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GREEN HYDROGEN AND THE PATHWAY TOWARD A DECARBONISED ENERGY ECONOMY

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INTRODUCTION

In the 21st century, the global energy industry is rapidly shifting toward low-carbon energy sources, with hydrocarbon resources like coal and oil gradually losing penetration. Global coal power capacity under development decreased by 13% in 2021, with the EU's 27 member states retiring 12.9GW worth of capacity in 2021 alone.[i] Non-hydro renewables like solar photovoltaic (PV) and wind are expected to grow substantially, reaching an estimated capacity of 3,100GW and 1,850GW by 2040, up from 843GW and 825GW, respectively, in 2021.[ii] This energy evolution/transition is now one of the most prolific and impactful global mega trends, spurred by the need—and potential—for cleaner energy to contribute to the world's aspirations for net-zero.

As we move forward, we can expect to see decentralisation[iii], decarbonisation[iv] and digitalisation[v] as the main pillars shaping the next wave of energy evolution.

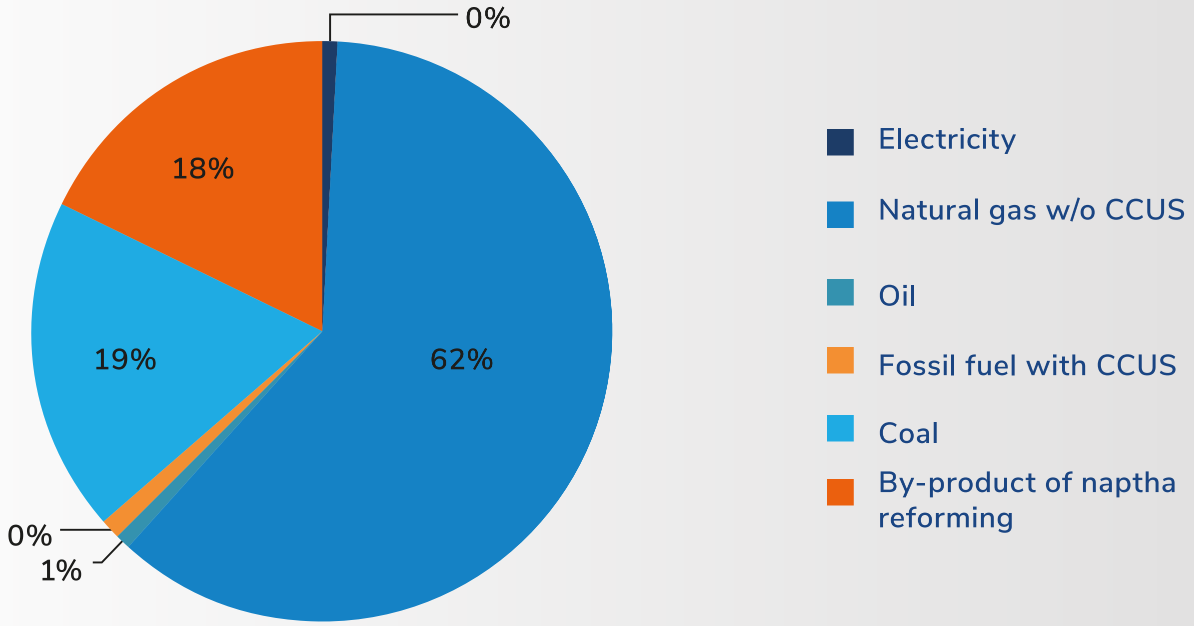
Decarbonisation	Digitalisation	Decentralisation
A potential to achieve 20-25 giga tons emission reductions annually by 2050 through clean energy	Potential energy savings of 6,000 to 6,500TWh by 2040	Potential to provide sustainable electricity to 700 million-800 million people globally

The world is increasing the focus on tackling climate change by reducing emissions. The last COP26 summit indicated that the current nationally determined contributions (NDCs) committed by 120 countries as of 2021 would only reduce emissions by 7.5% by 2030, while a 55% reduction is required to maintain global temperature rise within 1.5°C. At the COP27 summit, member countries have reaffirmed their commitment to limit global temperature increase to 1.5°C above pre-industrial levels. The Sharm el-Sheikh Implementation Plan has also highlighted the need for USD 4-6 trillion/ year for undertaking a global transformation to a low-carbon economy.[vi] This makes decarbonisation one of the most important factors driving the future of energy through the use of technologies that target the reduction and elimination of hydrocarbon-based fuels from the value chain. In the quest to decarbonise the economy, one term consistently garnering global attention has been "hydrogen," which can replace as much as 10% of the total final energy consumption by 2050.[vii]

Hydrogen is the simplest and most abundant chemical element in nature. Hydrogen combustion generates energy in the form of heat, with water being generated as a by-product of the combustion process. Hydrogen being a zero-emission source of energy has led to its resurgence as a modality for reducing greenhouse gas (GHG) emissions and helping global economies achieve their net-zero emission mandates.

