is well-suited to exporting hydrogen and ammonia via ships, as evidenced in recent hydrogen deals targeting exports to Asian markets. Because hydrogen's volumetric energy density (MJ/m^3) is low, even in compressed or liquefied form, long-distance transport of native hydrogen will be costly. Therefore, conversion of hydrogen to ammonia or other hydrogen carriers is a more attractive option for longer distances. ADNOC's Ta'ziz blue ammonia facility can therefore export hydrogen in the form of ammonia to external markets at a much lower cost than as pure hydrogen. If pure hydrogen is required, the ammonia can be reconverted at its destination. Ammonia can also be used directly as a fuel in modified gas power plants and ships, although this requires further testing and experience.

> *"Hydrogen has been on our radar as an opportunity to further lower our carbon footprint in every sector of the UAE economy. It is not only a potential clean energy source in the power mix but can also localize value creation through various derivatives and end uses for the domestic economy."*
>
> **H.E. Sharif Salim Al Olama, Undersecretary of the UAE Ministry of Energy & Infrastructure**

Another alternative could be to use hydrogen domestically to manufacture and export decarbonized products, including iron and steel, cement, methanol, fertiliser, synthetic methane and synthetic liquid fuels, which could be sold for higher value with a "green premium". This could be an attractive route in the long-term because of the higher density of most of these products, and because it would localise more of the value creation, lending support to the UAE's In-Country Value (ICV) programme. Power-to-X and e-fuel applications could potentially become new hydrogen markets in sectors like aviation, shipping, chemical, and petrochemicals, where alternative options to decarbonise are either limited, lacking, or costly. The carbon footprint of these products will feature in the sale price and requires standardised accounting.

The oxygen by-product from green hydrogen production could also be utilized in a number of industries including glass-making, gas power generation with CCUS, synthetic fuels production, metals oxidation, and municipal solid waste gasification. For instance, ThyssenKrupp will build an 88 MW water electrolysis plant in Quebec, where the oxygen by-product will be used in a biofuel plant to produce biofuels from residual waste for the transportation sector[39].

The UAE's step-by-step approach may be most appropriate example for scaling the hydrogen business elsewhere in the region. For example, the strides made by Masdar, Siemens, and DEWA in piloting green hydrogen for use in high-value applications, such as mobility and transport, can enable scale-up to large projects (including both blue and green hydrogen) with significant export potential. Scale-up can also be driven by government policy and national-level directives which target collaborations with international hydrogen pioneers like Japan, Australia, South Korea, Germany, and others, while at the same time developing a regulatory framework to create a market for hydrogen and hydrogen-derived products.

Policies for hydrogen therefore need to synchronise the development of hydrogen production and imports with the creation of infrastructure, standards, markets and end-users. Required regulatory frameworks will have to be combined with the right financial incentives until low-carbon hydrogen technology becomes cost-competitive in large-scale uses. Such tools include certification systems that guarantee low-carbon, and in the future, carbon-free, or carbon negative, hydrogen supply; production incentives[40]; border tariffs; or output-based rebates[41].

Other mechanisms include vertical integration, long-term contracts (to provide a hedge on hydrogen prices for the offtaker while advancing carbon abatement goals), dedicated infrastructure (for transport, storage, distribution, and use), availability of energy inputs, and an overarching enabling policy environment that maintains the competitiveness of the local economy.

Table 4: SWOT Analysis for the establishment of the UAE Hydrogen Economy

Strengths	Weaknesses
• Existing well-established industry and other offtakers for hydrogen; potential for embodied hydrogen sold at green premium • Robust gas transmission network • Cheaper logistics • Strong R&D capabilities to reduce unit cost of blue and green hydrogen • Sophisticated institutional and technical capabilities • Cheap, large-scale renewable energy; lowest tariffs in the world • Improved manufacturing, technological innovation • Lower financing costs • Strategic geographical location for exports; well-characterised subsurface formations for CO2 storage; salt domes for H2 storage • Strong international and public-private partnerships for technology-led growth • High credit and sovereign rating	• Market uncertainty over evolution of cost-competitiveness between blue and green hydrogen • Current small market size • Technology challenges to optimise efficiency and capacity factors for green hydrogen • Current high use of precious metals in electrolysers – can be addressed by localising electrolyser development • Nascent hydrogen infrastructure and regulation
Opportunities	**Threats**
• Green Champion of the region and a Global Hydrogen Leader • Rapid displacement of current grey hydrogen in domestic use • Local applications of hydrogen in transport (Masdar, DEWA already active in this space) • Decarbonisation of industries; creation of new industries • Supports Ministry of Industry & Advanced Technology's 'Make it in the Emirates' initiative • Establishment of the UAE as a regional hydrogen industrial ecosystem	• Growing competition from peers in the region, such as Saudi Arabia and Oman – but opens potential for regional partnerships • Still high-cost of electrolyser technology for green hydrogen • Risk of business interruption costs

