TECHNICAL ARTICLE

2 USD/KG HYDROGEN PRODUCTION COST THRESHOLD COULD BE A NEAR-TERM POSSIBILITY IN THE GCC REGION WITH USE OF CHINESE TECHNOLOGIES.

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INTRODUCTION

Our future energy demands carbon-free electrons and molecules, especially for heavy industry and transport applications (which are difficult to electrify). Hydrogen is the most promising energy vector for decarbonising fuel molecules because it is excellent for long-term energy storage, provides seamless integration with existing energy infrastructure, and could fuel transport applications as well. Conventionally, we have produced hydrogen through steam methane reforming of natural gas (grey hydrogen). Grey hydrogen is produced at 1-3 USD per Kg (Bloomberg NEF), and the production cost highly depends on the natural gas price.

In 2023, global hydrogen production was 97 million tons (MT) up 2.5% from 2022. Most of this hydrogen was grey, with green (electrolytic) and blue (natural gas plus carbon capture) hydrogen contributing only 0.1 MT and 0.6 MT, respectively (IEA). For now, low-emission hydrogen has a marginal role in global decarbonisation, but 2024 saw substantial growth in announced projects, reaching 49 million

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tons per annum (MTPA), a 30% increase over 2023 (IEA Global Hydrogen Review 2024). This is coupled with a fivefold increase in projects reaching financial closure, amounting to 3.4 MTPA, evenly split between green (1.9 MTPA) and blue hydrogen projects (1.5 MTPA).

The potential for decarbonising hydrogen demand with green and blue hydrogen has become a policy objective to curb climate change and enhance energy security, achieve technology leadership benefits from its exports, and support socio-economic agendas. As of May 2024, 54 countries have implemented hydrogen strategies (IRENA). China has been leading global green hydrogen deployment and is projected to exceed its 2025 target of 0.2 million tons of green hydrogen production capacity. While blue hydrogen projects dominate in the US, some green hydrogen projects are attaining financial closure on the back of fiscal incentives offered in Europe.

Here in the Gulf Cooperation Council (GCC) region, Saudi Arabia, Oman, and UAE have set hydrogen as a clear national priority, with NEOM green hydrogen facility materialising as the first large-scale facility (4 GW solar/wind, 600 tons per day, to be commissioned by the end of 2026). Besides NEOM, other projects in the GCC region remain in the pre-feasibility or feasibility stage, often attributed to high production costs and lack of fiscal incentives. At Penspen, we expect the region's good history of solar and wind developments and the declining costs of batteries, solar photovoltaic and electrolysers to kick-start numerous green hydrogen projects soon.

While there is a strong desire for green and blue hydrogen, the key obstacle is the cost of production. Blue hydrogen requires a bespoke design to accommodate the carbon sequestration requirements, if available, so cost varies geographically with access to carbon sequestration sites, but green hydrogen can be produced globally using standardised, modular technologies. Green hydrogen production costs range from 4.5 to 12 USD per Kg (Bloomberg NEF) and require some form of financial incentive to attain cost parity with competing energy commodities. At Penspen, we are performing detailed hydrogen production cost modelling to understand what combination of available technologies unlocks the lowest hydrogen cost in the GCC region and facilitates its scaled deployment.

UNDERSTANDING HYDROGEN'S COST COMPETITIVENESS TO OTHER ENERGY COMMODITIES

Green hydrogen can be integrated within existing industries and used with fuel cell technology for transport applications. Fertilizers, refineries, and steel industries can use green hydrogen for feedstock and energy.

With respect to natural gas, Europe and Asia are key importers of high-priced natural gas, compared to the United States and Middle East (where low-cost gas is accessible). Considering the Dutch and Japanese/Korean markets, the gas prices are currently around 10 USD per MMBTU mark, rising to 15 USD per MMBTU during the later part of the decade (IEA), which translates to 5 US cents per kWh (1 MMBTU = 293 kWh). Green hydrogen at 2 USD per Kg is the equivalent to natural gas priced at 15 USD per MMBTU (hydrogen HHV of 39.4 kWh per Kg). However, it is crucial to note that 2 USD per Kg is only hydrogen production cost and excludes any transportation costs. Transportation costs can be substantial, so space permitting, on-site green hydrogen production with captive solar is the most competitive option in the GCC region.

Interestingly, coal prices are declining from a record high of 350 USD per MT (2022) to 100 USD per MT in 2026 (World Bank forecast). If, in the medium term, coal prices stabilise at 150 USD per MT, assuming 8,141 kWh of energy per MT of coal, this results in an energy price of 1.8 US cents per kWh, significantly lower than natural gas. Hence, even if hydrogen production costs achieve the 2 USD per Kg threshold or 5 US cents per kWh, they will not be able to compete with coal prices without carbon penalties imposed on coal.