However, hydrogen as a source of energy is not a recent development. It has a long-standing relationship with the industry because gas has been effectively used to power internal combustion (IC) engines, hydrogen balloons and even space missions since the 18th and 19th centuries. In the industry, a vast majority of hydrogen is produced and used on-site. Across the industrial segment, hydrogen is widely used in ammonia production and oil refining. Ammonia is used as a nitrogen fertilizer and for the production of other chemicals. At petroleum refineries, hydrogen is added to heavier oil to produce different transportation fuels. Ammonia production and oil refining account for two-thirds of global hydrogen use.[viii] Global hydrogen demand has increased threefold since 1975 and is only expected to increase as hydrogen plays a critical role in decarbonization for key global economies.[ix] As of 2021, global hydrogen production has been estimated at 94 million tons of hydrogen (Mt H_2), with demand being met primarily through fossil fuels.[x] The graphic below provides an overview of hydrogen production through different sources.

Hydrogen Production Mix, 2021[xi]



As is evident from the above graphic, the contribution of electricity for hydrogen production is limited to less than 1% or roughly 35kt H_2 via electrolysis.[xi] As such, hydrogen production from renewable resources also remains largely restricted, with the fuel currently having limited relevance to decarbonisation and energy transition efforts. However, this situation is primed to undergo a rapid transition, with governments and other global entities shifting focus to hydrogen as a key modality toward a greener and sustainable energy future. As a versatile energy carrier, hydrogen is strongly positioned to tackle critical challenges due to its capability of being produced from multiple sources, its application across multiple end-use segments, and its ability to be stored and transported across traditional systems. The importance of hydrogen will stem from new applications and an overall need to decarbonise the production and supply of hydrogen. If production costs reduce by 50% by 2030, hydrogen will have a key role to play in the future global energy mix.[xii]

TYPES OF HYDROGEN

Hydrogen can be produced through multiple sources and their associated technologies. Depending upon the type of production employed, a color-based classification has been assigned to differentiate between the various types of hydrogen.[xiii]

- **Grey hydrogen:** The most common form of hydrogen production, grey hydrogen, is produced from natural gas or methane using steam methane reformation but without capturing the greenhouse gases made in the process.
- **Blue hydrogen:** Blue hydrogen is produced mainly from natural gas through steam reforming. Unlike grey hydrogen, the carbon dioxide produced during the reforming process is captured and stored through carbon capture and storage (CCS).
- **Green hydrogen:** Green hydrogen is produced using the surplus electricity from solar and wind power plants through a process called electrolysis without any harmful emissions.
- **Black and brown hydrogen:** Hydrogen produced through coal (black) or lignite (brown) is referred to as black or brown hydrogen
- **Pink hydrogen:** Hydrogen produced through electrolysis powered by nuclear energy is called pink hydrogen. Nuclear-produced hydrogen can also be referred to as purple hydrogen or red hydrogen.
- **Turquoise hydrogen:** While yet to be proven commercially, turquoise hydrogen is produced through methane pyrolysis to produce hydrogen and solid carbon.
- **White hydrogen:** White hydrogen is a naturally occurring geological hydrogen found in underground deposits and created through fracking. There are currently no strategies to exploit this hydrogen.

Depending on the fuel source and the manufacturing process employed, different types of hydrogen vary in terms of their carbon emissions, the most sustainable being "green hydrogen" produced through renewable electricity.