5. PROJECTS AND PARTNERSHIPS

The UAE and its corporate entities have been highly active since late 2020 in developing partnerships

Global interest in hydrogen as an energy carrier saw a dramatic acceleration from mid-2020, with the number of Google searches almost tripling. The UAE has been highly active since then in signing cooperation deals on hydrogen with international partners. Internal partnerships are also important, particularly the Abu Dhabi Hydrogen Alliance.

Table 5: ADNOC / UAE Recent Partnerships for Blue Hydrogen

Partners	Deal Type	Signed	Competency	Market
ADNOC, Total	Strategic Framework Agreement (Partnership)	November 2020	Emissions reduction technologies, including CCUS and hydrogen	Local, export
ADNOC, Japan Ministry of Economy, Trade and Industry (METI)	Cooperation Deal (Partnership)	January 2021	Development of supply chain competencies or blue ammonia in the UAE	Export to Asia markets (Japan)
Mubadala, Snam	Memorandum of Understanding	March 2021	Collaboration on investment and development of hydrogen in the UAE and globally	
ADNOC, Korea GS Energy	Opportunity Exploration Agreement (Partnership)	March 2021	Joint exploration of opportunities in blue hydrogen and ammonia as carrier fuels	Export to Asian markets
UAE Ministry of Energy and Infrastructure, Japan Ministry of Economy, Trade and Industry (METI)	Collaboration Agreement (Partnership)	April 2021	Collaboration in hydrogen production, including blue ammonia, and development of a supply chain for exports to Japan	Export to Asian markets (Japan)
India-ADNOC	Dialogue		Oil & gas, energy trade and exports	Supporting India's rising demand for clean energy fuels, by making the full portfolio of ADNOC products available to the Indian market.
ADNOC, Wood PLC Pre-FEED Contract	EPC for pre-FEED for 1 Mtpa blue ammonia production plant	May 2021	EPC for pre-FEED for 1 Mtpa blue ammonia production plant, utilising Wood PLC's international expertise in hydrogen	Local, export
ADNOC, INPEX, JERA, JOGMEC	Joint Study Agreement (JSA)	July 2021	Exploration of the commercial potential of blue ammonia	Export to Asia Markets (Japan)
ADNOC, INPEX	Collaboration Agreement	Upcoming	Demonstration cargoes for blue ammonia	

"This Alliance integrates [ADNOC's] complementary strengths as energy and financial leaders to address the global challenge of meeting energy demand, while reducing emissions."

H.E. Dr Sultan Al Jaber, UAE Minister of Industry and Advanced Technology and ADNOC Managing Director and Group CEO

In January 2020, the Energy Partnership with Germany held a public expert workshop on hydrogen in Abu Dhabi, opened by HE Dr. Matar Al Neyadi, former Undersecretary at MoEI, Thorsten Herdan, Director General at BMWi, and HE Ambassador Ernst Peter Fischer, German Embassy Abu Dhabi. Bringing together around 80 experts from research institutes, industry, and public authorities, the dialogue focused on the future role of hydrogen and areas for potential cooperation. Siemens, TenneT, ADNOC, EWEC, ThyssenKrupp, IRENA, Khalifa University, Abu Dhabi Department of Energy, and Guidehouse presented their expertise. The EP stresses the UAE's excellent hydrogen production potential, which is currently leveraged for the Siemens-DEWA green hydrogen facility[42].

