RENEWABLES FIRST

Insights on Green H_2

For Pakistan

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Disclaimer:

All the information and analysis provided in this document are accurate and to the best of our knowledge and understanding, in case you identify any error, please email: info@renewablesfirst.org

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Contents

Glossary

Carbon Capture and Storage (CCS) / Carbon Capture, Utilization and Storage (CCUS)

It's an umbrella of technologies used to capture carbon dioxide emissions produced from point source of emissions in industrial processes. The captured CO_2 can be stored underground in geological formations, such as depleted oil and gas fields, to prevent it from entering the atmosphere in order to contribute to climate change. In CCUS captured carbon can be utilized further to manufacture useful products such as chemicals, fuels, or building materials to create an economic value of the process.

Combine Cycle Gas Turbines (CCGTs)

CCGTs are used to generate electricity in industrial and marine applications. Their operating process combines two or more thermodynamic cycles to enhance overall efficiency and hence reduce fuel costs. Mainly natural gas is used as fuel, however other fuels can also be utilized. They are known for their efficiency, having multistage operations and heat recovery to generate more electricity as compared to conventional power plants.

Carbon Border Adjustment Mechanism (CBAM)

A Carbon Border Adjustment Mechanism (CBAM) is a policy tool being developed by European Union (EU) to address the issue of carbon leakage, which can occur when companies move production to countries with no carbon caps or regulations, leading to an increase in global emissions. CBAM aims to put a carbon price on imported goods based on their carbon emissions. EU anticipates decarbonizing its import economy by implementing CBAM regulations by 2026.

Electrolysis

Electrolysis involves passing an electric current through a substance, typically an electrolyte (a liquid or solution that conducts electricity), to break it into individual compounds. This process can be used to produce elements like hydrogen and oxygen from water, or to extract metals from their ores.

Electrolyzers

It is an equipment to carry out electrolysis using electricity to extract hydrogen and oxygen gases. Electrolyzer assembly comprises of electrodes submerged in electrolytes.

Electrolyte

Electrolytes are substances that conduct electricity when dissolved in a solvent, typically a liquid or a gel. They are commonly used in batteries, fuel cells, capacitors, and other devices where the flow of ions is essential for their operation.

Electrodes

Electrodes are electrical conductors that are used to transfer electrons to or from an electrochemical cell, where chemical reactions take place.

Fuel Cell Vehicles (FCVs)

Fuel Cell Vehicles (FCVs) use a special kind of technology called fuel cells to power them. FCVs use hydrogen gas to generate electricity, which then powers an electric motor to drive the vehicle. The only byproduct of this process is water vapor, making FCVs a clean alternative to traditional gasoline-powered cars.

Hydro-treating

It is a catalytic process to remove sulfur from the natural gas and other petroleum products to improve fuel quality as the presence of even small traces can lead to fuel poisoning. The process is also known as Hydrodesulfurization.

Levelized Cost of Electricity (LCOE)

The LCOE incorporates the entire life cycle operational expenses of a power plant for generating electricity. This includes all costs related to construction, operation, maintenance, fuel prices, and any financial incentives or subsidies. It is a key parameter for assessing the economic viability of renewable energy projects measured in $/

kWh.considering everything from building the power plant to generating the electricity itself.

Levelized Cost of Hydrogen (LCOH)

Similar to LCOE, LCOH represents the average cost of producing hydrogen over the entire lifespan of a hydrogen production system, measured in $/kg of hydrogen generated by the plant.

Platinum Group Metals (PGM)

Sustainable Aviation Fuel (SAF) is a type of fuel for airplanes that is made from renewable sources, like plants or waste materials, instead of fossil fuels. It's called "sustainable" because it is produced in a way that doesn't harmthe environment or deplete natural resources. SAF can help reduce the carbon footprint of air travel by emittingfewer greenhouse gases compared to traditional jet fuels.

Sustainable Aviation Fuel (SAFs)

Sustainable Aviation Fuel (SAF) is a class of fuels sourced from low carbon feedstocks as an alternative to current aviation fuels. They are from renewable sources, like plants or waste materials, instead of fossil fuels. SAFs can help reduce the carbon footprint of air travel by emitting fewer carbon emissions as compared to traditional jet fuels.

Technology Readiness Level (TRL)

Technology Readiness Level (TRL) is a method for evaluating the maturity of technology for commercialization. It was originally developed by NASA in the 1970s to test space technologies, later became an institutionalized tool used by various organizations, industries, and research institutions, to assess the readiness of technologies for commercialization from scale 1 to 9. In reference to energy systems, the International Energy Agency (IEA) expanded the TRL scale by adding two more stages: stage 10, which signifies technology integration into energy systems, and stage 11, which represents full predictable growth.

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List of Abbreviations

ADB	Asian Development Bank
BF-BOF	Blast furnace – basic oxygen furnace
BEV	Battery Electric Vehicles
CAPEX	Capital expenditure
CBAM	Carbon Border Adjustment Mechanism
CCUS	Carbon capture, Utilization, and storage
CO2	Carbon dioxide
COP	Conference of Parties
DFI	Development finance institution
DRI	Direct reduced iron
EU	European Union
EC	European Commission
EHB	European Hydrogen Bank
FCVs	Fuel Cell Vehicles FCVs
FDI	Foreign direct investment
GHG	Greenhouse gas
H2	Hydrogen
IRENA	International Renewable Energy Agency
IEA	International Energy Agency
Kg	Kilogram
KPIs	Key performance indicators
LCOE	Levelized costs of energy
LCOH	Levelized costs of hydrogen
LH2	Liquefied hydrogen
LOHC	Liquid organic hydrogen carriers
MDBs	Multilateral development banks
MoU	Memorandum of Understanding
Mt	Million tons
MW	Megawatt
MWh	Megawatt hour
NDCs	Nationally determined contributions
NREL	National Renewable Energy Laboratory
O&M	Operations and maintenance
OPEX	Operations expenses
PEM	Proton exchange membrane
PGM	Platinum group metals
PPA	Power purchase agreement
PPP	Public-private partnership
PtX	Power-to-X
R&D	Research and development
RE	Renewable energy
SAF	Sustainable aviation fuel
SDGs	Sustainable Development Goals
SOEC	Solid oxide electrolyzer cell

Executive summary

The global narrative of building a hydrogen economy is one of the key pillars of energy transition and decarbonization. The International Energy Agency (IEA) forecasts that in pathways aligned with Paris Agreement goals, the utilization of hydrogen and its derivatives is expected to increase from 1% of the total final consumption to 4% by 2030 and further to 13% by 2050 [1]. This uptake will be influenced by multi-dimensional geopolitical factors, technological innovation, low-levelized cost of hydrogen (LCOH $/kg), achieving economies of scale, and risk management of developing the green hydrogen projects.

The geopolitical bifurcation will revolve around countries engaged in exporting and importing green hydrogen. The countries in the global south possess significant renewable energy potential, enabling them to attain a low Levelized Cost of Hydrogen (LCOH). They can capitalize on their role as exporters, while countries with substantial demand can function as importers. This situation creates an opportunity for the Global South to take a leading role in climate mitigation efforts and simultaneously achieve economic empowerment through participation in cross-border trade.

The countries interested in exploring hydrogen opportunities to decarbonize their industry have successfully devised strategies for its utilization and have established precise targets to produce green hydrogen. Considering the global impetus towards green hydrogen, Pakistan also anticipates formulating its Green Hydrogen strategy by 2025. The goal should be to reduce reliance on imported natural gas in industrial sectors like fertilizer and methanol production as well as adress the issue of depleting local gas reserves. The adoption of green hydrogen is crucial for both energy and food security, serving as a cleaner option to facilitate the transition to a low-carbon future.

The formulation of a strategy to embrace the green hydrogen economy necessitates comprehensive development of policies and establishment of a strategic roadmap. This roadmap should be designed to align with the vision to capitalize on opportunities, address gaps, and confront challenges associated with the transition towards a green future. It is anticipated that an effective hydrogen strategy will provide clear and transparent projections for production targets and attainable cost estimates for LCOH. It entails evaluating crucial parameters essential for the development of green hydrogen projects, including capital requirements, market acceptance, learning rate, strategies for financial risk mitigation, and bilateral trade agreements.

Pakistan is positioned to attain a low LCOH for green hydrogen in the coastal regions, owing to the abundant availability of renewable energy resources (Solar PV and Wind energy) along with the availability of water for electrolysis. The principal hurdle in developing a hydrogen market lies in the capital , energy, and water intensive nature of the process, and this challenge can be mitigated by establishing a framework that addresses the role of hydrogen in both decarbonization and achieving energy independence. The global momentum toward decarbonization will lead to the widespread adoption of green hydrogen across diverse regions and sectors, facilitating an expedited pace to attain economies of scale.

This report is an effort to support researchers, policymakers, and decision makers as an initiating point towards their journey on exploring green hydrogen and its dynamics. The comprehensive development of insights aims to bridge the knowledge gap within the national context, with a shared interest in fostering optimism about building a hydrogen economy.

Introduction- Green Hydrogen is essential to achieve Net-Zero emissions

Pakistan's vulnerability towards climate change and the energy-economy-environment trilemma influences its decarbonization goals to achieve climate neutrality. Pakistan has made an unconditional pledge of reducing 15% of its carbon emissions by 2030 in its Nationally Determined Contributions (NDCs) under the Paris Agreement [2]. The target is ambitious, considering the socio-economic context of the country, however, Pakistan is also keen to define its national Net-Zero emission targets and a long-term vision for sustainable development. The way forward towards a Net-Zero future places significant emphasis on direct electrification by harnessing renewable energy potential, Carbon Capture Storage & Utilization (CCUS), bioenergy, and utilizing green hydrogen for decarbonizing hard-to-abate sectors.

Pakistan has planned to develop a hydrogen strategy by 2025 under its National Electricity Plan 2023-2027 [3]. The motivation behind this report is to provide a comprehensive overview and dedicated support to establish a green hydrogen strategy vested in the country's future decarbonization ambitions.

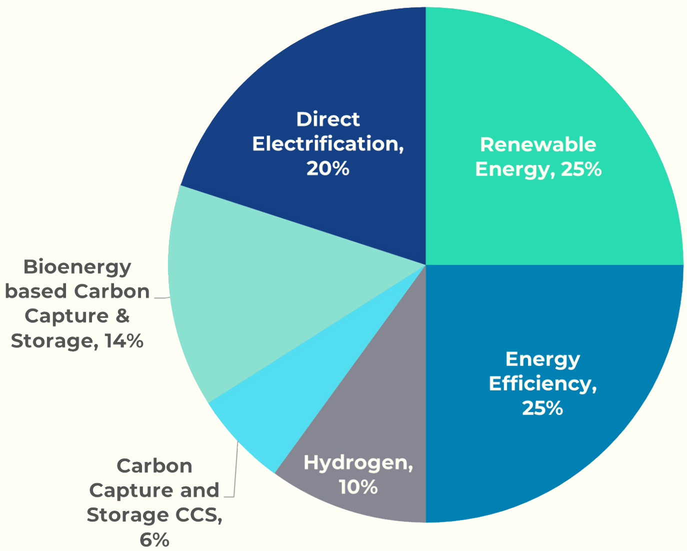


Figure 1 - Decarbonization alternatives in 2050 scenario (IRENA World Energy Transition Outlook 2022)

International Renewable Energy Agency's (IRENA) forward-looking analysis projects a surge of green hydrogen demand from 0.5% to 10% in the final energy share presented in Figure 1, which equates to 25,000 TWh of renewable electricity supply and 5,500 GW of electrolyzer capacity additions [4]. Despite differences in forecasts among various think tanks and agencies, the crucial role of hydrogen by 2050 presented in Figure 2, highlights the a shared consensus regarding hydrogen's essential role in attaining future global net-zero objectives.