DECARBONISATION OF THE ENERGY SECTOR AND THE ROLE OF GREEN HYDROGEN

Fossil fuel consumption, coupled with rising industrial activity and transportation requirements, has been predominantly responsible for Green House Gas (GHG)-linked temperature rise and climate change. In an attempt to curb the temperature rise and reverse the negative impacts of climate change, governments around the world have committed to reducing fugitive emissions and achieving net-zero emissions by 2050 and 2060. While a majority of the focus has been on increasing the share of renewable energy and energy storage in the overall energy mix, specific attention is also paid to realising sustainable forms of heating and transportation fuel, which constitute a major portion of global GHG emissions. This requirement of a multi-modal, sustainable fuel source is where hydrogen and, more particularly, green hydrogen will have a key role to play in a future decarbonized energy mix. While the current use of hydrogen is primarily as a chemical feedstock, this fuel could play a different role in future energy systems, finding applicability across the industry, transportation, power generation and storage.

ELECTROLYZERS ARE MODULAR PROCESSING UNITS THAT USE AN ELECTRICAL CURRENT TO SPLIT WATER INTO ITS INDIVIDUAL COMPONENTS—HYDROGEN AND OXYGEN.

Green hydrogen as a fuel offers multiple pathways for economies to achieve decarbonisation and has a vast and increasing spectrum of applications, including:

Industry – Feedstock for industries ranging from chemicals to steel. Major European steelmakers are currently building or testing hydrogen-based reduction for use in electric arc furnaces (EAFs). Their goal is to use purer streams of hydrogen to perform the chemical reduction process to avoid emissions. The conversion of hydrogen to energy carriers such as ammonia and methanol that can be used for heating and power generation applications is another industrial application for hydrogen that is being explored by countries such as Japan to meet their emission targets, especially with respect to sustainable power generation.

Power generation – Direct combustion in gas turbines or through fuel cells for electricity generation.

Transportation – Suitable for large-scale/heavy transportation requirements, including large road vehicles, aviation and maritime, where higher energy storage capabilities with lower weight are a key requirement. Energy for motive applications can be met through fuel cells or the combustion of liquefied hydrogen, ammonia and synthetic fuel derived from hydrogen or hybrid options that use a combination of hydrogen combustion and fuel cells.

Energy storage – Hydrogen can be effectively used as a long-term energy storage solution to account for seasonal variations arising from high renewable energy capacity in the grid. During periods of excess generation, excess electricity from renewable plants can be used to power electrolyzers for hydrogen production, which can then be stored in liquid, gas or chemical (ammonia) form. In periods of peak demand, stored hydrogen can be released to produce power through hydrogen power plants or retrofitted gas power plants.

Fuel blending & transportation – In areas where electrification opportunities are remote, green hydrogen could be used to refuel the country's natural gas infrastructure. Green hydrogen can be mixed with natural gas without any infrastructural change, helping decarbonise the natural gas infrastructure.

While hydrogen is being touted as an effective modality to decarbonise the industry, power generation and transportation, it would not necessarily offer the same impact across all forms and scales of end use. For light transportation and passenger vehicles, battery-operated electric vehicles offer more practicality and higher efficiency of energy conversion compared to Hydrogen-powered fuel-cell electric vehicles. Similarly, despite its long energy storage capabilities, the lower round-trip efficiencies offered by hydrogen storage means a lower proportion of the initial energy would be available for final usage.

Globally, countries and organisations are taking note of hydrogen's value proposition while developing ambitious plans and targets to meet net-zero-emission commitments. The European Union, Germany and the United Kingdom are among the leading global economies that have developed supply-side initiatives in relation to green hydrogen:

European Union – It will have 40 GW electrolyzer capacity and up to 10 Mt/year of renewable hydrogen by the 2030, European Clean Hydrogen Alliance and Special EIB fund for clean hydrogen.

Germany – It plans to deploy up to 5 GW of green hydrogen generation capacity by 2030 and invested €700 million under the National Innovation Programme in Hydrogen.

United Kingdom – It is scaling up green hydrogen manufacturing capacity to 1 GW/year by 2025, with £28 million to fund the Hydrogen Supply program and £240 million for the Net Zero Hydrogen Fund.

Along with governments, industry, utilities, and private enterprises have also stepped out of their core businesses and started to explore new hydrogen-related opportunities.

Across Europe, one of the world's leading renewable energy developers is targeting over 600MW of electrolyzer capacity by 2025 and 3GW by 2030.[xiv] The company is currently developing Europe's largest industrial green hydrogen project in Spain for a fertilizer manufacturer comprising of 100MW of solar PV capacity, battery storage and a 20MW electrolyzer. The company has also ventured into the hydrogen value chain through a new undertaking with a specific focus on the distribution of industrial-scale electrolyzers for customers with a significant demand for hydrogen. It has also been awarded a contract to supply Barcelona's transport operator with hydrogen for its fleet of buses, further cementing the company's position as a key player in the hydrogen value chain.