With transport applications, hydrogen-fuelled cars offer numerous benefits such as minimal maintenance due to lack of moving or frictional parts; 50-90% reduction in greenhouse gas emissions by emitting only steam and waste heat; energy efficiency of fuel cells is 40-60% compared to 30-35% for gasoline and diesel engines; increased range compared to diesel-powered vehicles; quick re-fuelling times; and quiet operation. With currently available hydrogen fuel cell-based cars, the fuel efficiency is 7.6-10 g/km for passenger vehicles and 20-150 g/km for commercial vehicles.[1]

For instance, Toyota Mirai consumes 7.6 g of hydrogen per km, resulting in 1.5 USD per 100 Km (at 2 USD per Kg hydrogen). In comparison, a conventional internal combustible engine-based passenger car costs 7.6 USD per 100 Km (at 10 litres per 100 Km fuel efficiency and 2.8 AED per litre fuel price). Hence, even in markets with lower fuel prices, such as the GCC region, hydrogen can be cost-competitive operationally to conventional vehicles and even cover the higher initial costs of fuel cell vehicles. However, it would need to be more competitive to displace the emerging ubiquity of battery-powered vehicles and their highly distributed charging infrastructure.

INFLUENCING FACTORS IN COST MODELLING

As per IEA Global Hydrogen Review 2024, considering the optimistic IEA's Net Zero Emissions by 2050 Scenario, the cost of green hydrogen will fall to 2-9 USD per Kg by 2030, which is half of today's value. While research publications have predicted green hydrogen production close to the 2-4 USD per Kg mark already, practical applications are resulting in higher pricing. Hence, most green hydrogen projects aspire for fiscal incentives, whether subsidies, tax credits, or contracts for differences, to attain financial closure.

What complicates this analysis further is the role of associated technologies in developing a winning hydrogen business model. Many factors contribute to the overall cost competitiveness of hydrogen projects. At Penspen, we include the following factors in our internal cost modelling exercises and try to update these models with the latest regional reference points:

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[1] Performance, emissions, and economic analyses of hydrogen fuel cell vehicles, Pobitra Halder

1) The availability of captive solar and/or wind electricity generation, based on hourly capacity factors for specific locations.

2) Solar and wind capital as well as fixed operation and maintenance costs back calculated from the latest local auctions. Also, the renewable generator degradation, lifetime, replacement costs and land requirements need to be considered. However, like solar and wind developments in the region, land is assumed to be provided by the government for free.

3) Utility-scale batteries are considered for maximising renewable resource utilisation when renewable capacity is upsized compared to electrolyser capacity. Aspects of the batteries to be considered include battery power, duration of storage, round-trip efficiency, minimum and maximum charging levels, maximum number of cycles before battery replacement, replacement costs, and land requirement.

4) The possibility of using grid power to maximise hydrogen production and reduce the cost of production needs to be considered. The price of clean energy certificates is assumed given information related to local auctions such as those organised by Emirates Water and Electricity Company in Abu Dhabi. The International Organization for Standardization (ISO) has released a methodology for determining GHG emissions associated with hydrogen production, transport, and conversion/reconversion (ISO/TS 19870:2023 Hydrogen technologies — Methodology for determining the greenhouse gas emissions related to the production, conditioning, and transport of hydrogen to consumption gate). This will be the basis for a full standard expected by 2025 or 2026, which could serve as a standard methodology to enable the mutual recognition of certificates globally. Such standards shall require the use of clean energy certificates to characterize hydrogen based on the emissions incurred.

5) The usage of grid electricity shall entail grid connection costs which are considered free similar to renewable developments in the region. Grid electricity usage shall also require a transformer for adjusting the Alternating Current (AC) power to appropriate voltage required by the rectifier (AC to DC conversion) to meet the demand of the electrolyser. For the current analysis, the cost of the transformer and rectifier is not separately included. However, in subsequent revision this shall be resolved based on consultation with OEMs.shall be resolved based on consultation with OEMs.

6) Different electrolyser technologies, such as alkaline liquid electrolyses, proton exchange membrane electrolysers, or solid oxide electrolysers, can be considered in terms of their capital, fixed operation and maintenance costs, efficiency, minimum and maximum loading levels, feed water consumption, forced outage hours, stack replacement costs, electrolyser degradation, cooling water requirement, and land requirements. For this analysis, the electrolyser, as a system, includes the gas separation (for gas liquid separation) and hydrogen purification units (removal of trace impurities). Similarly, the auxiliaries such as cooling water equipment, air compressor, nitrogen equipment, lye preparation equipment, and hydrogen production management system are also considered to be part of the overall system.

7) In the case of off-grid hydrogen production, hydrogen storage can be necessary to provide a constant hydrogen output even with variable renewable generation. Hydrogen storage can be considered in different mediums, whether small-scale compressed gas tanks or large-scale salt caverns. The key factors considered are storage capital costs, operational and maintenance costs, storage volume, storage pressure, storage compressor requirement and associated compressor and motor efficiency, minimum and maximum storage levels, compressor lifetime, and land requirements.

8) Green hydrogen production consumes water for electrolysis, cooling, and grid electricity. These commodities are priced according to local industrial tariffs. However, if the marginal cost of electricity and water production is available from utilities, it could be used to evaluate the cost of hydrogen production and the savings for the utility sector in terms of displacing their primary fuels with green hydrogen.

9) The interest rate for debt, the return on equity, the debt-to-equity fraction, and the tax rate are considered according to the best values achieved in the GCC region. These factors are used to calculate the Weighted Average Cost of Capital (WACC), which is then used for annuity calculation.

10) The modelling also considers a construction finance factor and a project finance factor, as per the NREL costing methodology (NREL Annual Technology Baseline).