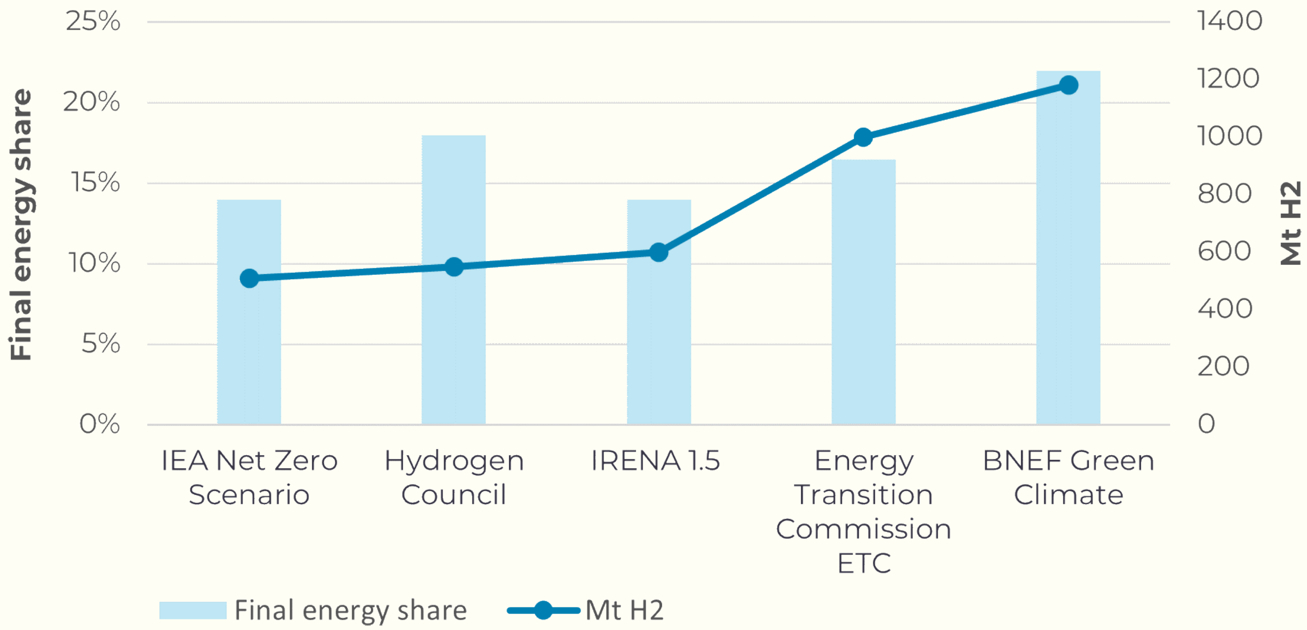


Figure 2 - Anticipated demand and final energy share of green hydrogen by 2050 [5]

To begin with the development of a green hydrogen strategy it is crucial to comprehend the geopolitical landscape, trade dynamics and individual efforts of each region in the world. Geopolitical aspects will play a major role in developing a green hydrogen economy. Countries possessing significant renewable energy potential can produce affordable green hydrogen, providing them with the opportunity to export it. Countries facing high production costs may find themselves dependent on importing green hydrogen.

At present, 34 countries have developed their green hydrogen strategies highlighting the role of green hydrogen in their economies, with an additional 17 countries in the preparatory stages (see Figure 3). These developments also necessitate a substantial increase in electrolyzer deployment, addition of dedicated renewable energy capacity, and the establishment of infrastructure for hydrogen transmission and storage. To bridge the economic gap between hydrogen based decarbonization solutions and conventional alternatives, unlocking the complete potential of hydrogen requires concerted efforts on three key fronts as presented in Exhibit-1.

The cost of green hydrogen remains the most challenging parameter, and some countries have already put cost reduction targets in their national roadmaps. The European Commission (EC) has planned to establish a European Hydrogen Bank (EHB) with a proposed investment of €3 billion in green hydrogen. The German government has allocated over €6 billion in subsidies to support green hydrogen auctions. The H_2 Global Stiftung has devised an auction mechanism for implementing ten-year offtake agreements, promoting the growth of green hydrogen imports to Germany [6]. There is an anticipated decrease of LCOH from €5 per kg to €1.5 per kg by 2050. India has ambitiously announced to drop the cost of green hydrogen to $1.5 per kg by 2030 in its National Green Hydrogen Policy [7]. However, the market liquidity of green hydrogen will only occur once a competitive LCOH is achieved.

Exhibit 1 - Key fronts to bridge the economic gap between decarbonization solutions and conventional alternatives.

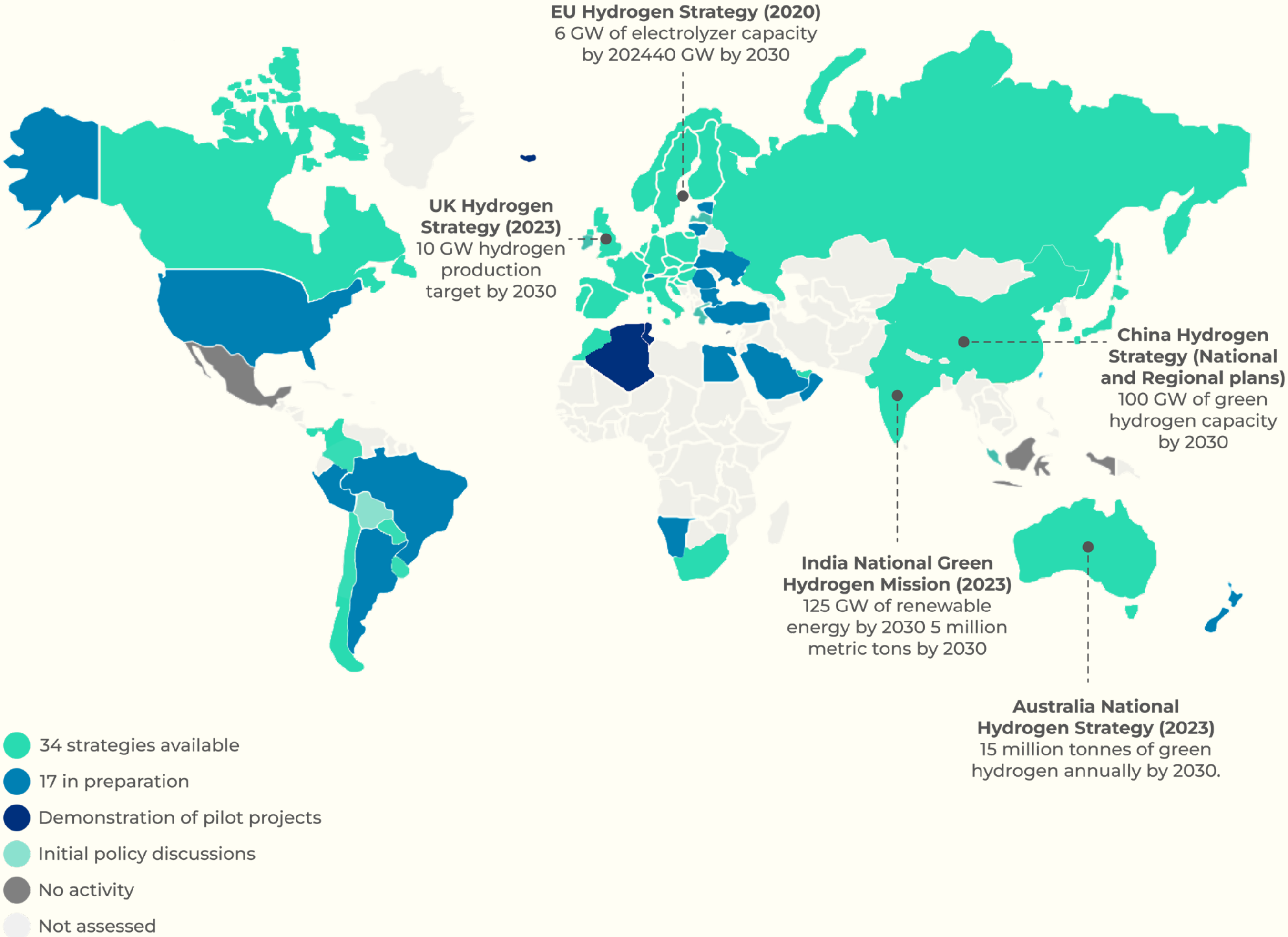


Figure 3 - Green hydrogen momentum around the globe. EU Hydrogen Strategy (2020), National Green Hydrogen mission-India (2023), China's Hydrogen Strategy: National and Regional plans, UK Hydrogen strategy (2023), Australia's National Hydrogen Strategy (2023) [8]

Insight 1 - In Pakistan, the sectoral uptake of green hydrogen will be established based on its specific no-regret end-use applications

The development of a green hydrogen economy hinges entirely on its end-use applications. A comprehensive examination of country-specific requirements, analysis of demand, market adoption, and efforts towards decarbonization is crucial due to the diverse applications of hydrogen. The global evaluation of green hydrogen is based on the availability of alternative decarbonization methods, as detailed in Exhibit 2. This cascade presents a promising opportunity in the industrial feedstock space where no alternative could be anticipated to decarbonize that segment i.e., fertilizers and methanol production, desulphurization processes in refineries, and reduction processes in the steel industry.

Competitive	Controversial	Uncompetitive
Ammonia for fertilizers	Shipping / Coastal & river vessels	Domestic heating
Hydrotreating / Desulphurization	Long distance transport: remote trains / off-road vehicles	Mid / Low temerature industrial heat
Reducing agent in steel industry	High temperature industrial heat	Passenger vehicles / Metro-trains
Chemical feedstock	Energy storage for enhanced flexibility	Bulk E-fuels
Methanol production	Long haul aviation	Power generation

Exhibit 2 - Global stock take on hydrogen viability sourced from Liebriech Associates [9]

Green hydrogen is the key to decarbonize industrial applications

The global demand for hydrogen is distributed mainly in ammonia and methanol production as presented in Figure 4 [10]. The current processes of extracting hydrogen have high carbon emissions. Green hydrogen will play a pivotal role in the decarbonization of industries for climate neutrality, especially in cases where direct electrification is impractical.

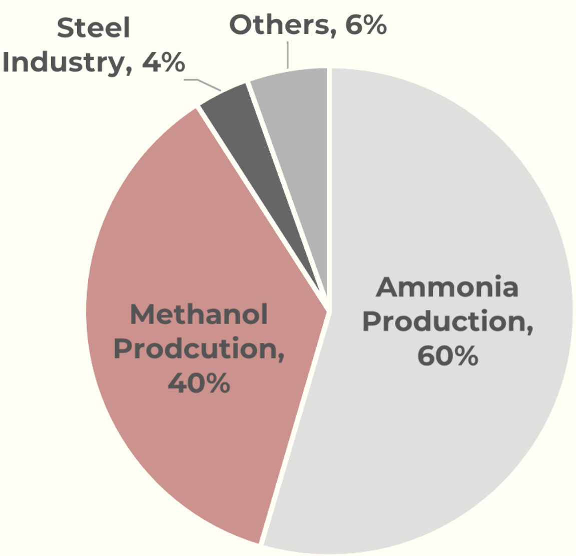


Figure 4 - Global hydrogen demand by IEA-2023

The primary application of hydrogen is to produce ammonia, the most used substrate for fertilizers. Within refineries, hydrogen is integral to the common practice of hydro treating, aimed at desulphurization to eliminate sulfur content from fossil fuels. Hydrogen, serving as a feedstock, yields various derivatives, including methanol and hydrogen peroxide. The steel industry employs hydrogen as a reducing agent in the primary process of extracting iron from ore.