STATUS OF DEPLOYMENTS AND FUTURE PROJECTIONS

To date, an estimated 99% of global hydrogen is dependent on fossil fuels for its production. Low-emission hydrogen comprises production from electrolysis, and fossil fuels with carbon capture, utilisation and storage (CCUS) accounted for less than 1% of the global hydrogen production in 2021. However, the amount of hydrogen produced through water electrolysis increased by 20% compared to 2020.[xiv]

Despite the low contribution of water electrolysis to hydrogen production, installed capacity for electrolyzers has witnessed an upward trend, increasing to 510MW by the end of 2021, which is an increase of 210MW over the capacity recorded in 2020. The completion of the 150MW Ningxia Solar Hydrogen Project in China was a major contributor to this increase in electrolyzer capacity in 2021. The rapid scale-up in global electrolyzer capacity is expected to continue in the coming decade, with an estimated 460 projects that are currently under deployment or construction. Estimates project the global installed electrolyzer capacity to reach 1.4GW by the end of 2022, with China and Europe leading deployments. Based on the current pipeline of projects, electrolyzer capacity could increase to anywhere between 134GW to 240GW by 2030, depending on the realization of projects that are currently in the early stages of development. Europe, Australia, and Latin America are expected to be the key regions driving installed capacity growth based on the pipeline of announced projects.

TABLE 1: AN OVERVIEW OF THE LARGE-SCALE GREEN HYDROGEN PROJECTS THAT ARE EXPECTED TO BE COMMISSIONED OVER THE NEXT 10 TO 15 YEARS GLOBALLY[XVII]

Sr. No	Project Name	Capacity	Stipulated Completion Year	Location
1	HyDeal Ambition	67GW	2030	Western Europe – extending from Spain, France to Germany
2	Reckaz	30GW	2028	Kazakhstan
3	Western Green Energy Hub	28GW	2028	Australia
4	Aman	16-20GW	NA	Mauritania
5	Green Energy Oman	14GW	2038 (33% completion by 2028)	Oman
6	Asian Renewable Energy Hub	14GW	2027-2028	Australia
7	NorthH2	~10GW	2040 (1GW by 2027; 4GW by 2040)	Netherlands
8	Aquaventus	10GW	2035 (30MW by 2025 and 5GW by 2030)	Germany

ELECTROLYZER TECHNOLOGIES

Electrolyzers are modular processing units that use an electrical current to split water into its individual components—hydrogen and oxygen. When the source of electricity used for electrolysis is from a renewable resource like solar, wind, biomass, etc., the resultant hydrogen produced is green hydrogen.

At present, there are three electrolysis technologies[xviii] that are commercially viable:

1. **Alkaline electrolysis:** A mature technology, alkaline electrolysis can produce hydrogen at an industrial scale. The technology utilizes a liquid electrocatalyst, which negates the requirement for costly metallic materials. Alkaline electrolysis cells are known for their long-term stability and advancements to technology, such as "pressurized alkaline technology," which work effectively with variable renewable energy loads. However, the corrosive nature of the liquid electrolyte remains a challenge that impacts the lifetime of critical components like electrodes, valves, pipes, etc.
2. **Polymer Electrolyte Membrane (PEM) electrolysis:** PEM is another mature electrolysis technology that uses sulfonic acid polymer as the electrolyte. PEM has several advantages over alkaline electrolysis because it offers high energy efficiency, a faster rate of hydrogen production, low gas permeability and the capability to operate at high current densities with faster response times to variable power levels. However, due to the acidic nature of the system, costly rare metals such as platinum and iridium are required for cell construction, which increases capital costs associated with the plant.
3. **Solid Oxide Electrolysis Cells (SOEC):** SOEC is a less mature technology compared to alkaline and PEM electrolysis. SOEC is performed at high temperatures (typically between 700 and 1,000 °C). Effective utilisation of the waste heat can improve system efficiency by reducing the need for input electrical energy.

In addition to these electrolysis techniques, technologies such as anion exchange membrane (AEM), protonic ceramic electrochemical cell (PCEC) and photoelectrochemical (PEC) water splitting are in the developmental stages.

Current developmental work is also focusing on improving electrolyzer efficiency and performance, reducing the amount of precious metals in PEM systems and advances in electrode technology for alkaline systems.