Table 6: ADNOC / UAE Recent Partnerships for Green Hydrogen and Other

Partners	Deal Type	Signed	Competency	Market
UAE Ministry of Energy and Industry (MoEI), German Ministry for Economic Affairs and Energy (BMWi)	Energy Partnership	January 2017	Green hydrogen	Potential for exports to Germany
ADNOC, Mubadala, ADQ	Abu Dhabi Hydrogen Alliance	January 2021	Oil & gas, petrochemicals, power and renewables, nuclear energy, rail, ports, aviation, aluminium, steel, cables, other industry	Green hydrogen in UAE: green and blue hydrogen for export
Mubadala Investment Company-Siemens Energy	MoU for strategic partnership	January 2021	Green H_2 and synthetic fuels, including creating a world-class Abu Dhabi synthetic fuels player	Emerging green H_2 markets
Mubadala, Snam	Memorandum of Understanding	March 2021	Collaboration on investment and development of hydrogen in the UAE and globally	
EDF, ENEC	Memorandum of Understanding	June 2021	Collaboration on potential hydrogen production from nuclear power	

> *"As a responsible investor, we are actively engaged in a number of new energy investments that will contribute to more efficient and lower emission energy solutions. Hydrogen offers significant potential in this regard and with the renewables expertise and experience of Masdar, we are well placed to develop leadership in the green hydrogen value chain."*
>
> **H.E. Khaldoon Khalifa Al Mubarak, Managing Director and Group CEO of Mubadala**

Real projects are essential to build on these partnerships

Tangible projects are essential to build on the momentum of these partnerships. This is especially so given progress by several other regional states.

In January, Masdar, alongside Siemens Energy, the Abu Dhabi Department of Energy, Marubeni Corp., Etihad Airways, German airline Lufthansa, and Khalifa University, joined forces to support the development of Abu Dhabi's green hydrogen economy. The initiative aims to establish a demonstrator plant at Masdar City to explore and demonstrate the concept of sustainable aviation fuel production from green hydrogen as a basis for a large-scale facility. The solar-powered electrolysis facility will showcase green hydrogen production, of which part will be used to demonstrate the use of green hydrogen for ground transportation in the UAE. The main part of the produced green hydrogen will be converted into jet fuel in a kerosene synthesis plant. Decarbonised fuels for the maritime sector will also be explored as part of the program.

The pre-front end engineering and design (FEED) phase of this project has already been initiated and is expected to be completed by the end of 2021, with the construction phase taking two years[43]. It will be financed by different developers, with a cost yet to be determined.

This partnership is placed within the larger over-arching framework of the Abu Dhabi Hydrogen Alliance, established by ADNOC, Mubadala, and ADQ.

Table 7: UAE's planned and operational blue and green hydrogen projects

Developer	Project	Type	Status
Siemens Energy	In line with EXPO 2020 Dubai's main theme – Connecting Minds, Creating the Future – DEWA, EXPO 2020 and Siemens Energy launched MENA's first electrolysis facility at MBR solar park. The MW-scale hydrogen facility employs Proton Exchange Membrane (PEM) electrolysis, to provide fuel to FCEVs showcased by EXPO 2020. Each unit within the facility could produce up to 240 kg of hydrogen per day, at 1.25 MWe of peak power from the solar complex, which is planned to reach 5 GW capacity by 2030[44]. Managing director and CEO of DEWA, Saeed Mohammed Al Tayer, commented: "This is a system that allows for buffering renewable energy production, both for fast response applications, as well as for long-term storage. The plant has been built to accommodate future applications and test platforms for the different uses of hydrogen, including potential mobility and industrial uses.[45]"	Green	Operational
Air Liquide	Air Liquide, Khalifa University, Al-Futtaim Motors conducted a joint study, testing the Toyota Mirai, a zero-emission hydrogen-run fuel cell electric vehicles (FCEVs). In 2017, Air Liquide installed a hydrogen station in Dubai, in collaboration with ADNOC, Masdar and Al Futtaim Motors. Currently, the 40 kgH_2/day station fuels 55 Toyota Mirai vehicles imported by Al Futtaim for trial purposes[46].	Green	Operational
Aedas, City Diamond & Arcadis	ENOC group unveiled plans to establish a "futuristic" service station in Dubai's EXPO 2020 site. The station will use multiple energy sources including solar, hydrogen and hydrocarbons. The plant received the world's first LEED platinum certification. Zaid al-Qufaidi, ENOC Retail's managing director, says that the cost is around three times that of a regular station, estimating it at around AED 25 M. The main consultant is global architecture firm Aedas, the design and construction firm Arcadis and the main contractor City Diamond.	Green	Operational
Marubeni	Japan's Marubeni Corp. signed an MoU with 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 share 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.	Green	Ongoing
ADNOC's Ta'ziz	ADNOC announced it will develop a world-scale blue ammonia production facility in Ruwais, Abu Dhabi. Currently, the facility is in the design phase and will be developed at the new Ta'ziz industrial ecosystem and chemicals hub in Ruwais. The facility will have a capacity of 1 Mtpa. Wood has been awarded the design contracts for the pre-FEED work for the ammonia plant and the six additional Ta'ziz chemicals projects. Meanwhile, ADNOC will conduct a feasibility study on blue hydrogen supply to the plant from its operations in Ruwais. The project's FID is expected by 2022, while start-up is scheduled by 2025[47].	Blue	Planned 2025