Pakistan is a semi-industrialized economy, concentrating on specific sectors like fertilizers, refineries, textiles, and cement. Hydrogen finds its primary application in ammonia production within the fertilizer industry, making it the most suitable segment of industry to deploy green hydrogen. In steel segment Pakistan relies on a secondary smelting process carried out in electric arc furnaces, which restricts the potential integration of hydrogen in steel industry. The potential for growth in the national refinery sector is restricted in comparison to the fertilizer industry. Further details on industrial adoption are provided in Insight-2, for a thorough understanding.

Hydrogen based electricity is a long shot

By 2030, IEA predicts that hydrogen-based electricity will reach 5800 megawatts (MW) of capacity globally, in which 70% is anticipated to be based on Combined Cycle Gas Turbines (CCGTs) [10]. CCGTs are getting more significant as they use co-firing of hydrogen or ammonia blended with natural gas. In comparison, fuel cells for electricity generation are far away from reaching cost competitiveness. Most industrial giants in Asia-Pacific are considering co-firing options, while a successful demonstration of hydrogen-based gas turbine was reported by Siemens Energy [11]. In 2022, Japan also successfully demonstrated a 2 MW gas turbine operational on ammonia [12]. Nevertheless, experts are currently engaged in debates regarding greenhouse gas emissions, particularly nitrous oxides (NOx), linked to the co-firing of ammonia.

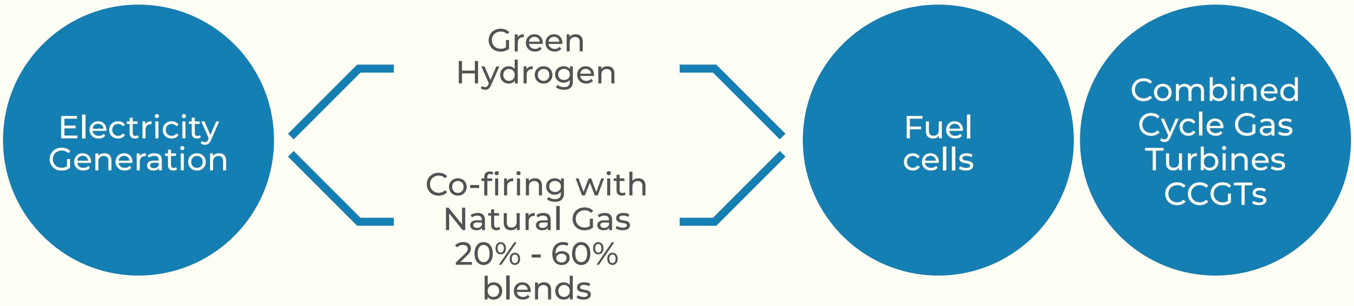


Figure 5 - Hydrogen-based electrification.

If Pakistan aims to advance its power generation market using hydrogen, considerable investments in infrastructure are essential. The extensive adoption of hydrogen-based power generation is capital-intensive and faces challenges in terms of technology readiness level. The main hurdle involves obtaining acceptance in the market, especially when comparing it to the more economical renewable-based electricity available as a mainstream alternative.

Hydrogen-based transport has limited growth in comparison to battery-based vehicles

The use of battery-based Electric Vehicles (EVs) are 43% more efficient than Fuel Cell Vehicles (FCVs) as of now. The efficiency of fuel cell conversion of hydrogen to electric current is limited at 60%. For every 1 kWh of electricity required for BEV, 2 kWh will be needed for fuel cell vehicles [13].

The transport sector will be dominated by electricity-based vehicles as presented in Figure 7. There has been an annual increase of 45 % FCVs in 2022-2021, while it still presents only 0.05% as compared to the sales of BEVs in the first quarter of 2023 exhibited in Figure 6 [14] More expansions will be based on the production of long-haul transportation, as China unveils plans of manufacturing 130 FCVs models mainly for trucks and buses [15].

In 2023, 4699 units of FCVs were purchased in comparison with 10 million BEVs

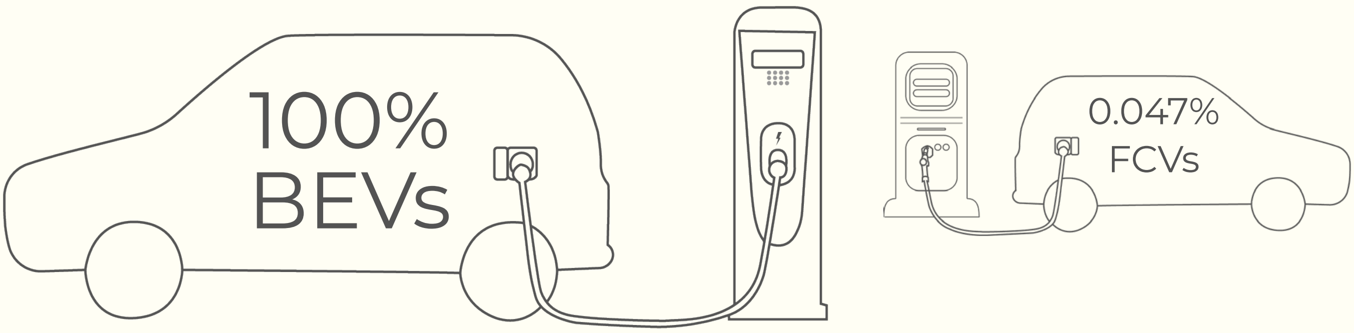


Figure 6 - Sale comparison between FCVs and BEVs market uptake in (January-May) 2023 [14]

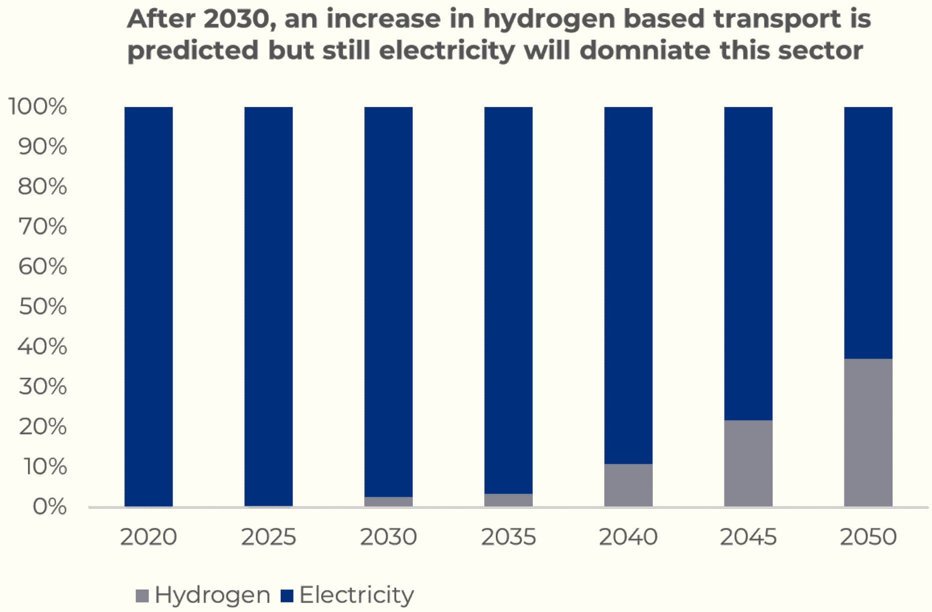


Figure-7. Role of hydrogen in transport sector 2020-2050 [16]

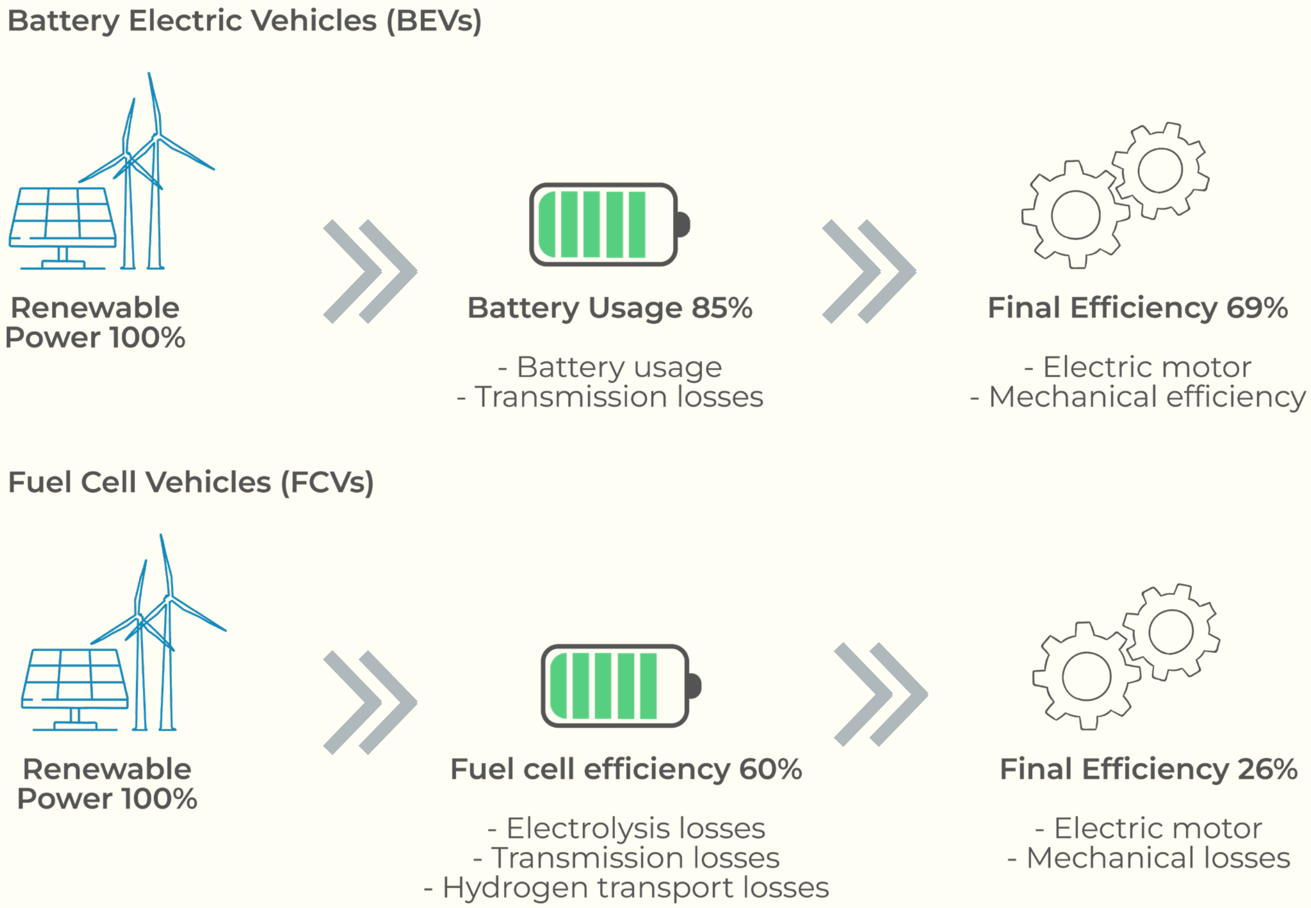


Figure 8 - Efficiency comparison between BEVs and FCVs (source: Agora Verkehwende)

Considering the future of the transport landscape, Pakistan has already published an Electric Vehicle Policy in 2019, with tax exemptions on EVs and charging station infrastructure. The lack of public transport infrastructure also presents an opportunity to develop FCVs on long-distance routes, however, it will require a huge investment in infrastructural development of hydrogen refueling stations. Long-distance trains require 80% less electricity than buses, making the electrification of train transport a more favorable choice over fuel cells [13]. In the case of buses, Fuel Cell Vehicles (FCVs) could become a viable option if they can compete with the cost of Battery Electric Vehicles (BEVs).