MODELLING ASSUMPTIONS

On-site captive solar, wind or hybrid renewable power generation

The levelized cost of solar energy for fixed-axis solar PV systems in 2024 ranges from 20 USD per MWh to 117 USD per MWh, depending on the class of renewable resource or capacity factor (NREL). However, in the GCC region, even lower solar prices have been achieved, ranging from 12.8 to 13.2 USD per MWh in the UAE, while 10.4 USD per MWh was achieved in Saudi Arabia. These exceptionally low levelized costs have been achieved in return for various factors which include long-term low-risk power purchase agreements with financially secure utilities; overnight installation costs of utility-scale solar PV falling below 40 US cents per watt; low cost of capital owing to equity returns of 7%, debt interest rates approaching 4-5% and debt to equity ratios of 85%; no up-front grid connection charges; no land costs; low fixed operation and maintenance costs (approaching 10 USD per kW per year) owing to the lower labour charges; and improvements in technology (bifacial gain of 5, NREL). These inputs were evaluated based on the latest solar auctions in the UAE.

For wind, the levelized cost of onshore wind energy ranges from 23 USD per MWh to 139 USD per MWh, while offshore wind remains expensive, with fixed installations averaging at 70 USD per MWh while floating systems are at 320 USD per MWh (NREL). While wind is costly, but it also provides a higher capacity factor ranging from 25 to 35% for onshore wind, but it could increase to 40% for offshore wind farms. The Arabian Gulf has set world record prices for wind energy, approaching 15.6 USD per MWh for the Al Ghat project in Saudi Arabia, followed

followed closely by the Wa'ad Alshamal project, achieving the second-lowest LCOE at 17 USD per MWh. Such projects are the basis for the assumptions for capital and fixed operation and maintenance costs for wind energy in the GCC region. It is meaningful to note that if solar and wind are deployed together, the capacity factors could be higher given wind speeds increase at night.

It is important to note here that commodity pricing, especially the price of silicon and steel, has a proportional impact on the capital cost for solar and wind plants. The solar and wind pricing was 10-15% higher compared to 2020 levels owing to higher commodity and freight prices, which have declined in 2024 (Renewable Energy Market Update - June 2023, IEA). Today, most manufacturers offer time-bound offers for such technologies, given the difficulty in predicting the price of raw materials given their rapid fluctuations.

On-site captive solar, wind or hybrid renewable power generation

Utility-scale batteries have already been deployed in the region. Abu Dhabi has already deployed 108 MW of batteries and has a tender for a further 400 MW battery energy storage system (EWEC 2024). Among utility-grade batteries, lithium-ion batteries are clear winners given they are lighter and more compact, are a well-established technology with a well-developed supply chain and production infrastructure and have higher round-trip efficiency. However, lithium-ion batteries have a limited lifespan and can degrade over time. Hence, battery replacement costs can be substantial.

Also, lithium-ion batteries can be subject to thermal runaway and pose a fire risk if damaged or improperly maintained. The battery system costs can be significant, and there is a storage component, which depends on the storage duration and power output.

Total System Cost (USD/kW) = Battery Energy Cost (USD/kWh) * Storage Duration (Hours) + Battery Power Cost (USD/kW)

As per the NREL 2024 Annual Technology Baseline report, the moderate view on battery energy cost is 356 USD/kWh, with the battery power cost at 347 USD/kW for 2024. For a 4-hour utility-scale lithium-ion battery, this translates into an overnight installation cost of 1770 USD/kW. It is important to note that while lithium-ion batteries themselves might only cost 600 USD/kWh, the overall cost of a grid-scale battery can be substantially higher owing to the balance of system, power equipment, controls and communication, systems integration, grid installation, EPC contractor and development costs. Chinese battery manufacturers offer far lower battery prices of 170 USD/kWh, including Balance of Plant (BOP) and service contracts, which translates to 680 USD/kW for a 4-hour battery pack.

Round-trip efficiency is the ratio of useful energy output to energy input. Based on Cole and Karmakar (Cole and Karmakar, 2023), a round-trip efficiency of 85% has been considered.

Electrolyser

At Penspen, we considered commercially available electrolysers, which include the following:

A) Alkaline Water Electrolyser (AWE)

AWE cells have two compartments separated by a porous diaphragm, which allows hydro-oxide ions to migrate while limiting gas cross-over. Within the AWE cells, water molecules are reduced at the cathode to produce hydrogen molecules, and hydro-oxide (OH—) ions migrate through the diaphragm and get oxidised at the anode to oxygen molecules.

The AWE uses Potassium Hydro-oxide (KOH) at very high concentrations (20%–40% KOH) as a liquid electrolyte. Such electrolysers are known for their reliability, long history of application, good efficiency (50-78%), scalability and long lifetime (80,000 Hrs). The overall lifetime of the electrolyser can be 30 years, but a membrane and electrode swap shall be required every 10 years, with replacement costs 15-20% of the capital costs. The efficiency of the electrolyser can also be interpreted in terms of kWh of electricity per kg of hydrogen. For instance, the HHV of hydrogen is 39.4 kWh per kg, with a 68% efficiency, 58 kWh of electricity shall be required to produce one Kg of hydrogen.