To meet the growing demand for electrolyzer systems that are aligned with the proposed government mandates for green hydrogen production, a significant increase in manufacturing and deployment of these electrolyzer systems is critical. Large-scale deployment of electrolyzer systems also necessitates significant cost reductions that can be achieved through technological innovations. Some of the critical areas of innovation in electrolyzers are summarised below:

Cell operation conditions and structure – Focus on cell operating parameters such as temperature, pressure and cell unit structure to improve efficiency and cost-effectiveness across a wide range of operating conditions, including voltage fluctuations. Initial research indicates cells operating at a higher pressure could reduce costs for hydrogen production.

Electrocatalyst materials – Focus on developing new solutions to reduce dependency on scarce materials. Scarce materials are a major challenge to electrolyzer cost reduction and scale-up. There has been a growing focus on research and innovation covering non-noble metals, alloys and ceramics for material cost reduction.

Separators – Focus on establishing a balance between the membrane structure, its lifetime and efficiency. The current area of research and innovation revolves around the usage and impact of ceramic and polymer separator membranes. Initial analysis reveals an improvement in efficiency that can be achieved through a reduction of membrane thickness.

Stackability of electrolyzers – Electrolyzer stacks account for 45% of the total cost of electrolyzers. Scaling up production and achieving standardisation can help reduce manufacturing costs. In this regard, the focus of research and innovation is on increasing stack production to automated production in GW scale manufacturing facilities that can help achieve cost reduction due to economies of scale.

Photoelectrolysis – This is the use of semiconductor photoelectrodes for hydrogen production. This technology uses solar energy to split water in a photoelectrochemical cell.

The entire objective of ongoing innovations in electrolyzer technology and efforts to scale up production and capacities of electrolyzers is to reduce the costs of the technology to enable wide-scale adoption of sustainable hydrogen production for end-use applications. As of 2021, hydrogen produced from natural gas was valued at US$ 1.50/kg, while green hydrogen produced through renewable electricity was valued at ~US$ 5.00/kg. As per DOE's Hydrogen Shot, the goal is to reduce the price of green hydrogen by 80% to ~US$ 1.00/kg by 2031.[xx]

A major cost component for green hydrogen production is the electricity used to carry out the electrolysis. Over the past decade, electricity generated through renewable sources like solar and wind has witnessed a tremendous decline. Since 2010, the costs of solar PV-based electricity have dropped by over 85%, while the costs of onshore and offshore wind power have reduced by about half.[xxi] With a further drop in renewable costs anticipated over the upcoming decade, there is now a growing need to focus on reducing the electrolyzer procurement and construction costs while also improving the performance, efficiency and durability of electrolyzers to achieve further cost reductions.

Based on an IRENA analysis,[xxii] achieving the stated target of green hydrogen at US$ 1.00/kg would require the following metrics to be achieved:

- 80% reduction in electrolyzer costs.
- Electricity at USD 20/MWh.
- Electrolyzer efficiency to increase from 65% to 76%.
- Full load hours to increase from 3,200 hours to 4,200 hours.
- Lifetime of electrolyzers to increase from 10 years to 20 years.
- Weighted average cost of capital (WACC) to reduce from 10% to 6%.

GCC: STRATEGICALLY POSITIONED IN THE GLOBAL GREEN HYDROGEN MARKETPLACE

Realising the impact of climate change on human civilization and the economy, each of the Gulf Cooperation Council (GCC) member countries has ratified the Paris Agreement to transform their developmental agendas to set the world on a course for sustainable development while limiting warming to 1.5 to 2 °C above pre-industrial levels. Nationally determined contributions (NDC) form the backbone of the Paris Agreement and represent efforts by each country to reduce national emissions while adapting to climate change impacts. Each GCC member country declared its own NDCs and the modalities for achieving them. GCC countries currently seek to achieve energy sustainability through a combination of renewable energy integration, energy-efficiency implementations and hydrogen production and transport, which will drive the evolution of the energy sector in the region.

In line with global trends, hydrogen has gained increasing recognition as a key contributor to the evolution of the energy sector and is expected to play a key role in decarbonising the economy across end-use sectors in the GCC. GCC countries, especially UAE, KSA and Oman, are working on national strategies aimed at developing the hydrogen market in the region and positioning themselves as future hydrogen exporters. GCC countries currently use large quantities of natural gas-based grey hydrogen, and the availability of low-cost natural gas coupled with the ease of CCUS allows for the cost-competitive production of blue hydrogen.