The scope of hydrogen in shipping and aviation is limited in our national landscape

The emerging zero-emission vessel technologies in shipping are based on green ammonia combustion, fuel cells, and methanol. The EU has enacted a recent regulation called Fuel EU Maritimes, offering incentives for the adoption of low-carbon emission fuels. Globally aviation will account for 16% of energy usage from hydrogen and its derivative fuels by 2050 [10]

Sustainable Aviation Fuels (SAFs) are based on low-carbon fuel derivatives based on e-kerosene, e-diesel, and other jet fuels. The use of e-kerosene in jet fuels derived from green hydrogen does not require any technological retrofitting. The market uptake seems promising in net zero scenarios globally; however, the primary constraint remains the production cost of these fuels, only allowing a long-term opportunity to offtake green hydrogen. Pakistan's shipping sector comprises of only five bulk carriers [17]. This limited fleet size presents a limited opportunity for hydrogen in this sector.

Hydrogen blending with natural gas in heating applications is not a cost-effective option

The injection of hydrogen in the gas grid and its associated infrastructure development may not be justifiable as the blend will lead to an increase in gas prices. As per Agora's findings, a 20% blend of green hydrogen will lead to a 33% rise in gas prices while only decarbonizing 7% of the grid [5]. Since Pakistan is already suffering from energy shortages, it will top up the crisis leading to energy poverty. Heat pumps and heat grids are already technologically mature and present a more cost-effective alternative as compared to blending.

The possibilities for Pakistan

Table 1 - Anticipated timeline for green hydrogen usage

Short-Term (2025-2035)	Medium-term (2035-2050)	Long-term (2050-Onwards)
Ammonia production in fertilizers	Long haul transport	Passenger cars
Desulphurizing agent in refineries	Industrial power generation-Combined Cycle Gas Turbines CCGTs	Storage option for flexibility
Methanol production	Reducing agent in steel industry	Shipping and aviation
		Fuel cells-based electrification

Table 2 - The possibilities based on end-use case

End use case	Possibilities	Intervention
Industrial feedstock	Yes	Direct applications i.e., green ammonia for fertilizers, refineries, and steel
Shipping and aviation	Yes	E-fuels (e-kerosene-ammonia and e-diesel) will be required for decarbonization.
Hydrogen blending	No	The blending will increase the fuel cost without a significant reduction in emissions.
Personal vehicles	No	Electric vehicles provide better efficiency than fuel cell vehicles.
Public transport i.e., Trains and buses	No	Electrification of public transport is more cost effective.
Electrification	No	Fuel cell-based power generation is not commercially viable.
Buildings	No	Building level heating can be done by direct electrification.
High temperature industrial applications	May be	If the technology achieves cost competitiveness it may present an opportunity.

Insight 2 - In the industrial sector of Pakistan, the fertilizer segment stands out as the most promising opportunity for green hydrogen.

Worldwide hydrogen consumption is primarily in refineries, fertilizer production, methanol synthesis, and use as .a reducing agent in steel-making processes to address the carbon-intensive nature of these industrial processes, To decarbonize the industrial segment, Power to X (PtX) loops are developed to decarbonize chemical streams in industrial applications. PtX refers to the conversion of electricity, particularly renewable energy, to develop an energy carrier 'X' as presented in Figure 9. Green hydrogen or its various derivatives typically stands for X. Under the PtX process, there is an increasing focus on e-fuels like e-methanol, e-kerosene, and e-diesel.

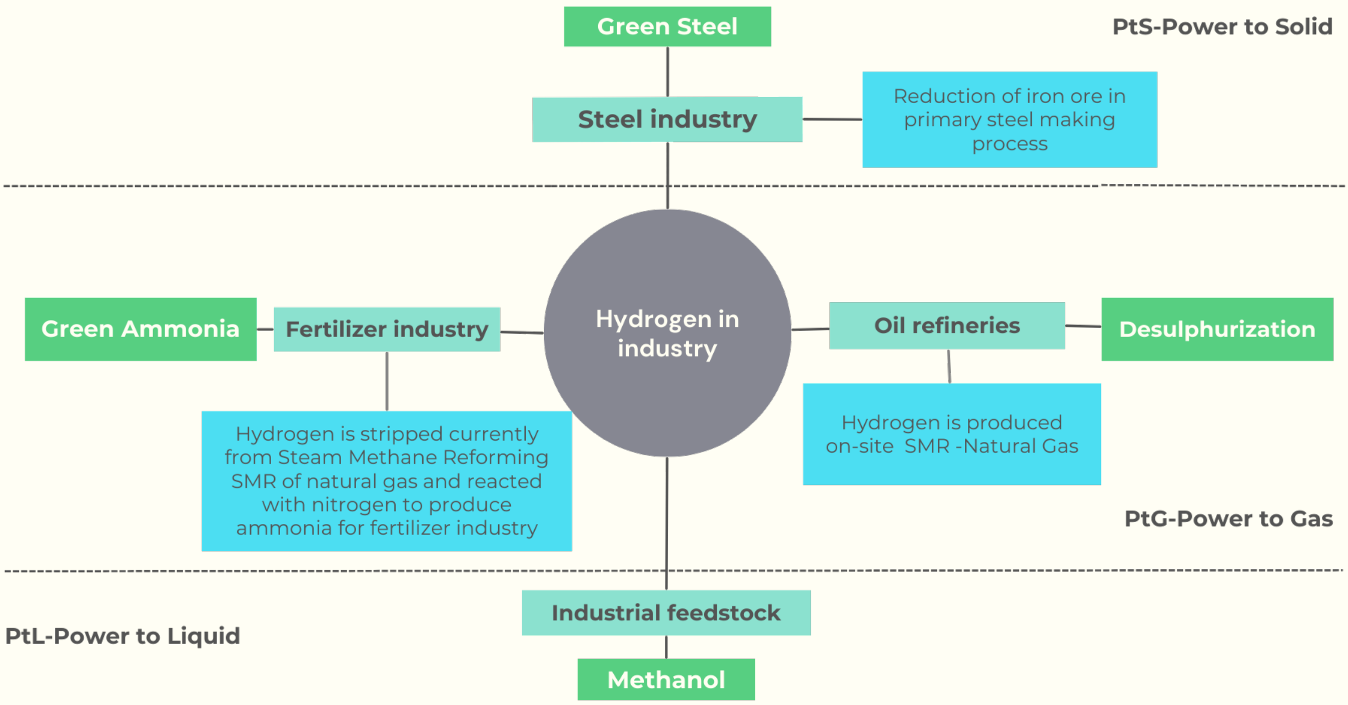


Figure 9 - Hydrogen has an important role to play for a range of industries.

The industrial segment overarching green hydrogen, particularly green ammonia, offers an optimum and low-risk opportunity to establish early hydrogen infrastructure by 2030, both on a global and national scale. Key players are actively seeking to establish an early-mover advantage, particularly emphasizing the production of green ammonia. Yara, a leading fertilizer company has collaborated with ENGIE to produce ~10 million tons of green ammonia at their Western Australia facility annually [18]. YARA has also teamed up with Ørsted, a well-known offshore wind developer in the Netherlands, to explore the production of 75,000 tons of green ammonia each year [19]. Air Products has formed a partnership with the Saudi Arabian Government to announce a 4 GW solar project located in NEOM [20]. The project's objective is to generate green ammonia through this solar capacity. However, the green hydrogen uptake is reliant on the dominant industrial sector within the country.

Need of energy independence and decarbonization

Currently, hydrogen production relies primarily on the carbon-intensive Steam Methane Reforming (SMR) process of natural gas. The unexpected shifts in global energy trends following the Russia-Ukraine War in 2022 introduced unpredictability to the international fossil fuels market. Nations heavily dependent on imported fossil fuels faced shortages and increased import costs, leading to challenges such as non-availability, and rising import bills. This situation resulted in a 20% decrease in European fertilizer production [10].

Pakistan also experienced similar difficulties, struggling to import sufficient natural gas and coal, leading to the closure of industries due to unmet energy needs. The depleting reserves of natural gas highlight an escalating reliance on imported fuel to meet local demand. The need of the hour is to explore indigenous alternatives that can establish energy independence. Consequently, the exponential growth of the global green hydrogen market envisioned and planned for, is not solely driven by robust policies for achieving Net-Zero scenarios but is also intertwined with energy trends and domestic imperatives for energy security.

Green Ammonia in fertilizers is the most viable option

Ammonia holds the position of being the second-largest commodity chemical produced on a global scale, with an annual production exceeding 180 million tons. Globally, 77.5% of ammonia is channeled into fertilizer production as presented in Figure 10, while 22.5% finds applications in diverse sectors like plastics, explosives, and synthetic fuels [10].

From 2022-2023, Pakistan generated 2.15 million tons of nitrogenous fertilizers, employing the Haber-Bosch synthesis method for ammonia production [21]. The Haber-Bosch process emits three tons of carbon for each ton of ammonia production [22].

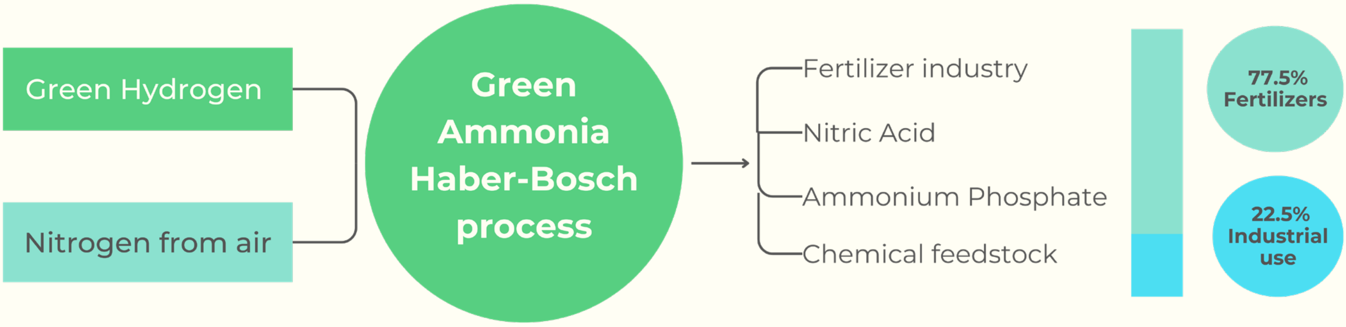


Figure 10 - The Haber Bosch Process is widely utilized for production of ammonia in Industry.

Green ammonia is pivotal to generating carbon-neutral fertilizers, facilitating the decarbonization of the agricultural value chains. Projections indicate that global green ammonia production capacities could soar to 26 million tons by 2035 [22]. Exhibit 3 illustrates various advantages of green ammonia, primarily focused on reducing dependence on fuel imports, enhancing food security, and addressing the decarbonization requirements. In the pursuit of decarbonizing an agrarian economy, green ammonia assumes a pivotal role within the fertilizer sector. Transitioning to ammonia production through green hydrogen and nitrogen extracted from the air holds the promise of lowering carbon emissions significantly by 6 million tons. Moreover, its adoption not only contributes to strengthening food security but also reduces reliance on imported fuels.