B) Proton Exchange Membrane Electrolysis

Proton Exchange Membrane Electrolysis (PEM) electrolysers work in an acidic environment without a liquid electrolyte and conduct hydrogen protons or positive hydrogen ions instead of negative hydrogen-oxide ions. At the anode, the water is split into electrons, and hydrogen protons. The hydrogen protons gain an electron at the cathode and form hydrogen gas.

Platinum is often used at the cathode, and iridium or iridium-based electrocatalysts are typically employed at the anode. These elements are used to withstand the corrosion induced by the acidic environment and are more expensive than AWE, especially Iridium, which is in short supply globally. PEM electrolysers operate between 50 and 80 degrees centigrade, offer high current density and higher efficiencies in 50%-83% range. The key distinguishing feature of PEM electrolysers is their rapid response time, which is in the order of milliseconds, enabling improved performance with variable renewable energy generators. However, their durability is moderate, and they have a shorter life span (around 50,000 hours).

C) Solid Oxide Electrolysis (SOE)

SOEs are composed of two porous electrodes and a solid electrolyte generally made of Zirconium Oxide (ZrO_2) doped with Yttrium Oxide (Y_2O_3). SOE operates at a higher temperature of 700-850 degrees centigrade. SOE offer the highest efficiency possible (80-90%), resulting in lower electricity consumption. However, the stack lifetimes are low (< 40,000 Hours), resulting in additional costs for stack replacement.

The capital cost for electrolysers is primarily dependent on indirect costs. For instance, for PEM, the manufacturing cost of the electrolyser itself is in the range of 550-700 USD per kW, but the system installed cost, inclusive of installation and soft costs, is in the range of 1300-1700 USD per kW (as per Updated Manufactured Cost Analysis for Proton Exchange Membrane Water Electrolysers, NREL, February 2024). Almost 50% of the installed cost of electrolysers is indirect and includes the expenses for engineering, project management, commissioning, insurance, land acquisition, grid fees, and contingencies.

Out of the other 50% direct costs, only 15-30% are the stacks, while the remaining 70-85% of the costs are attributable to BOP, utilities, process automation, power supply and electronics (Gigawatt Green Hydrogen Plant – State of the art design and total installed capital costs).

In our analysis, a forced outage rate of 10% is assumed for PEM and 15% for Alkaline and Solid Oxide electrolysers. Further, the unit size for electrolysers was limited to 1 MW.

Table 1 Specifications for different types of electrolyser technologies.

Specification	AWE	PEM	SOE
Electrolyte	Alkaline (KOH)	Solid Polymer	Solid Ceramic
Temperature	70°C –90°C	50°C - 80°C	700°C - 850°C
Efficiency	50% - 70%	50% - 83%	89%
Pressure, bar	<30	<70	1
Current density, A/cm2	0.2 - 0.8	1-2	0.3-1
Voltage range, V	1.4-3	1.4-2.5	1.0-1.5
Response Time	Seconds	Milliseconds	Seconds
Scalability	High	Moderate	Moderate
Lifetime, hr	80,000	50,000 - 80,000	<40,000
Application	Large-scale	Small to medium scale	Large-scale
Hydrogen Purity	99.5% - 99.9998%	99.9% - 99.9999%	99.90%
Development Status	Mature	Commercialised	R&D
CAPEX (USD/kW USA)	700-1000	1300-1700	NA
CAPEX (USD/kW China)	340-400	700-800	NA
Forced Outage Rate	15%	10%	15%

Hydrogen Storage

In hydrogen cost modelling, gaseous hydrogen storage can be used to (1) provide a consistent hydrogen supply; or (2) produce additional hydrogen for storage during off-peak hours or high availability of renewable energy.

While hydrogen has a high energy density on a mass basis (142 MJ/Kg – HHV), it has a low volumetric energy density ranging from 5.6 MJ/L for compressed gaseous hydrogen at 700 bars to 8 MJ/L for liquefied hydrogen. This is lower than gasoline, which offers 32 MJ/L at ambient conditions. Hence, compression is essential for hydrogen storage.

The isothermal compression results in 1.5 and 2.0 kWh of work per kilogram of hydrogen compressed to pressures of 250 and 1000 atmospheres, respectively. However, parasitic compression losses raise this power consumption to 2.5 and 4.0 kWh/kg (compression efficiency of 60% and motor efficiency of 90%).

Diverse options exist for hydrogen storage. These include:

A) Line packing (use of transportation and distribution pipelines) for a very short duration of storage.

B) Underground (salt caverns or former oil and gas reservoirs) for all other durations if geographically available, as no other option offers such a high cost-effectiveness for long-term storage.

C) Gaseous hydrogen pressure vessels as buffers for a short duration of storage.

D) Cryogenic/Liquefied hydrogen for daily or weekly storage and for longer-term storage where underground storage is unavailable.

In this current study, we considered compressed gaseous hydrogen using a type IV pressure vessel with capital costs of 700 USD per Kg of hydrogen as per the Hydrogen Storage and Transport—Technologies and Costs study conducted by the Institute of Transportation Studies at UC Davis in 2024. Fixed operation and maintenance costs were assumed to be 2.5% of the capital costs and the maximum tank volume was constrained at 10 m3.