Developer	Project	Type	Status
Fertiglobe	Fertiglobe signed an agreement to join Ta'ziz as partner in the world-scale blue ammonia project in Ruwais. This partnership further strengthens the country's hydrogen value proposition, given ADNOC's deep experience in CCUS and Fertiglobe's world leading capabilities in ammonia production. Both companies are conducting joint pre-FEED and FEED work.	Blue	Planned 2025
Chinook Sciences	Sharjah waste management company Bee'ah will develop the region's first waste-to-hydrogen project, which was awarded to UK-based Chinook Sciences. The project is part of a US$ 180 M gasification undertaking in Sharjah. It will include a plant and a fuel station for FCEVs. By having the H_2 plant adjacent to the refueling station, the project will avoid transportation-associated costs.	Green	Unspecified
Helios Industry	Abu Dhabi will build a US$ 1 B solar-powered hydrogen and ammonia plant, located at the Khalifa Industrial Zone Abu Dhabi (KIZAD) and built by Helios Industry – a privately-owned special project vehicle company (SPV) in Abu Dhabi. Initially, the facility will include a 100 MW solar plant, which will increase to 800 MW in the future (date not disclosed). Hydrogen produced from the plant will be converted into ammonia for export. The plant will have a peak capacity of 40 ktpa of green hydrogen, which will be used to make 200 ktpa of green ammonia.	Green	Planned Q2 2024
TAQA	Abu Dhabi National Energy Company (TAQA) and Abu Dhabi Ports will develop a 2 GW green ammonia project. The end-product will be used in ships as bunker fuel and for export from Abu Dhabi Ports through gas carriers. The facility will tap a 2 GW solar PV plant to power an electrolyser, producing green hydrogen which will then be converted into liquid ammonia. The project will also take place in KIZAD and will be connected by pipeline to a planned Khalifa Port storage facility to allow for large volumes of ammonia to be delivered directly to the port. This positions the latter as a future hub for exporting green ammonia to international markets. TAQA will also supply Emirates Steel with green hydrogen – a move that could bolster the UAE's efforts to lower the emissions of its energy-intensive industrial activities. TAQA is looking to combine its solar PV water and energy know-how to unlock opportunities in the low-carbon sector.	Green	Unspecified

The Ta'ziz blue ammonia project "is a significant milestone in the development of our blue hydrogen and ammonia business, building on the UAE's strong position as a producer of competitive, low carbon natural gas and our leadership role in carbon capture and underground storage. As we collectively navigate the global energy transition, we believe hydrogen, and its carrier fuels such as ammonia, offer promise and potential as zero carbon energy sources."

H.E. Dr Sultan Al Jaber, UAE Minister of Industry and Advanced Technology and ADNOC Managing Director and Group CEO

Future partnerships can target additional capabilities

The UAE's partnerships so far concentrate on government-to-government, research, and engineering and equipment firms. Future partnerships could aim to build on distinct capabilities, in particular:

Technology	• Advance CCUS solutions, leveraging subsurface and chemical engineering expertise, and experience from carbon capture hubs in the USA, Australia and north-west Europe
Global Network	• Leverage the UAE's deep tradition of working with leading international oil firms, to develop hydrogen markets in a similar template to the early days of LNG • Build on the strengths of ADNOC LNG by working with major LNG traders and customers, such as Vitol, Uniper and JERA, to develop long-distance hydrogen-related trade, leveraging synergies with LNG facilities
International Standards	• Collaborate with certification organisations, such as TÜV-NORD and DNV, to develop standards for hydrogen and derivatives that appropriately account for their carbon footprint • Work with trade organizations (e.g., World Steel Association) and international sectoral organization (e.g., International Maritime Organization) to develop standards for low-carbon products, materials, fuels, and services built on low-carbon hydrogen
Infrastructure Development	• Work with energy infrastructure companies such as Snam, global utilities, for instance, ENGIE, and others, including recent investors in ADNOC's gas pipeline unit, to evolve the gas business to incorporate hydrogen, and understand how hydrogen can be effectively
Hydrogen Transport	• Partner with shipping firms, such as Maersk, which plans to operate a carbon-neutral vessel by 2030, and maritime experts such as LR, to develop hydrogen-based low-carbon solutions for shipping fuels • Work through companies such as Dubai Ports World, Abu Dhabi ports, ADNOC and Emirates National Oil Company, with other international operators to create logistical hydrogen-related solutions for delivery, storage and use of hydrogen-based fuels at global ports
Investment in Hydrogen	• Invest internationally through strategic companies such as Mubadala, in select parts of the hydrogen value chain, to capture value and accelerate progress • Grow participation in innovation partnerships, such as Mission Innovation, focused on accelerated development and commercialization of technologies that enable blue, green, and other low-carbon hydrogen production pathways
Regional Cooperation	• Consider select cooperation with regional peers, recognising that there is a degree of competition, but also potential synergies in areas such as logistics, technology development and CCUS infrastructure • Develop bilateral trade partnerships for hydrogen and zero-carbon synthetic fuels
Localization	• Identify the segments of the blue and green hydrogen value chain with potential for execution or basing in the UAE, and negotiate or offer targeted incentives to encourage their establishment in-country, in line with existing programmes to promote inward investment, industrialisation and innovation. Localisation has, of course, to be compatible with driving down hydrogen costs as fast as possible, as the UAE's solar sector has achieved

6. COMPETITION AND CHALLENGES

Since the sharp emergence of interest in mid-2020, hydrogen has become an increasingly competitive space, particularly for green. Numerous world-scale projects have been proposed or launched, many with backing from large and capable energy and engineering companies[48]. Key areas of intended hydrogen production activity alongside the UAE include North Africa (Morocco), Chile, Australia, north-west Europe and, in the GCC, Oman and Saudi Arabia[49]. Interest is simultaneously growing in Canada, where Air Products has announced a large new blue hydrogen project beyond three existing ones[50], and in the US, where the proposed bipartisan infrastructure bill includes US$ 8 billion for hydrogen hubs[51]. These projects are based primarily on green hydrogen and ammonia, with a combination of solar and onshore and offshore wind, as well as blue hydrogen where natural gas is cheap and plentiful. Russia's plans are relatively less advanced but it could also be an important player in blue and green hydrogen.

The UAE has to address four competitive factors.

Lowering the cost and carbon footprint of blue hydrogen production in the UAE requires:

- Substantial cost savings in gas production, along with reductions in CCUS costs and maximising the value of captured CO_2 through EOR or other beneficial uses
- Maintaining market acceptability and avoiding excess carbon charges by increasing the share of captured versus fugitive CO_2 in the production process
- Supportive market structures to incentivise large-scale adoption. Carbon prices under systems like the European Trading Scheme have risen sharply recently but are probably still insufficient to justify hydrogen take-up on their own

Reducing the cost of green hydrogen production in the UAE requires:

- Developing an appropriate blend of solar PV, CSP, off-peak nuclear and batteries, to balance high-capacity factors with low electricity costs, including optimisation against electricity demand, hydrogen operations and weather conditions
- Increasing the scale and reducing electrolysers' cost , by cutting their use of precious metals
- Building on the UAE's industrial partnerships with equipment suppliers such as Siemens; selective investment in promising technology firms; and the research programmes advanced by institutions including Khalifa University

Establishing the hydrogen export market:

- The UAE will most likely deliver by ship, incurring higher costs and greater complexity (pipeline exports to South Asia could be an option). The shipping of decarbonised products may well prove to be more economic than transporting hydrogen directly in compressed or liquid form.
- Rather than discriminating against blue H_2 ; understand the eventual incentives – could include a 'contract for difference' to bring H_2 to market parity; specific mandates for levels of H_2 use; and/or performance standards for certain industries to effectively require the use of H_2 and accelerate decarbonization and encourages investment

The UAE has an attractive localisation opportunity across the value chain:

- Opportunities to be exploited in the manufacturing activities – electrolysers' technological maturity, limited electrolyser capacity. This represents 20-40% of the share of total value chain
- Engineering & design, installation and operation & maintenance activities could be localized as demand rises and necessary capabilities are developed; advance R&D projects to gain technological leadership across the value chain.
- H_2 infrastructure, including the retrofitting of gas pipelines to handle H_2 blends, the construction of new pipelines, and the creation of storage and export facilities, is another activity with high expected local content
- Zero-carbon synthetic fuels are likely to prove key markets and fuels for shipping, which could create demand for H_2 fuels from the UAE, underscoring its potential role both as a produce and logistics hub

Developing supportive domestic regulation.