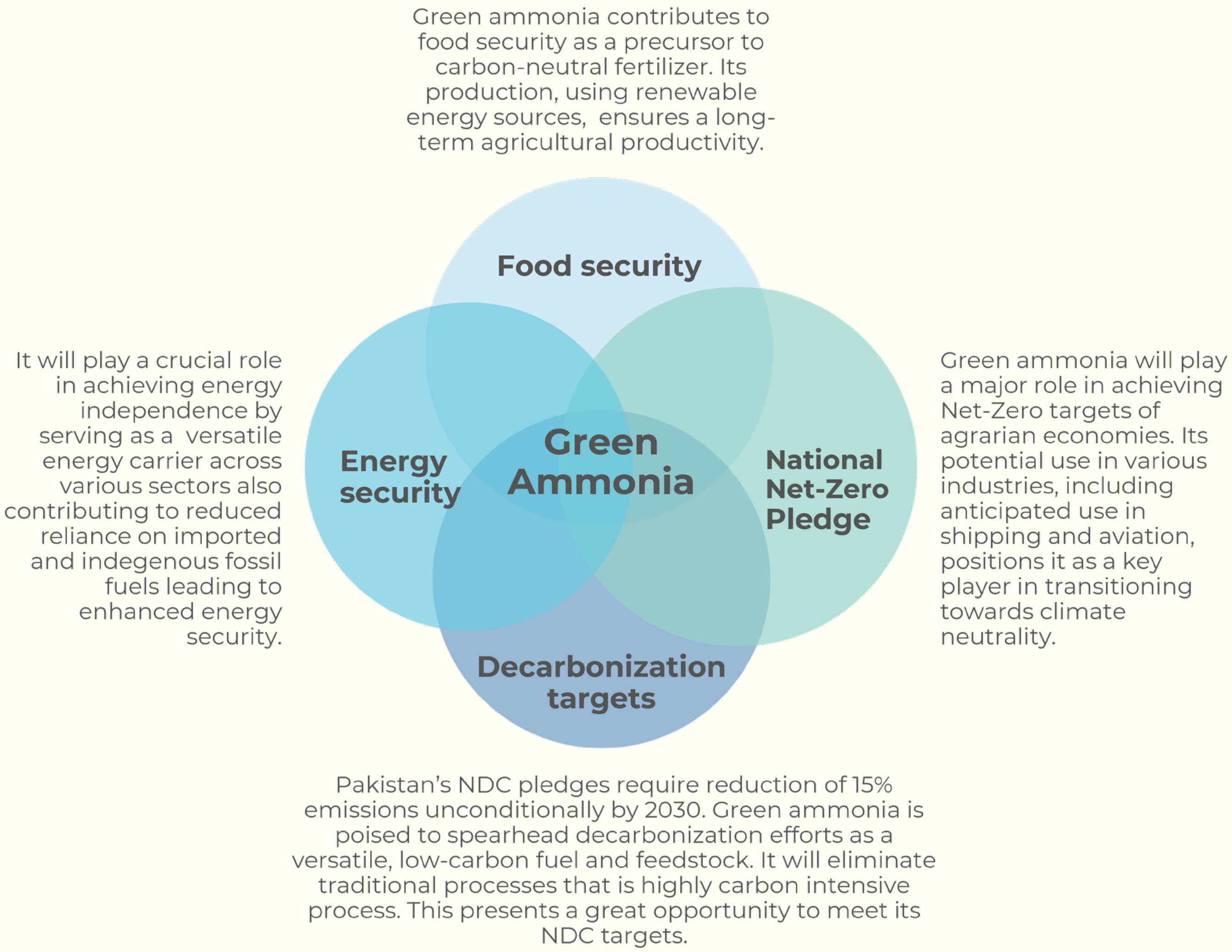


Exhibit 3 - Green ammonia can provide multiple benefits on a national scale beyond just emission reduction.

Box 1.1 Sustainable carbon sourcing for Urea production

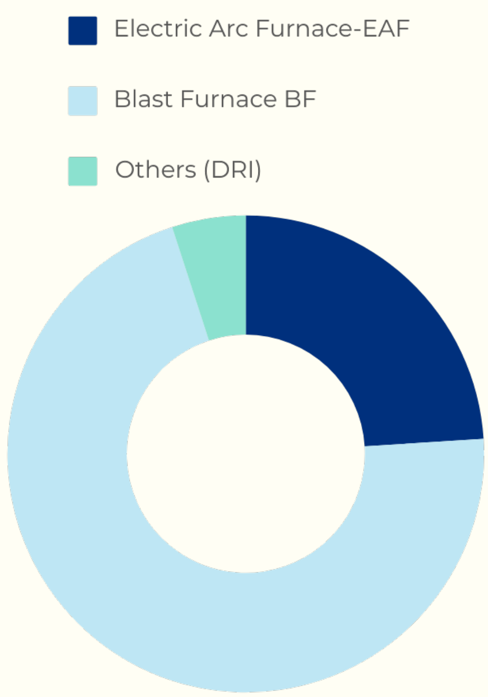
Urea is the most dominant fertilizer in the world including Pakistan. Conventionally, urea is produced from reacting ammonia and carbon dioxide obtained during the SMR process as a byproduct. There is concern regarding how to source carbon to produce urea, while using green ammonia as a precursor.

For PtX energy carriers (urea, methanol and other e-fuel i.e kerosene/SAFs) sourcing of sustainable carbon becomes a challenge. To address the sustainability of carbon molecules, it is anticipated that CCUS technologies will be crucial to provide carbon captured from point source of emission from industrial processes. Refineries could also serve as an additional source of carbon, given that reliance on certain carbon-based products will inevitably continue.

Hydrogen in steel industry

Hydrogen is used in steelmaking as a reducing agent in iron ore extraction process. The production of steel is classified in two categories: Primary process and the secondary process detailed in Figure 11. The primary process to steel production includes Basic-Oxygen Furnace (BOF) as the main equipment. This process of BF-BOF incorporates the use of hydrogen during extraction of iron from the ore. The secondary process is smelting steel and iron scrap in the Electric Arc Furnace. The use of hydrogen replaced by green hydrogen produces green steel.

Globally, the countries with thriving steel exports are considering the opportunity of green steel. The European Union's regulatory authorities have introduced initiatives like the Carbon Border Adjustment Mechanism (CBAM) to be implemented by 2026 for decarbonizing imports. India, being the primary steel exporter to the EU, has highlighted the significance of green steel in its national strategy for green hydrogen [23].



Blast Furnace-BF

The production of primary steel directly from iron ore. It contributes to 71% of steel globally.

Electric Arc Furnace-EAF

EAF produces secondary steel by melting steel scrap. Globally 24% of steel is produced from EAF method.

Figure 11 - Technologies in steel industry

In the case of Pakistan, 92% of its steel demand is met by importing both raw iron and steel scrap, engaging in the secondary process of steelmaking. The local production only stood at 0.7 million metric tons in 2022 as compared to the import of 7.6 million tons. The imported finished steel and iron products, meeting the country's requirements, contributed to a total import expenditure of 3 billion USD, equivalent to 5.5% of the GDP. The struggling economy needs to tap its indigenous iron ore reserves totaling 1400 million tons to meet its national demand and uplift the manufacturing sector [24]. The increased localization efforts for steel production could offer the potential to integrate green hydrogen into the steel production process in later stages of development.

Hydrogen in Refineries

In refineries, hydrogen is utilized for two processes: hydrotreating and hydrocracking. Hydrotreating is the process of adding hydrogen to remove sulfur content and other contaminants while hydrocracking is using hydrogen to breakdown low-quality fossil fuels into useful products i.e., it is employed to produce diesel oil. The refineries are specifically drawing attention to the role of green hydrogen in reducing overall carbon footprint associated with Sulphur removal. In recent efforts to decarbonize refineries by using green hydrogen, the EU has developed the REFHYNE project collaborating with ITM Power and the major stakeholders of the oil and gas industry i.e. Shell Deutschland Oil GmbH, SINTEF, and Element Energy [25].

The national refining landscape sees a limited opportunity to utilize green hydrogen. There are six functional refineries primarily managing both local and imported crude oil. Pakistan generated around 3.8 tons of crude oil domestically while importing an additional 8.6 million tons. Under the new Pakistan Oil Refining policy of 2023, the groundwork is laid for adherence to Euro V standards, and this involves restricting the carbon emissions from fossil fuels [26]. In long-term planning, the refinery sector can utilize green hydrogen for decarbonization in Pakistan.

Box 1.2 Methanol market

Methanol is also an extensively produced organic chemical at approximately 110 million tons annually, [10] as a foundational material for products like polymer fibers, plastics, glues, paints, and solvents. In addition to LNG and ammonia, green methanol is being explored as an alternative fuel for maritime applications. It can be blended with traditional liquid fuels or employed as the sole fuel for systems entirely reliant on 100% methanol.

Insight 3 - Additional supply of renewable energy will be pivotal to produce green hydrogen

To achieve the green hydrogen production targets, an additional supply of renewable electricity for electrolysis is required. Renewables-based hydrogen is anticipated to increase by 70% by 2050 as presented in Figure 12. By 2050, additionality will play a major role, as dedicated solar PV and an additional 3.6 TW of off-grid wind energy will be integrated to produce green hydrogen [27]. However, presently (2022) hydrogen produced by electrolysis comprised only 0.1% of the global production presented in Figure 13 [10].

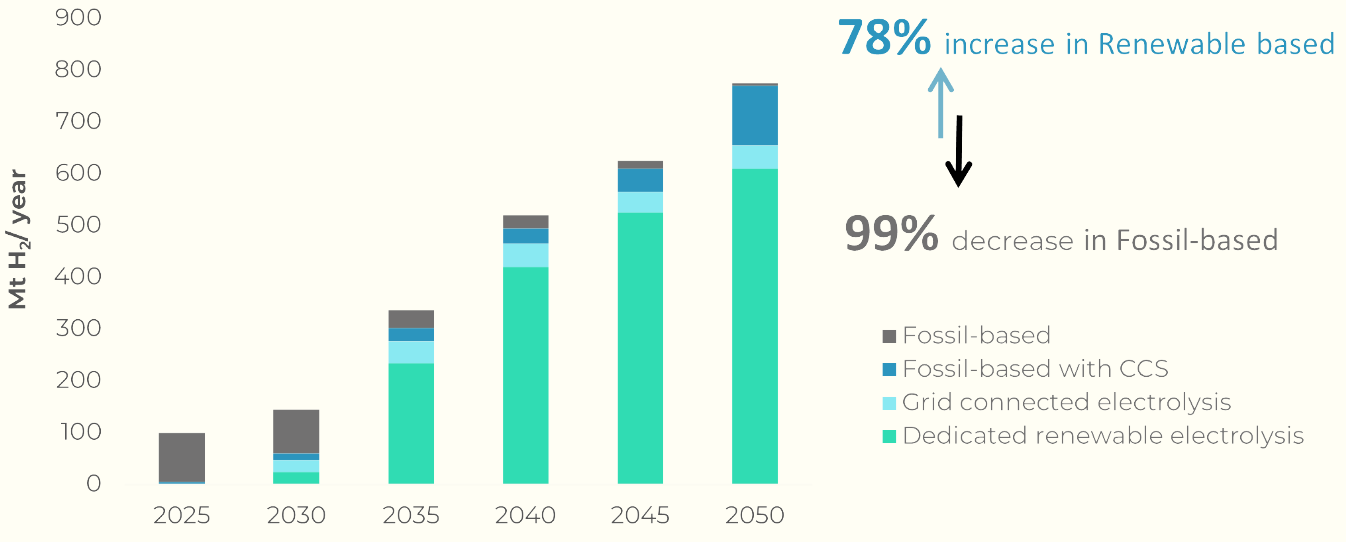


Figure 12 - Global distribution of hydrogen production techniques (2025-2050) (source: DNV Pathway to net-zero emissions 2023)