RESULTS

The collective impact of the hydrogen value chain (renewable generation, utility-scale battery, electrolyser, compression, and gaseous hydrogen storage) on the Levelized Cost of Hydrogen Production (LCOH) is shown in Figure 1. This analysis is performed for a project lifetime of 25 years, with hourly calculations for (1) renewable generation, (2) battery charging and discharging, (3) electricity imported and exported to the grid, (4) electrolyser operation, (5) water usage, (6) compressor energy usage, and (7) storage of compressed gaseous hydrogen.

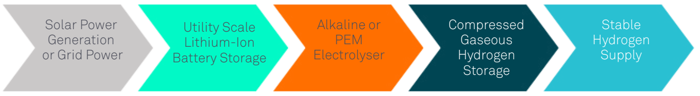


Figure 1 Modelled steps of the hydrogen value chain (with or without grid connection).

Grid-connected electrolyser operation and costing.

The grid allows for stable, continuous electrolyser operation at maximum load, resulting in higher annual hydrogen production and lower levelized costs. The availability of the grid eliminates the need for any hydrogen storage or batteries, which incur substantial capital costs.

Table 1 shows the operation of a 1000 kW electrolyser under eight different grid-connected scenarios where electrolyser technology, electrolyser replacement time, solar capital costs, availability of battery storage and net metering are varied. In terms of electrolyser technology, PEM and ALK technologies are considered, which have markedly different capital costs in the USA (based on NREL technology baseline report 2024) and

China (based on a market survey).

For the GCC region, solar PV is the cheapest electricity available. With the latest solar auctions achieving sub 1.3 US cents per kWh levelized cost of solar production, back calculation results in a solar capital cost of 400 USD/kW. However, the latest n-type solar PV modules produced by Chinese manufacturers are being priced below 100 USD/kW (adding a similar cost for the balance of plant and soft costs), this amounts to 300 USD/kW overnight capex costs.

With 350 USD/kW ALK electrolysers and 300 USD/kW solar PV, the lowest LCOH of 3.5 USD per Kg was achieved as per Scenario 6 (with a solar capacity of 2000 kW PV). This price excludes any land or grid connection costs and considers a low WACC of 5.1% (to raise interest from developers). This LCOH can be further reduced based on possibility of exporting power under a net-metering arrangement (15 USD/MWh export price resulted in 0.1 USD/Kg reduction in LCOH).

Table 3 and the associated figure show the cost breakdown of a generic grid-connected hydrogen production value chain consisting of solar generation, battery storage, ALK electrolyser, grid power at Abu Dhabi industrial tariff, net-metering, and oxygen sales. The battery and electricity charges are the dominant cost drivers. Also, the electrolyser CAPEX, oxygen sales and price of clean energy certificates for imported grid power impact the LCOH.

Off-grid electrolyser operation and costing

Off-grid electrolysers, batteries, and hydrogen storage add substantial fixed costs, increasing the LCOH. Table 2 highlights 8 scenarios for various modes of off-grid hydrogen production and the resulting LCOH. With US-based pricing of PEM electrolysers at 1500 USD/Kg, a LCOH of 5.8 USD/Kg was achieved for a simple configuration devoid of electric batteries or hydrogen storage. However, with Chinese ALK electrolysers priced at 350 USD/kW and solar PV capex at 300 USD/kW, very low LCOH of 2 USD/Kg is possible (excluding land costs, grid connection fees, battery, or hydrogen storage). This low LCOH is only possible for large-scale solar and electrolyser deployments; for smaller scales, the electrolyser costs shall be higher, even from Chinese manufacturers. However, it does point to the direction that LCOH in the GCC region can reduce significantly with the adoption of Chinese technologies if the long-term durability and reliability of these technologies can be ensured. Adding hydrogen storage and compression converts the variable hydrogen supply to a stable hydrogen supply but adds an additional LCOH of 0.7-1 USD/Kg.

Table 4 and the associated figure show the cost breakdown of an off-grid hydrogen production value chain consisting of solar generation, battery storage, ALK electrolyser, and oxygen sales. The battery CAPEX and Fixed Operation and Maintenance Rate (FOMR) are the dominant cost drivers for the LCOH.

Comparison with other reference points

IEA predicted the cost of hydrogen production using solar in 2023 to be 3.8-12 USD/Kg as per its latest Global Hydrogen Review 2024. This view is based on a levelized cost of solar PV of 20-120 USD/MWh whereas we are considering the results of the GCC regional solar auctions in the range of 12-14 USD/MWh. This results in a lower projection on solar CAPEX cost of 300-400 USD/kW. Also, IEA considered the electrolyser cost to be 950 USD/kW, which is considerably higher than the view of Chinese manufacturers (at World Future Energy Summit 2025 in Abu Dhabi) and the recent bids in China (approaching 200 USD/kW for ALK electrolysers). Also, IEA considered 6-20% for WACC, while our analysis considered 5%. The possibility of electricity export to the grid and oxygen sales is not considered in the IEA analysis. In conclusion, considering the best possible assumptions, LCOH in the GCC can drop to 2-4 USD/Kg in the next three years. This is a good signal for the local hydrogen market in the region.and the maximum tank volume was constrained at 10 m3.

Table 2 Levelized cost of hydrogen production in USD per Kg for three different grid-connected 1000 kW electrolyser scenarios with varying captive solar generation capacity.