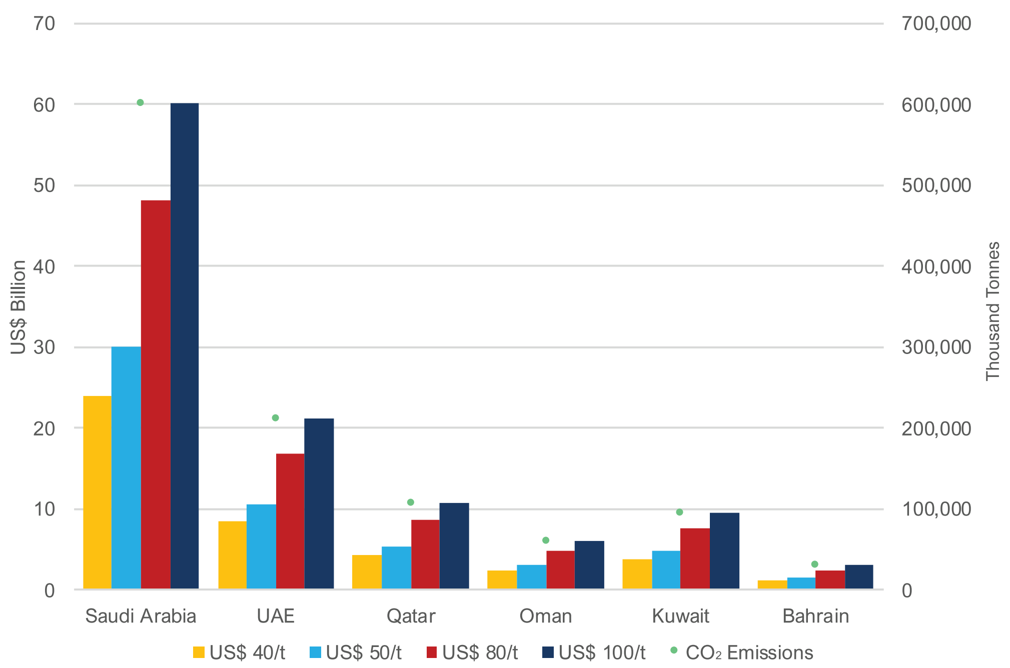
Since low-carbon hydrogen is currently more costly than 'grey' hydrogen and fossil fuels, it requires supportive policies to encourage its adoption. The intention is that scale-up and technology advances will lower costs to bring hydrogen closer to direct competitiveness, as has been achieved by renewables and electric vehicles.

International policies to encourage the use of low-carbon hydrogen include targets, funding research and demonstration projects, subsidies for production and conversion of existing infrastructure, and mandates for adoption or blending in sectors such as power, transport and home heating. General policies that have the effect of supporting hydrogen include carbon pricing (particularly the EU Emissions Trading Scheme), carbon border tariffs on imports from high-emitting countries, and vehicle emissions targets such as California's Low Carbon Fuel Standard. Even with significant carbon pricing, above €50/tonne as seen in the EU from May 2021 onwards, hydrogen is unlikely to be competitive today, and therefore will require additional policy support in the short to medium term.

The EU is moving towards the introduction of a border carbon tariff on imports of energy-intensive goods from jurisdictions without carbon pricing or equivalent regulation. Other countries and regions may follow, which could present a penalty to some UAE exports. The UAE, in common with the rest of the GCC, does not yet have a carbon pricing mechanism. The use of low-carbon hydrogen domestically and for export-oriented industries could be encouraged by a combination of direct regulation and carbon charges. Carbon revenue could be recycled to promote innovation in hydrogen and other decarbonisation technologies or to build key infrastructure. During its participation in the meetings held by the United Nations Framework Convention on Climate Change (UNFCCC) in June 2021, the UAE climate negotiation team[52], presided over by the Ministry of Climate Change and Environment, joined the discussion around carbon pricing[53] and climate equity.

For example, under a US$ 40/tCO_2 scenario, the UAE's carbon price revenues are almost three times higher than the total revenues estimated from value added tax (i.e., US$ 3.3 billion). Revenues from the carbon pricing program could reach up to US$ 21 billion at a price of US$ 100/tCO_2 in the UAE.