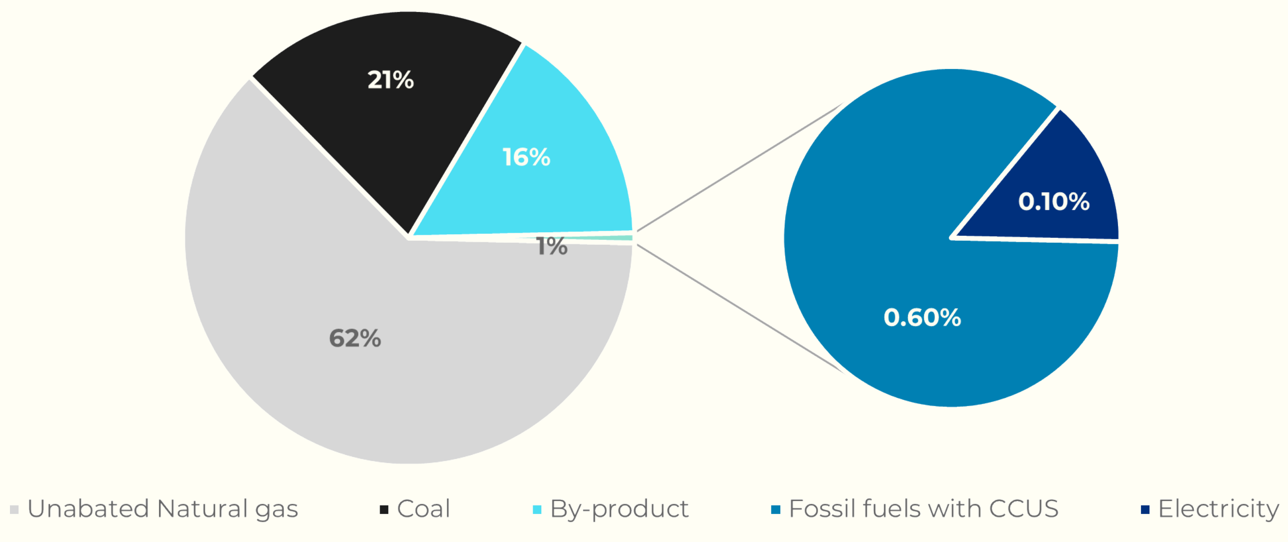


Figure 13 - Share of Hydrogen production sources in 2022 (source: Global Hydrogen Review 2023 - IEA)

Hydrogen can address the curtailment issue by increasing flexibility in power systems.

Flexibility in the power systems is the key enabler for integrating high shares of variable renewable energy to address challenges at all levels of the electricity supply chain. The future energy systems are reliant on weather conditions, their unpredictability requires them to flexibly accommodate the variable generation output from wind turbines and solar PV plants. Hence, flexibility will be crucial to provide demand-side management, peak shaving, and grid management. In a few countries, surplus renewable energy is curtailed due to the absence of appropriate energy storage solutions. Hydrogen and its derivatives can play an active role in increasing flexibility as an energy carrier to store energy for extended durations.

Pakistan faces wind power curtailment because of the inadequate transmission infrastructure, which impacts the basket price of the overall power system. The government is obligated to make hefty payments for unutilized electricity as per the terms of power purchase agreements [28]. This curtailment issue can be addressed by developing onsite electrolysis projects to store the generated energy.

Pakistan will need additional renewable energy to produce green hydrogen.

Grid-connected electrolysis represents a limited share in the Net-Zero scenario as presented in Figure 12. However, it might form a possible starting point to venture into the clean hydrogen economy at a domestic level. The carbon footprint of the hydrogen obtained from the grid is in correlation with the degree to which the grid has been decarbonized. It is important to establish standardized regulations for grid-connected electrolysis to ensure that the grid meets emission standards associated with the hydrogen produced from renewable electricity.

Green hydrogen production is energy-intensive by nature; for every GW of electrolysis capacity, it requires three to five GW of renewable electricity depending on the source. Solar PV requires more active capacity due to limited production hours as compared to wind turbines.[5]

Concerns are raised that the integration of additional renewable energy will create grid bottlenecks. However, in Pakistan's landscape, the national policy (ARE-2019) has set forward the targets to add 30% of VRE by 2030 [29]. Also IGCEP (2022-2031), a national power planning document outlines the addition of approximately 13 GW of solar PV capacity by 2030 [30]. Figure 14 compares the targets along with the required capacity additions to produce green hydrogen. The anticipated expansion in infrastructure allows us to infer that adding more renewable electricity may not lead to any grid bottlenecks.

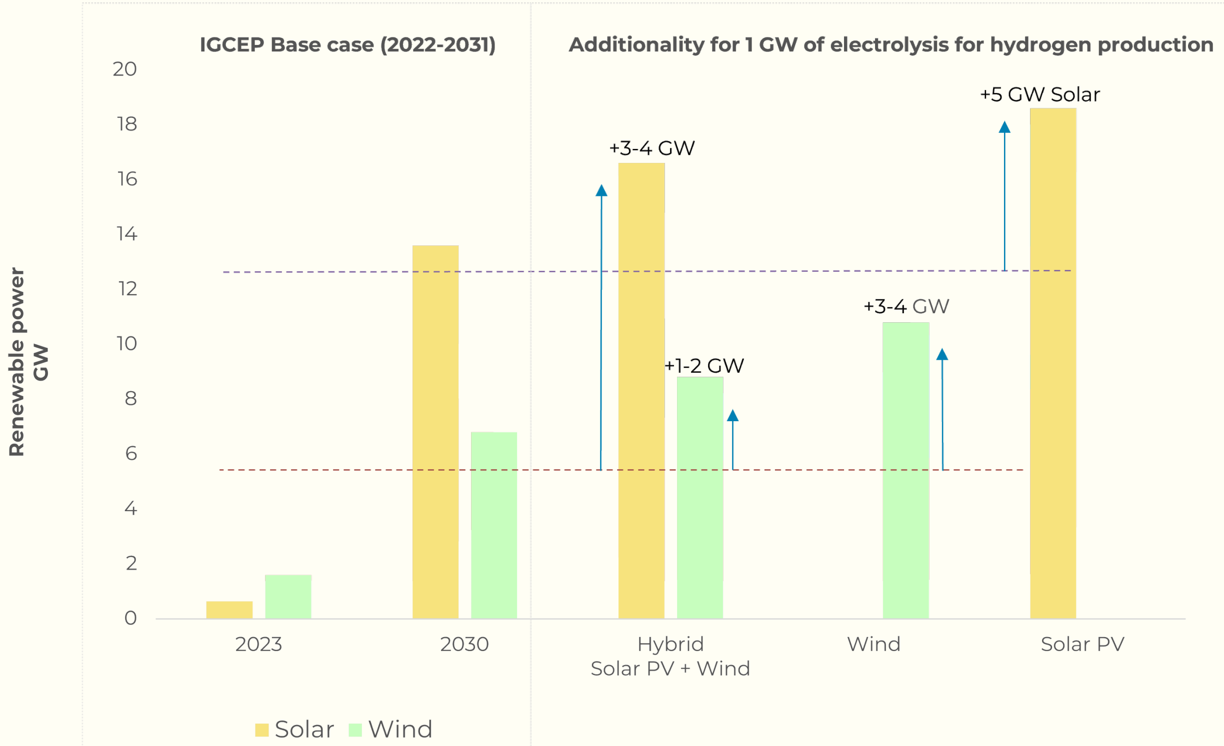


Figure 14 - Addressing additionality for green hydrogen production (sources: IGCEP 2022-2031, ARE policy 2019, Agora Energiewende-12 Insights)

Potential locations for hydrogen production

Pakistan holds significant potential for renewable energy, as more than 90% of the country's terrain exhibits adequate irradiance levels. The Gharo-Jhimpir wind corridor, situated along the southern coastal lines of Pakistan with a length of 60 km, holds the potential for approximately 40 GW of exploitable wind energy. The National Renewable Energy Laboratory (NREL) of the US in its survey report estimated Pakistan's total theoretical wind power potential to be 346 GW [31]. The wind corridors in Sindh and Balochistan offer a unique hybrid opportunity along the coast as illustrated in Figure 15. Balochistan emerges as a "Golden Goose" for the renewable energy potential of the country [32].

Given the exceptional solar and, particularly, wind resources in the western part of the province, it is economically viable to establish massive solar-wind farms. Nevertheless, potential remains unutilized across the terrain. Pakistan also has offshore wind energy, that remains unexplored and untapped.

The feasibility studies conducted on the national low-carbon hydrogen landscape also present hydrogen storage option. The Potohar Plateau is a promising location for underground hydrogen storage near demand centers, such as urban areas and industrial zones to address the challenges and affordability regarding hydrogen storage [33].

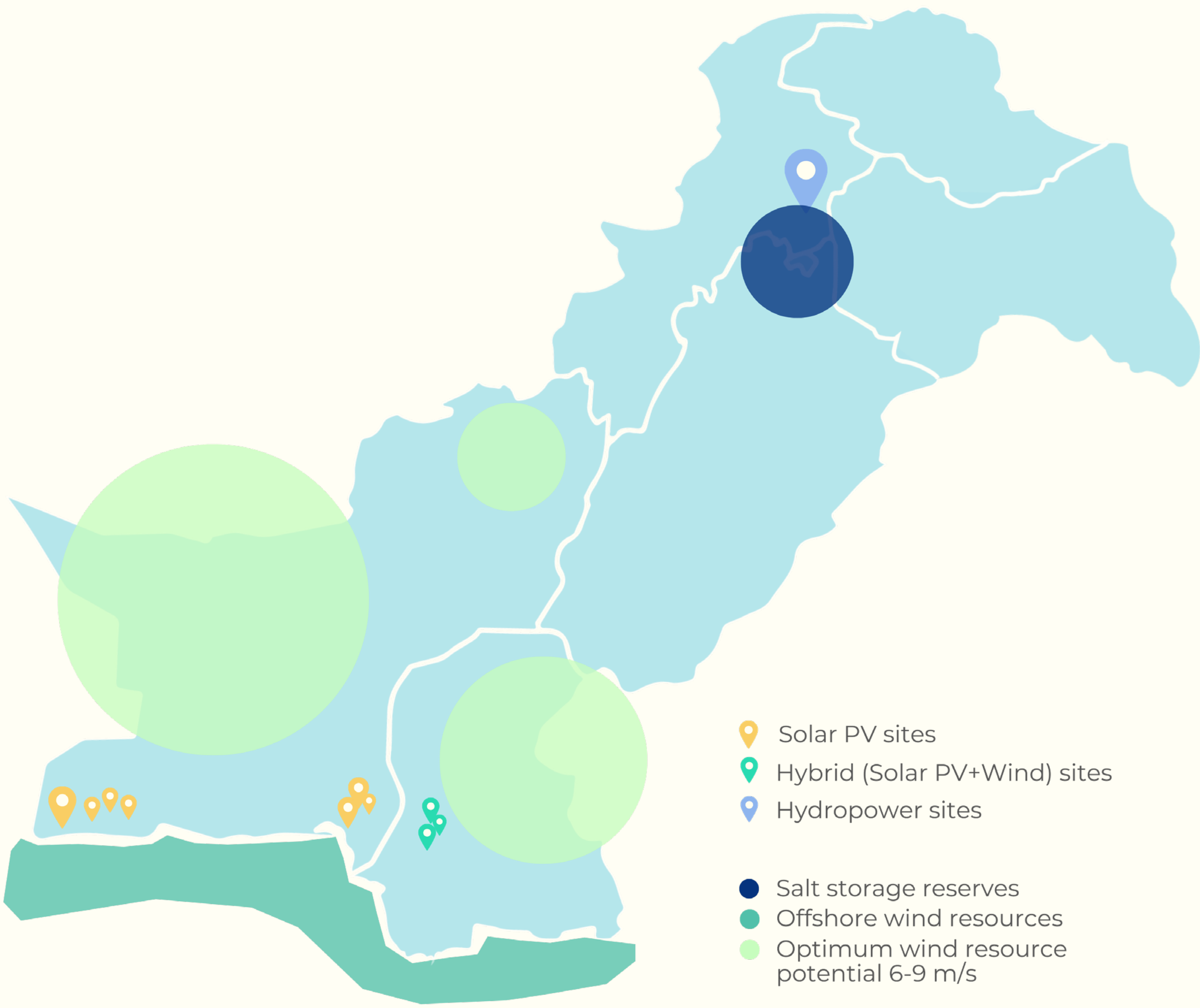


Figure 15 - Overview of renewable resource potential sites for hydrogen production (sources: PtX Atlas-Fraunhofer-November 2023, Wind Atlas, Solar Atlas, SbH4 Consultants)

Insight 4 - The market uptake of green hydrogen is dependent on policy support for electrolyzers and infrastructure requirements.