On-Grid Hydrogen Production

Parameters Per Scenario	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**	**Scenario 6**	**Scenario 7**	**Scenario 9**
Electrolyser Technology, Ref., Price	PEM (NREL) @ 1500 USD/kW	PEM (NREL) @ 1500 USD/kW	PEM (NREL) @ 1500 USD/kW	PEM (NREL) @ 1500 USD/kW	ALK (USA) @ 850 USD/kW	ALK (China) @ 350 USD/kW	PEM (China) @ 700 kW	ALK (China) @ 350 USD/kW
Electrolyser Stack Replacement	65000 Hrs	65000 Hrs	65000 Hrs	65000 Hrs	80000 Hrs	80000 Hrs	65000 Hrs	80000 Hrs
Captive Renewable Technology	Solar @ 400 USD/kW	Solar @ 400 USD/kW	Solar @ 400 USD/kW	Solar @ 400 USD/kW	Solar @ 300 USD/kW	Solar @ 300 USD/kW	Solar @ 300 USD/kW	Solar @ 300 USD/kW
Grid Availability	Yes (AD/UAE Industrial Tariff)	Yes (AD/UAE Industrial Tariff)	Yes (AD/UAE Industrial Tariff)	Yes (AD/UAE Industrial Tariff)	Yes (AD/UAE Industrial Tariff)	Yes (AD/UAE Industrial Tariff)	Yes (AD/UAE Industrial Tariff)	Yes (AD/UAE Industrial Tariff)
Utility Scale Lithium Ion Battery (kW)	No Electric Storage	No Electric Storage	No Electric Storage	1000 @ 1770 USD/kW	No Electric Storage	No Electric Storage	No Electric Storage	1000 @ 680 USD/kW
Utility Scale Lithium Ion Battery (Hours)	No Electric Storage	No Electric Storage	No Electric Storage	4	No Electric Storage	No Electric Storage	No Electric Storage	4
Hydrogen Storage (Lined Tanks)	No Hydrogen Storage	No Hydrogen Storage	No Hydrogen Storage	No Hydrogen Storage	No Hydrogen Storage	No Hydrogen Storage	No Hydrogen Storage	No Hydrogen Storage
Clean Energy Certificates (USD/MWh)	Not Applied	Not Applied	Applied at 13.6 USD/MWh	Not Applied	Not Applied	Not Applied	Not Applied	Not Applied
Net Metering	No Export	Export @ 15 USD/MWh	Export @ 15 USD/MWh	No Export	No Export	No Export	No Export	No Export
Land and Grid Connection	Free	Free	Free	Free	Free	Free	Free	Free
Oxygen Scales	Oxygen Sales @ 0.1 USD per kg	Oxygen Sales @ 0.1 USD per kg	Oxygen Sales @ 0.1 USD per kg	Oxygen Sales @ 0.1 USD per kg	Oxygen Sales @ 0.1 USD per kg	Oxygen Sales @ 0.1 USD per kg	Oxygen Sales @ 0.1 USD per kg	Oxygen Sales @ 0.1 USD per kg
WACC	5.10%	5.10%	5.10%	5.10%	5.10%	5.10%	5.10%	5.10%
Results								
Solar Capacity (kW)	LCOH (USD/Kg)	LCOH (USD/Kg)	LCOH (USD/Kg)	LCOH (USD/Kg)	LCOH (USD/Kg)	LCOH (USD/Kg)	LCOH (USD/Kg)	LCOH (USD/Kg)
0	5.8	5.8	6.7	10	5.1	4.6	5.0	6.5
500	5.4	5.4	6.2	9.6	4.7	4.2	4.6	6.1
1000	5.0	5.0	5.7	9.3	4.3	3.8	4.2	5.7
1500	4.7	4.7	5.3	8.9	4.0	3.5	3.9	5.3
2000	4.7	4.6	5.2	8.6	3.9	3.5	3.8	4.9
2500	4.8	4.6	5.0	8.8	3.9	3.5	3.9	4.9
3000	4.9	4.6	5.0	8.9	4.0	3.5	3.9	4.9
3500	5.0	4.6	4.9	9	4.1	3.6	4.0	5.0
4000	5.1	4.6	4.8	9.1	4.2	3.7	4.1	5.1
4500	5.2	4.7	4.7	9.2	4.3	3.8	4.2	5.2
5000	5.3	4.8	4.7	9.4	4.4	3.9	4.3	5.3

Table 3 Levelized cost of hydrogen production for three off-grid 1000 kW electrolyser scenarios with variable solar power generation capacity.