Figure 13: GCC annual revenues from carbon pricing per scenario[54]



7. CONCLUSIONS

Hydrogen has, quite suddenly, become an essential part of the strategy of every major energy producing and consuming company. There are many announcements, but understandably, tangible projects are mostly at early stages.

The UAE and its key proponents, notably ADNOC, Mubadala, ADQ and DEWA, have made a strong start, leveraging existing assets and several years of groundwork in CCUS and renewable energy. Some potentially important partnerships have been established, internationally as well as the Abu Dhabi Hydrogen Alliance.

A formal national strategy is still in preparation, but principal elements have already emerged, including a balance between pursuing blue and green hydrogen, a focus on cost competitiveness, and an approach to serve domestic needs while also advancing export opportunities.

Despite its nascent stage, hydrogen has become a very competitive sector, both against other decarbonisation options, and between regions and countries vying for leadership. Companies venturing into hydrogen still need to understand the policies and incentives that will be put in place, and the business models that may emerge. A liquid, liberalised system like that of gas in North America and Europe is likely a long way off. Instead, as with the early days of LNG, vertical integration, bilateral deals, government guarantees and sector-specific approaches are likely required for the hydrogen market to take off. Relatively high transport costs also suggest a more geographically segmented market than for oil or LNG. This is further complicated by the varying production methods, intermediate and final products, transport options and end-use cases.

Key to success in this emerging market will be the ambition to shape it, to build up scale and so drive down costs; and the adaptability to pursue new business models and partnerships, try different technologies and cope with policy and economic shifts. Specific advantages include low costs for fossil fuels, renewable generation and carbon dioxide storage; high-quality logistics; favourable geographic location; low cost of capital; willingness to move quickly and make substantial investments; experience in building durable partnerships with customers and technology providers; and agility in adapting existing operations, To these natural competitive strengths in hydrogen, some of which are shared by regional peers, the UAE adds its openness to international business and innovation.