However, the region also demonstrates several competitive advantages that can enable the GCC to play a key role in the global green hydrogen economy:

Solar & wind resource potential – GCC countries experience high global solar irradiation, and several areas across the region experience strong, consistent wind conditions for reliable renewable electricity production. The abundance and availability of such renewable resources make the GCC region a potential site for the competitive production of green hydrogen. IEA estimated the long-term production cost to reach between US$ 1.5 and 2.0/kg.

Export potential – The geographic location of the GCC region provides a strategic advantage through which global trade routes traverse. Not only does the region have strong connectivity with developed economies in Europe, but a network of ports and pipeline infrastructure provides the region access to fast-growing markets in Asia and Africa. These trade routes and connectivity are expected to play a key role in hydrogen transportation, which would prove critical in meeting end-user demand for the fuel as future large demand markets such as Europe and Japan could face challenges in ramping up hydrogen production to meet demand requirements.

Financing capabilities – Despite efforts to reduce the costs of electrolyzers and associated renewable energy projects, CAPEX remains a critical aspect of realizing a sustainable and carbon-neutral energy ecosystem. Through sustained oil and gas businesses, GCC economies have created significant financial reserves that are often channeled through sovereign funds toward developing strategically important projects.

Green hydrogen production in the GCC presents export and local consumption opportunities that governments and project developers can explore.

Future key large demand regions for green hydrogen can face obstacles in realising their potential for green hydrogen production due to one or several of the following:

- Less competitive renewable electricity.
- Limited financing capabilities.
- Competing mandates.
- Other concerns surrounding the development of large-scale renewable energy and hydrogen projects.

The limited capability of key demand regions in achieving self-sufficiency in hydrogen production and supply creates a strong opportunity for the GCC to provide cost-competitive green hydrogen and emerge as a key enabler in global decarbonisation. Price and carbon emissions associated with hydrogen production are expected to be key determinants for the hydrogen supply in European and Asian markets. Under such circumstances, it would be critical for the GCC to leverage a first-mover advantage and commit investments to achieve future cost competitiveness in the wake of rising competition from regions in North Africa, Europe, and Australia.

In addition to export opportunities, GCC countries can cater to their own demand, driven by regional applications in industry and transportation.

In this regard, GCC countries have already made progress toward green hydrogen production, storage, and supply, with several projects announced in 2020 and 2021.

The following is an overview of ongoing green hydrogen-linked initiatives in the region:

- Neom, Saudi Arabia – A 2GW green hydrogen facility for ammonia production and export
- Duqm Green Hydrogen Project, Oman – A 500MW electrolyzer powered by solar and wind
- Mubadala, UAE – Production of e-fuel with airlines as key offtakers
- Masdar, UAE – Pilot scale project in Masdar City, Abu Dhabi, to produce green hydrogen and sustainable fuels for road transport, aviation and shipping

The benefits of developing green hydrogen production capabilities in the GCC extend beyond local consumption and export. The localisation of technologies and products in the hydrogen value chain presents a significant opportunity for the GCC to leverage as part of its economic diversification initiatives.

Several opportunities for localization of the hydrogen value chain exist; the key ones are listed below:

- Plant installation, operation and maintenance
- Power electronics
- Balance of plant (BoP)
- Mounting structures and cables for renewable energy plants
- Wind turbine components
- Transport pipelines and storage tanks

The development of a green hydrogen economy and localisation of value chain elements present economic and employment benefits for the GCC, the impact of which can be manifold should the GCC seek a global role in achieving green hydrogen-led decarbonisation.

Decarbonisation of the energy ecosystem requires a multi-pronged, multi-modal approach. Collaborative cross-boundary efforts comprising government policy and entities, regulatory authorities, and technology providers will be crucial to achieving a measurable impact. The cost competitiveness of green hydrogen will be the key determinant of its wide-scale adoption, in which the GCC is strategically positioned to contribute.

However, to accelerate the adoption of a hydrogen ecosystem and play a leading role in global decarbonisation efforts, GCC countries must focus on:

- Developing cohesive policies and strategies with clearly quantifiable targets.
- Fostering an ecosystem for R&D and innovation.
- Developing strategic production, storage, transportation and export capabilities.
- Creating a local talent pool and upskilling.

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