Off-Grid Hydrogen Production

Parameters Per Scenario	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**	**Scenario 6**	**Scenario 7**	**Scenario 9**
Electrolyser Technology, Ref., Price	PEM (NREL) @ 1500 USD/kW	PEM (NREL) @ 1500 USD/kW	PEM (NREL) @ 1500 USD/kW	PEM (NREL) @ 1500 USD/kW	ALK (USA) @ 850 USD/kW	ALK (China) @ 350 USD/kW	ALK (China) @ 350 USD/kW@ 700 kW	PEM (China) @ 700 kW
Electrolyser Stack Replacement	65000 Hrs	65000 Hrs	65000 Hrs	65000 Hrs	80000 Hrs	80000 Hrs	80000 Hrs	65000 Hrs
Captive Renewable Technology	Solar @ 400 USD/kW	Solar @ 300 USD/kW	Solar @ 300 USD/kW	Solar @ 300 USD/kW	Solar @ 300 USD/kW	Solar @ 300 USD/kW	Solar @ 300 USD/kW	Solar @ 300 USD/kW
Grid Availability	No	No	No	No	No	No	No	No
Utility Scale Lithium Ion Battery (kW)	No Electric Storage	No Electric Storage	No Electric Storage	1000 @ 1500 USD/kW	1000 @ 750 USD/kW	No Electric Storage	No Electric Storage	No Electric Storage
Utility Scale Lithium Ion Battery (Hours)	No Electric Storage	No Electric Storage	No Electric Storage	4	4	No Electric Storage	No Electric Storage	No Electric Storage
Hydrogen Storage (Lined Tanks)	No Hydrogen Storage	No Hydrogen Storage	No Hydrogen Storage	No Hydrogen Storage	No Hydrogen Storage	No Hydrogen Storage	10 M3 35, MPA, 1200 USD/kW Comp	10 M3 35, MPA, 1200 USD/kW Comp
Clean Energy Certificates (USD/MWh)	Not Applied	Not Applied	Not Applied	Not Applied	Not Applied	Not Applied	Not Applied	Not Applied
Net Metering	No Export	No Export	Export @ 15 USD/MWh	Export @ 15 USD/MWh	Export @ 15 USD/MWh	No Export	No Export	No Export
Land and Grid Connection	Free	Free	Free	Free	Free	Free	Free	Free
Oxygen Scales	Oxygen Sales @ 0.1 USD per kg	Oxygen Sales @ 0.1 USD per kg	Oxygen Sales @ 0.1 USD per kg	Oxygen Sales @ 0.1 USD per kg	Oxygen Sales @ 0.1 USD per kg	Oxygen Sales @ 0.1 USD per kg	Oxygen Sales @ 0.1 USD per kg	Oxygen Sales @ 0.1 USD per kg
WACC	5.10%	5.10%	5.10%	5.10%	5.10%	5.10%	5.10%	5.10%
Results								
Solar Capacity (kW)	LCOH (USD/Kg)	LCOH (USD/Kg)	LCOH (USD/Kg)	LCOH (USD/Kg)	LCOH (USD/Kg)	LCOH (USD/Kg)	LCOH (USD/Kg)	LCOH (USD/Kg)
500	15.6	15.4	15.3	50	27.7	3.7	4.4	8.1
1000	8	7.7	7.7	25.5	14	1.9	3.1	4.9
1500	5.9	5.7	5.6	17.3	9.6	1.6	2.4	3.7
2000	5.7	5.4	5.1	13.4	7.5	1.7	2.5	3.7
2500	5.8	5.4	4.9	12.5	6.9	2.0	2.7	3.8
3000	6	5.5	4.8	12	6.7	2.2	2.9	4
3500	6.2	5.7	4.7	11.8	6.6	2.5	3.1	4.2
4000	6.5	5.9	4.7	11.7	6.6	2.7	3.4	4.4
4500	6.8	6.1	4.7	11.6	6.5	3.0	3.7	4.7
5000	7.1	6.4	4.7	11.6	6.5	3.3	3.9	4.9

Table 4 Generic grid-connected hydrogen production plant for analysing the cost segmentation

Cost Segementation of On-Grid Power Generation	
Parameters Per Scenario	Scenario
Electrolyser Technology and Reference	ALK (USA) @ 850 USD/kW
Electrolyser Stack Replacement	80000 Hrs
Captive Renewable Technology	Solar @ 300 USD/kW
Grid Availability	Yes (AD/UAE Industrial Tariff)
Utility Scale Lithium Ion Battery (kW)	1000 @ 680 USD/MWh
Utility Scale Lithium Ion Battery (Hours)	4
Hydrogen Storage (Lined Tanks)	No Hydrogen Storage
Clean Energy Certificates (USD/MWw)	13.6 USD/MWh
Net Metering	Export @ 15 USD/MWh
Land and Grid Connection	Free
Oxygen Sales	Oxygen Sales @ 0.1 USD per Kg
WACC	5.10%
Electrolyser Capacit	1000 kW
Solar Capacity	2500 kW
Battery Capacity	1000 kW