1. 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, while reducing over 6.5 gigatonnes of carbon dioxide-equivalent ($GtCO_2e$).
2. Blue hydrogen employs steam reforming and carbon capture technology which already exist in large-scale, industrial capacity, as compared to electrolysers' capacity which stands currently at only 0.2 GW worldwide.
3. https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/United%20Arab%20Emirates%20Second/UAE%20Second%20NDC%20-%20UNFCCC%20Submission%20-%20English%20-%20FINAL.pdf
4. https://www.osti.gov/pages/servlets/purl/1485127
5. http://wam.ae/en/details/1395302940064
6. https://www.thenationalnews.com/business/energy/gastech-2021-to-be-held-in-dubai-with-dedicated-hydrogen-focus-1.1237138
7. e.g. the International Energy Agency's report on reaching global net-zero carbon https://iea.blob.core.windows.net/assets/ad0d4830-bd7e-47b6-838c-40d115733c13/NetZeroby2050-ARoadmapfortheGlobalEnergySector.pdf
8. Estimates do not include life-cycle emissions from fabrication or maintenance, and do not include upstream emissions (e.g., methane leakage). CCS = carbon capture and storage (90% capture rates). SMR = steam methane reforming. ATR = autothermal reforming. Bio = biomass waste feedstock. EF = entrained flow. FB = fluidised bed; Source: GCCSI 2021, Qamar Energy Research for UAE estimate
9. Hydrogen as a component of syngas along with carbon monoxide and other gases
10. IEA, "The Future of Hydrogen", June (2019); Qamar Energy Analysis
11. Dii Desert Energy & Roland Berger, https://mcusercontent.com/3cb7aa0bdf946096e07e98867/files/93f8d2b3-367d-3f5e-2c03-fd1598a9a919/The_potential_for_green_hydrogen_in_the_GCC_region.pdf
12. GCC countries will dedicate only 300-420 GW for hydrogen production from their RE capacity, powering 150-210 GW of electrolysis, potentially producing 50-70 Mt of H_2 per year by 2050
13. GCC countries will dedicate 700-1,000 GW of RE capacity, powering 250-500 GW of electrolysis, potentially producing 80-100 Mt of H_2 per year by 2050
14. Vision Port of Rotterdam, Germany's National Hydrogen Strategy, EU Hydrogen Strategy, METI, Hydrogen Korea Team, Dii Desert Energy / Roland Berger
15. https://www.thenationalnews.com/uae/how-operation-300bn-and-make-it-in-the-emirates-will-turn-the-uae-into-a-manufacturing-powerhouse-1.1189205
16. https://www.globalccsinstitute.com/resources/publications-reports-research/blue-hydrogen/
17. Qamar Energy
18. https://www.energypolicy.columbia.edu/research/report/evaluating-net-zero-industrial-hubs-united-states-case-study-houston
19. Qamar Energy Research; emissions data from Ammonia Industry, Aluminium Insider, WorldSteel.Org, and other publicly available data sources
20. https://ajot.com/news/its-raining-solar-panels-in-the-uae-renewable-capacity-set-to-increase-fourfold-to-9-gw-by-end-2025
21. Khalifa University
22. Kuwait's 1.5 GW Al Dibdibah solar project was cancelled after being awarded for the country's lowest bid of US$¢ 3.6/kWh; Saudi received a US$¢ 1.61/kWh bid for the 300 MW Jeddah PV IPP in 2020 (shown in chart), the lowest at the time, which was later trumped by a US$¢ 1.04/kWh bid for the 600 MW Al Shuaiba PV IP project in April 2021
23. Qamar Energy forecasts, with discussion in https://www.energypolicy.columbia.edu/research/report/under-cloud-future-middle-east-gas-demand. Solar thermal may be partly replaced by additional solar PV with battery storage.
24. Qamar Energy Research: dark green signifies renewable energy projects, black projects signifies CCUS projects, green signifies green hydrogen projects, and blue signifies blue hydrogen projects.
25. https://www.globalccsinstitute.com/resources/publications-reports-research/blue-hydrogen/
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27. Offshore Energy Today, "ADNOC looking to expand carbon capture utilisation and storage efforts", February 25, 2020
28. IEA, "Future of Hydrogen", 2019; Qamar Energy Analysis for UAE hydrogen production costs using natural gas
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31. International Trade Administration, U.S. Department of Commerce
32. IEA; Qamar Energy Research; assumes 100% load factors for electrolysers with electricity at 5 USc/kwh (i.e. relatively cheap wholesale electricity)
33. Qamar Energy calculations based on midpoint of ranges for input parameters given by the IEA, https://iea.blob.core.windows.net/assets/a02a0c80-77b2-462e-a9d5-1099e0e572ce/IEA-The-Future-of-Hydrogen-Assumptions-Annex.pdf, P3
34. https://www.globalccsinstitute.com/resources/publications-reports-research/technology-readiness-and-costs-of-ccs/
35. https://mcusercontent.com/3cb7aa0bdf946096e07e98867/files/02330b71-0287-0f8a-ff11-e37c23d08364/The_potential_for_green_hydrogen_in_the_GCC_region.03.pdf
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39. ThyssenKrupp
40. https://www.energypolicy.columbia.edu/research/report/evaluating-net-zero-industrial-hubs-united-states-case-study-houston
41. https://www.energypolicy.columbia.edu/research/commentary/output-based-rebates-alternative-border-carbon-adjustments-preserving-us-competitiveness
42. Germany's Federal Ministry for Economic Affairs and Energy and the UAE Ministry of Energy & Infrastructure
43. Fawaz Al Muharrami, Acting Executive Director at Masdar Clean Energy
44. Only 1 kg of hydrogen is needed for an average FCEV for a range of 100 km, depending on the model and other factors.
45. Renewables Now
46. The cost of a hydrogen refuelling station ranges between around US$ 1-2 M in the UAE, compared to US$ 300,000 for a standard petrol station.
47. Chemical Engineering
48. See the GCC summary in https://www.rvo.nl/sites/default/files/2020/12/Hydrogen%20in%20the%20GCC.pdf
49. Some of these competitive challenges are covered in https://www.oxfordenergy.org/wpcms/wp-content/uploads/2021/05/OEF-127.pdf
50. https://www.airproducts.com/campaigns/alberta-net-zero-hydrogen-complex
51. https://www.wsj.com/articles/whats-in-the-bipartisan-infrastructure-plan-11624562676
52. UAE Special Envoy for Climate Change and representatives of the Ministry of Energy and Infrastructure, the Department of Energy, Dubai Electricity and Water Authority, the Dubai Supreme Council of Energy, and Emirates National Oil Company (ENOC)
53. Placing an explicit price on carbon pollution to reduce emissions and drive investments towards clean energy
54. Carbon Pricing Leadership

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