The achievement of the Net-Zero scenario requires the expansion of electrolyzer capacity, moving from the existing installed capacity of 0.5 GW to 350 GW by the year 2030 [34]. To meet the rising demand, there will be a need for a considerable increase in the production and deployment of electrolyzer. The main obstacle in green electrolysis is overcoming technological barriers to meet the market demand and lowering the overall production costs. The current availability of materials can only meet a portion of the manufacturing capacity required, necessitating the exploration of alternative solutions to reduce dependence on rare resources. Each electrolyzer technology uses a different mix of critical minerals, the use of platinum group catalysts, nickel, zinc, and copper. To provide context, for the most mature electrolyzer technology i.e. Polymer Electrolyte Membrane (PEM), the expense of acquiring 1kg of platinum group metals for a MW-scale PEM electrolyzer can surpass the cost of obtaining 10 tons of minerals and metals required for a 1-MW onshore wind turbine [35].

Electrolyzers are classified into four types depending on the nature of the technology: Polymer Electrolyte Membrane (PEM), Alkaline, Anion Exchange Membrane (AEM) and Solid Oxide Fuel Cells (SOFC) electrolyzers. The deployment share of electrolyzers based on technology shows a greater prevalence of alkaline electrolyzers, as illustrated in Figure 16. PEM electrolyzers, functioning at low temperatures, represent the most advanced technology. Meanwhile, other technologies such as SOFC and AEM are currently in the research and development phase with a limited installation base.

The electrolyzer assembly is classified into three main levels: System Level, Stack level, and Cell level, each level is further assessed for its required components presented in Exhibit 4. The biggest challenge is posed using expensive catalysts to enhance reactivity. Moreover, there exists a trade-off between adopting new materials for enhanced efficiency and catalyst durability. It is crucial to develop low-cost electrocatalysts and research remains pivotal on this front [36].

System level	Stack level	Cell level
Pure feed water	Membrane and seperators	Catalytic materials
Renewable electricity	Bi-polar plates or electrodes	Reaction kinetics
Electrolyzer stack	Pressure drop	Material degradation
Gas seperators	Transport phenomena	Durability
Storage components		

Exhibit 4 - Classification of the electrolyzer technology at various levels with defining parameters of efficiency

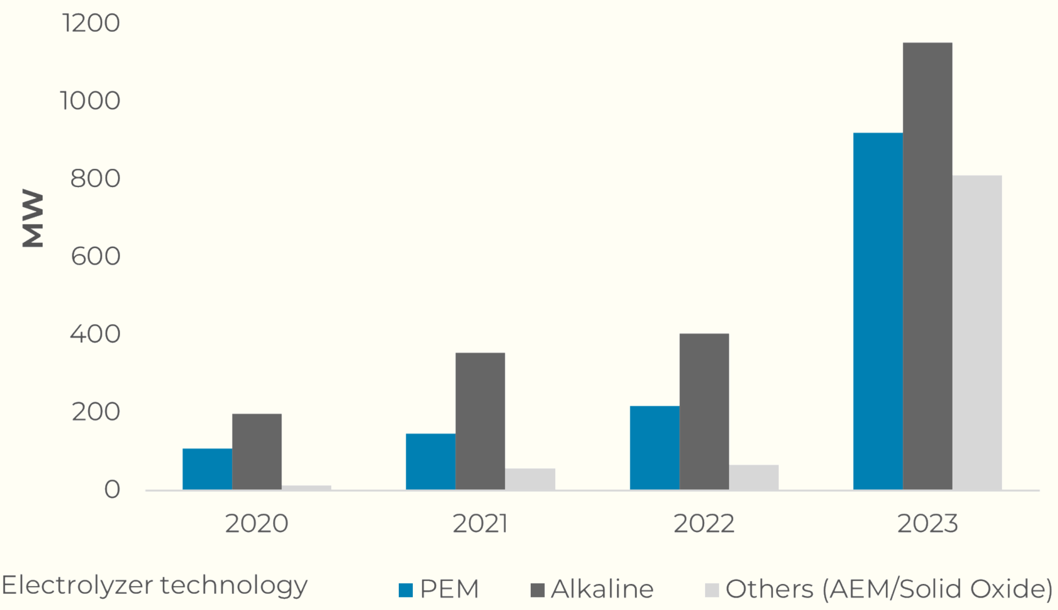


Figure 16 - Installed type and capacity of electrolyzers 2020-2023 (source: IEA - Electrolysers)

Table 3 presents the comparison of performance parameters of the technologies. The companies such as Enapter and Alchemr are actively engaged in substantial research and development efforts to promote AEM technology. Solid Oxide electrolyzers presents the highest efficiency along with elimination of the catalyst, however the high temperature for operation presents a critical limitation.

Table 3 - Comparison of electrolyzers types in relation with performance parameters

Electrolyzer type	Output pressure	Lifetime hours (103x hrs.)	Efficiency %/kg	Average Cost $/ kW	Maturity TRL	Deployed capacities (MW)
Proton Exchange Membrane PEM	<70	50-80	59%	600-800*	9	921
Alkaline electrolyzers	<30	60	61%	200-400*	9	1152
Anion Exchange Membrane AEM	<35	4	62%	-	6	-
Solid Oxide Electrolyzers	<10	<20	78%	-	7	-

Sources: IRENA Cost reduction (2020), International Energy Agency-Electrolyzes (2023)

*Chinese auction prices (Dec-2023) [37] Annexure-I

Box 1.3

Technology Readiness Level (TRL)

The primary emphasis for Technology Readiness Level (TRL) assessment is on electrolyzers. TRL offers a momentary evaluation of the maturity level of a specific technology across a defined scale, ranging from the conceptual stage to commercial viability presented in Exhibit 5. The technology journey starts at TRL-1, further innovation for its integration into energy systems. Value chains are deployed at TRL-10. This corresponds to the commercial acceptance, where the technology has achieved predictable growth by rapid subsidization and incentivization from the government.

Exhibit 5 - TRL from concept to commercialization

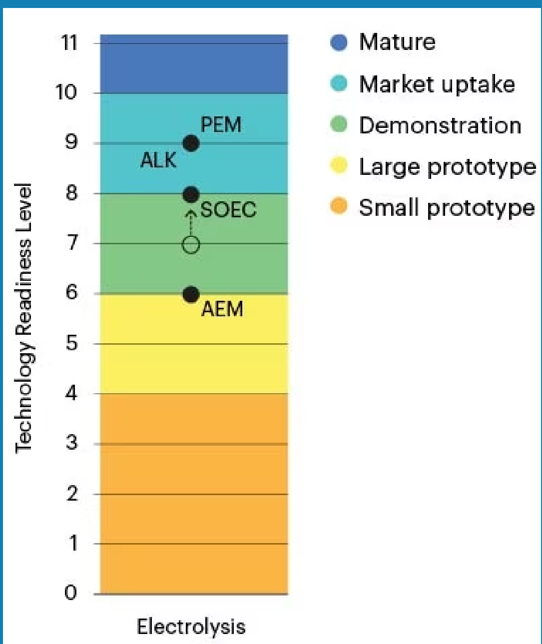


Figure 17 - The TRL of electrolyzers based on type. (Source: IEA-Electrolyzers)

Figure 17 entails the overall TRL scale of all the electrolyzer technologies available. Alkaline electrolyzers have already been successfully utilized on a commercial scale (TRL 9). PEM electrolyzers are less mature commercially but have been scaled up for current industrial applications (TRL 9). Solid oxide electrolyzers, which have the potential to significantly decrease electricity input requirements, are currently at the pilot stage (TRL 6) with less flexibility compared to PEM and AEM. The market uptake of the AEM electrolyzers is at the early stages of development, with few known projects to be commercialized.

The electrolyzer integration is complicated and requires thorough analysis.

The green hydrogen production facility comprises of electrolyzer system, along with the balance of plant and various interconnected processes. The interconnected processes include water requirement, feed flowrate, electrical requirements, and gas storage streams. The integration and commissioning of these plants results in highly tailored designs specific to their individual locations, uptake requirements and the type of renewable energy resource. Considering a comparison between designing a utility-scale PV power plant and a green hydrogen facility, the key considerations for green hydrogen plants are far greater than Solar PV plants, as it is just a component for generating renewable electricity in this facility.

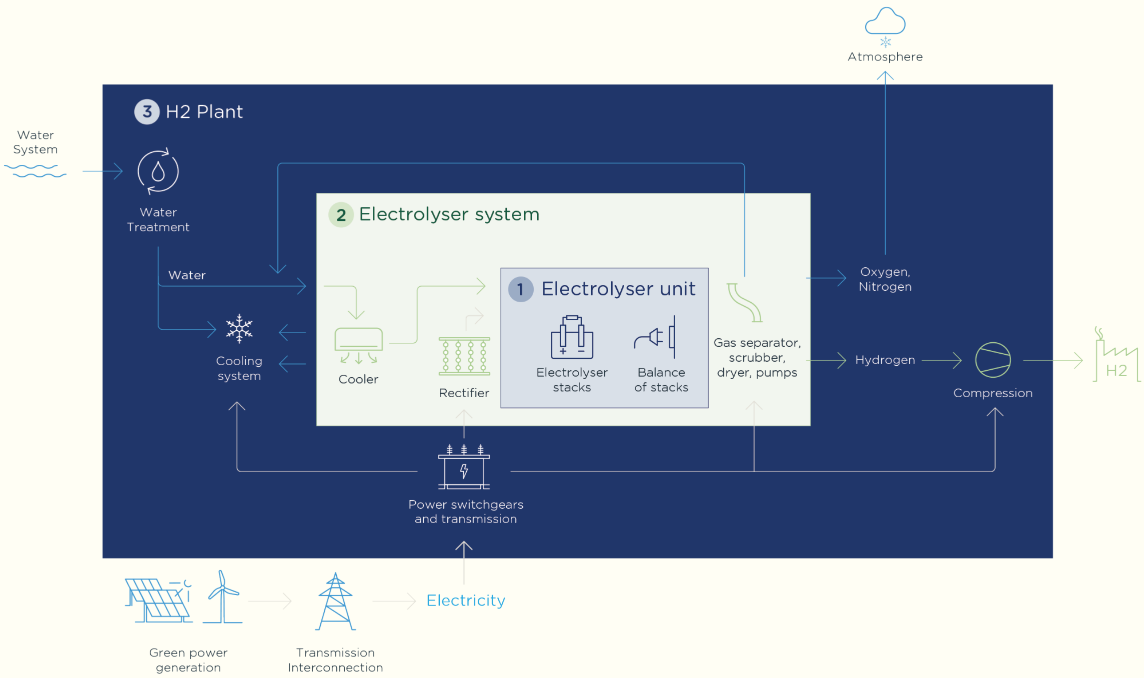


Figure 18 - The green hydrogen production plant (Source: Ramboll) [38]

The impact of electrolyzers on policy making

Innovation plays a critical role in electrolyzer uptake by reducing the cost and enhancing the performance of electrolyzers. The overarching parameters such as standardization and simplification of design, facilitating industries to scale up and enhancing the durability of electrolyzer in a longer span of time requires addressing the innovation bottlenecks. However, the choice of electrolyzer technology has a significant impact on the cost of hydrogen production and it also plays a vital role in shaping policies aimed at attracting key Original Equipment Manufacturers (OEMs) in the market creation process.