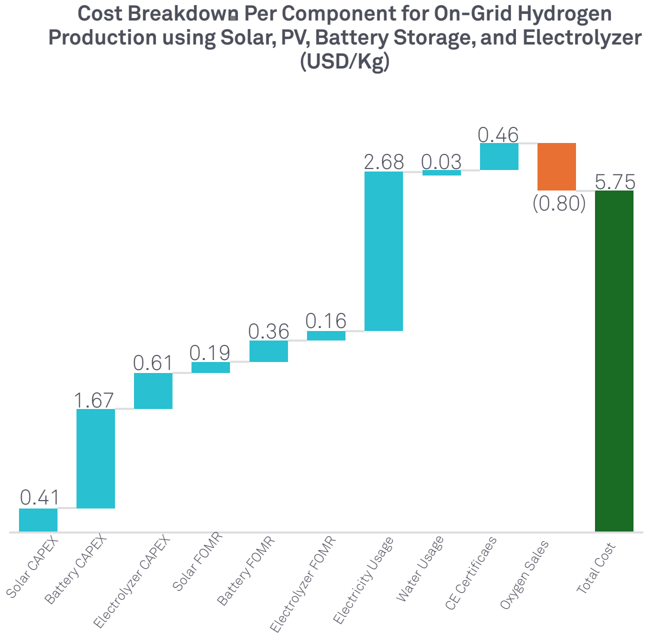
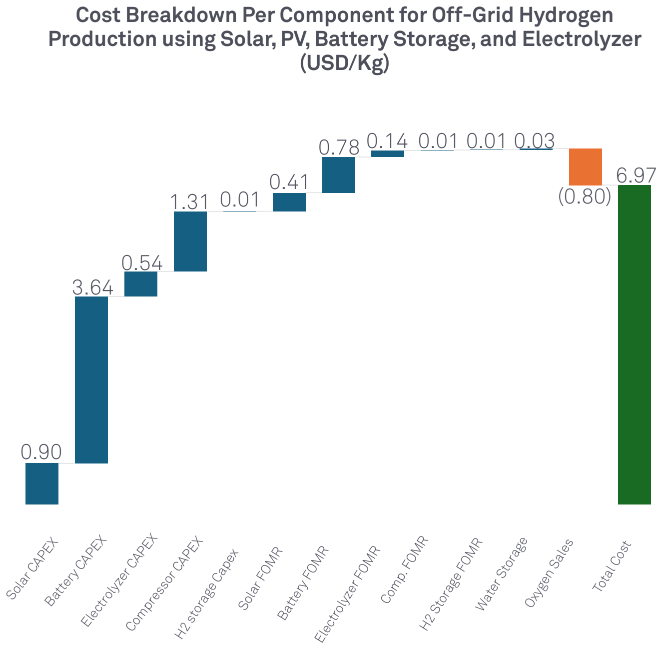

Cost Breakdown Per Component for On-Grid Hydrogen Production using Solar, PV, Battery Storage, and Electrolyzer (USD/Kg)

Table 5 Generic off-grid hydrogen production plant for analysing the cost segementation

Cost Segementation of On-Grid Power Generation	
Parameters Per Scenario	Scenario
Electrolyser Technology and Reference	ALK (USA) @ 850 USD/kW
Electrolyser Stack Replacement	80000 Hrs
Captive Renewable Technology	Solar @ 300 USD/kW
Grid Availability	Not Applicable
Utility Scale Lithium Ion Battery (kW)	1000 @ 680 USD/MWh
Utility Scale Lithium Ion Battery (Hours)	4
Hydrogen Storage (Lined Tanks)	10 M3 @ 35 MPA, 1200 USD/kW Comp
Clean Energy Certificates (USD/MWw)	Not Applicable
Net Metering	Not Applicable
Land and Grid Connection	Free
Oxygen Sales	Oxygen Sales @ 0.1 USD per Kg
WACC	5.10%
Electrolyser Capacit	1000 kW
Solar Capacity	2500 kW
Battery Capacity	1000 kW


Cost Breakdown Per Component for Off-Grid Hydrogen Production using Solar, PV, Battery Storage, and Electrolyzer (USD/Kg)

WAY FORWARD

The LCOH is a critical metric for the cost competitiveness of hydrogen projects in the GCC region. Low-cost green hydrogen production, given the land and solar resource in the GCC region and the decline in solar PV, battery and electrolyser prices, can result in financial closure of hydrogen projects.

In this respect, 2 USD/Kg is an important threshold for unlocking a major contribution of hydrogen within the energy transition. As of today, achieving this threshold depends on Chinese manufacturers, who have the capability to provide 300-400 USD/kW solar PV, 600-700 USD/kW utility-scale four-hour lithium battery, and 350-450 USD/kW ALK electrolysers. However, it is important for Chinese manufacturers to offer turn-key solutions, warranties, service contracts and long-term support to de-risk hydrogen projects. Also, the enabling environment offered to renewable energy developments in the form of free land and grid connection, and competitive financing, should be offered to hydrogen projects as well.

With technology prices reaching such low levels, for grid-connected electrolysers, electricity and water tariffs become major drivers of the LCOH. In this exercise, Abu Dhabi's peak and off-peak industrial tariffs were considered. These tariffs are higher than in-house solar generation. Hence, a solar capacity of 2-3 times is required to minimize electricity imports from the grid as well as the LCOH.

Finally, the utility sector, given the synergies between electricity and water production, hydrogen production and storage, and grid balancing, could benefit from the early adoption of hydrogen production, not only for its own consumption but for exports as well. In this respect, the utility sector could diversify its product range to include hydrogen, oxygen and even methanol, for instance.

ABOUT PENSPEN

Penspen is a global team of engineers who design, maintain, and optimise energy infastructure to improve access to secure and sustainable energy for communities worldwide. We help meet the world's evolving energy needs by providing consulting, project, and engineering slutions across the entire energy asset lifecycle.

For over 70 years, our teams have delivered more than 15,000 projects to in excess of 100 countries. By helping countries access lower carbon fuels and by extending the useful life of exisiting energy infrastructure, we help bring cleaner energy to millions of people in thousands of communities across the Middle East, Africa, Asia, Europe, the UK, and the US.

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