The recent developments in making hydrogen strategies around the globe are embedded primarily in the deployment of electrolyzer capacities. For example, the EU has enforced the most ambitious target of 40 GW of electrolyzer capacity by 2030 [39]. However, these targets have not yet been transformed into concrete regulatory measures. This makes it crucial to develop aligned policies in creating a green hydrogen market.

While navigating the emerging technologies landscape such as electrolyzer technologies, it is imperative to adopt a flexible approach when formulating policies. Strategic decision-making becomes crucial in identifying and supporting the most promising innovations. The key to success lies in securing market access and aligning with the proven technological trajectory such as in China, recognizing its pivotal role in shaping the global landscape. In Pakistani context, considering the recent decrease in Chinese AEM electrolyzer prices, the bilateral relations can be explored to enhance the trade and collaborative research in the electrolyzer space to create a win-win scenario for technological advancement and market penetration.

The bottleneck to attain ambitious green hydrogen targets by 2050 arises from the limited availability of the required mass production. This requires specific measures to define the electrolyzer production technology, definitive policy declarations, and robust standardization of the equipment. The absence of clear policy statements, particularly regarding hydrogen production technology, introduces uncertainty about the demand for electrolyzers. The opportunity to develop green hydrogen projects depends on financial backing from the government focused on a regulatory support system that is essential for the feasibility of the projects.

A targeted policy framework should specifically address electrolyzer technology to ensure scalability, acknowledging that plant design costs are intricately linked to the costs of these critical components. Striking the right balance is essential – to achieve scalable implementation.

Insight 5 - Green hydrogen strategy requires in-depth analysis of cost components for realistic commitments on Levelized Cost of Hydrogen (LCOH)

The Levelized Cost of Hydrogen ($/kg) is an important indicator for financial and commercial viability of green hydrogen production. It is calculated based on renewable electricity costs, the electrolyzer capital expenditure (CAPEX), operational hours commonly known as full-load hours (FLHs), operational costs and overall balance of plant. When assuming the LCOH, it is essential to incorporate realistic assumptions about the actual project-based conditions to prevent an overly optimistic number for LCOH in formulating trade and policy papers. The current global efforts are targeted to reach LCOH below 1USD/kg by 2050.

Policymakers will need clear estimates of the LCOH to develop appropriate support frameworks. The cost breakdown analysis of green hydrogen projects has shown an increase of 20-50% in real-world CAPEX cost, which in turn makes the viability of initial assumptions questionable. This stems from utilizing oversimplified cost calculations not incorporating the project-specific land acquisition, infrastructure development, and transmission costs [38].

The major key drivers that define the LCOH are renewable energy, national discount rate, electrolyzer CAPEX, engineering, procurement, and construction (EPC) costs, and stack replacement costs. These factors require careful consideration as they have a significant impact on costs. Figure 19 presents the breakdown of cost, water treatment plants, compression requirements, and land acquisition costs are minor cost drivers. All the cost components should be taken well into account before assuming LCOH. Moreover, the majority of electrolyzers produce end products at 30 bar pressure and gas injection to storage and transmission networks requires 85 bar pressure. Hence, the compression requirements for end products should be taken into consideration before calculating the LCOH [40].

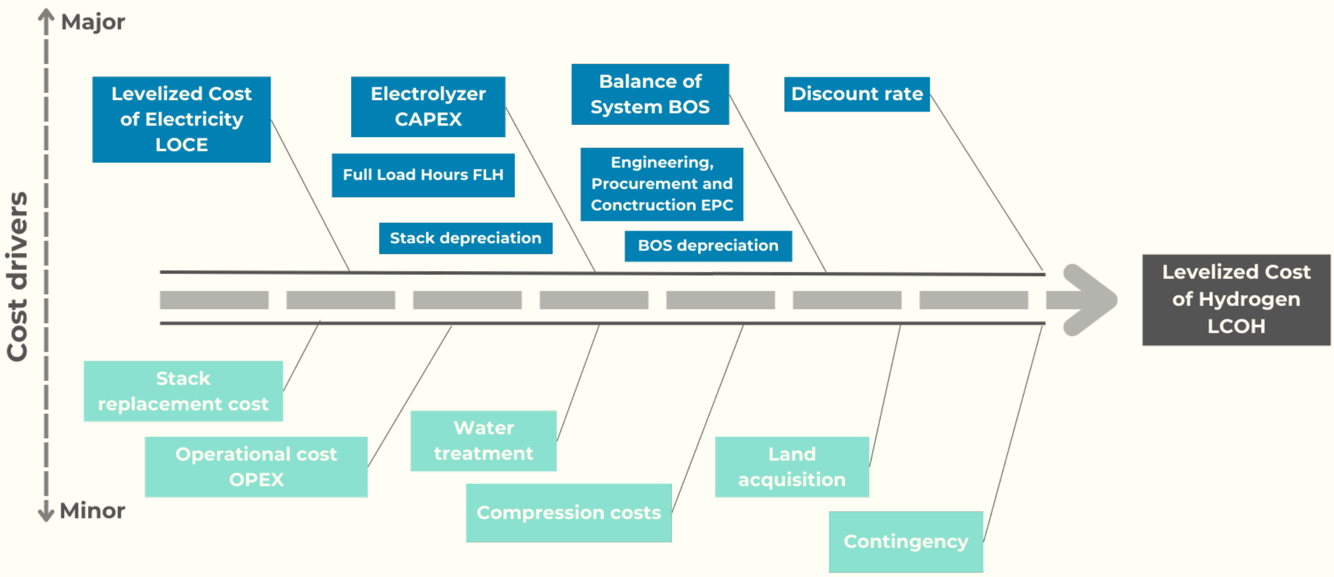


Figure 19 - Key drivers for defining the Levelized Cost of Hydrogen

The electrolyzers lifespan is a crucial determinant affecting the LCOH entailing stack degradation and efficiency loss. A longer lifespan results in the production of a greater quantity of hydrogen at a comparatively lower CAPEX. Figure 21 illustrates the optimal objective of reaching LCOH at 1$/kg by 2050 in most green hydrogen producing countries, necessitating an 80% reduction in electrolyzer costs, with ideal parameters for renewable energy ranging between 53-20 USD/MWh and a mix of maintaining optimal operational hours. IRENA suggests that improved electrolyzer design, efficient strategies to achieve economies of scale, and flexibility of operation will lead to a 40% decrease in CAPEX by 2030. By 2050, the cost of renewable energy, Solar PV is anticipated to decrease by 45% and onshore wind by 18% [41].

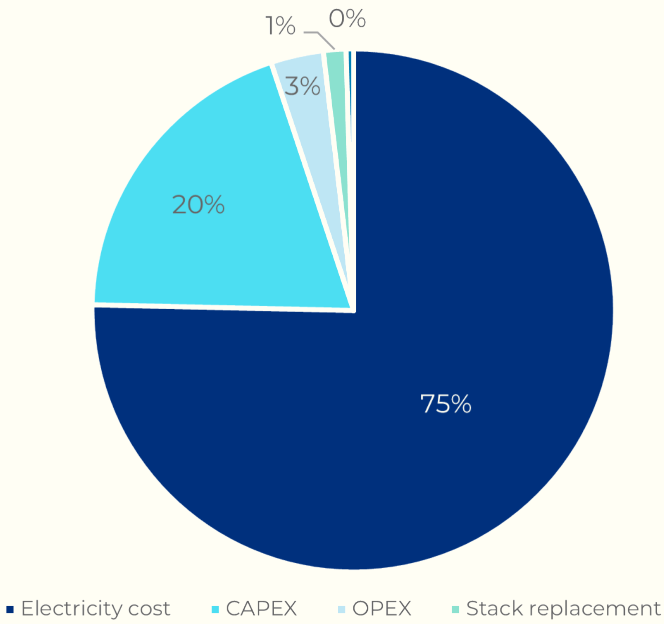


Figure 20 - Levelized Cost of Hydrogen LCOH breakdown [42]

Figure 21 - The parameters to consider achieving the ideal LCOH targets (Source: IRENA 2023) [34]

Levelized Cost of Hydrogen (LCOH) in Pakistan

The LCOH is anticipated to decrease significantly by 2030 due to rapid increase in technological advancements in electrolyzers, decrease in cost of electrolyzers and renewable energy prices with increased efficiency in production plants. The anticipated pattern for LCOH in Pakistan's coastal region is likely to follow a comparable trend, as illustrated in Figure 22. The LCOH (formula in Annexure-III) projected from Agora's PtX calculator presents a significant decline in the initial decade. The potential for constructing hybrid power plants presents an opportunity to achieve favorable LCOH of less than 2.20 USD/kg by 2050.

The discount rate holds paramount importance in constraining the LCOH projects in Pakistan. The nation's elevated risk premium, stemming from politico-economic conditions, distinguishes it as higher compared to other developing countries. Despite this challenge, there is an opportunity to devise mechanisms that facilitate market uptake and creation, addressing the unique circumstances that influence Pakistan's investment landscape. The need for higher contingencies also stems from anticipated uncertainties, particularly considering the extended timelines and regulatory barriers involved in developing projects.

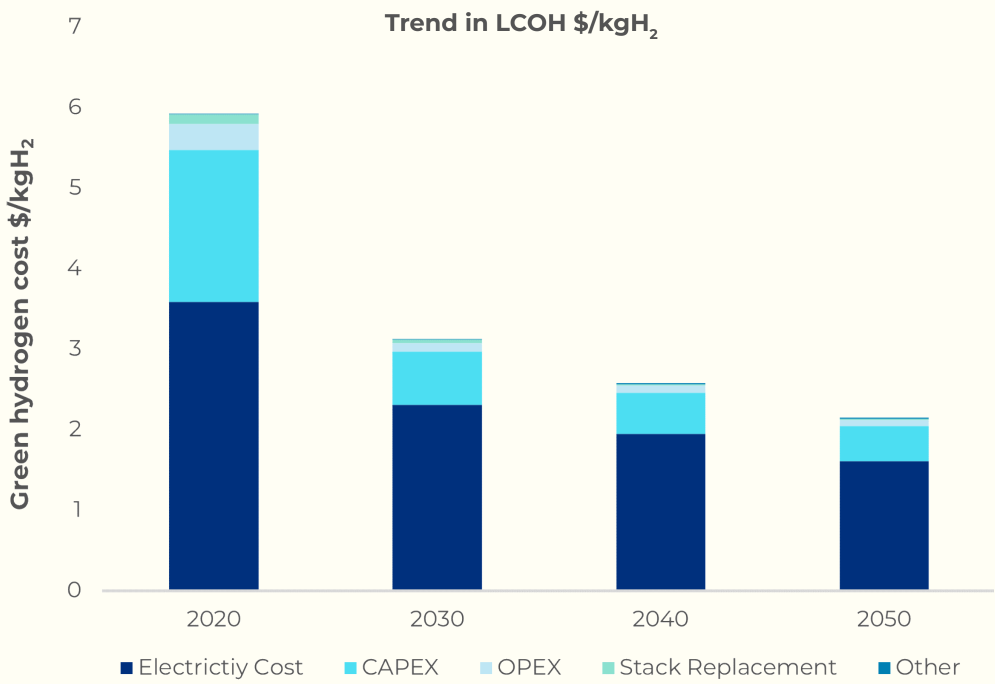


Figure 22 - Levelized Cost of Hydrogen LCOH for Pakistan in coastal areas (South-West)

Insight 6 - Bilateral trade flows require careful consideration of transport mechanisms, and the local gas infrastructure could be used for intercountry hydrogen delivery.

Developing a resilient global green hydrogen ecosystem based on bilateral trade requires addressing the challenges associated with transporting hydrogen, given its well-known flammability, low energy density, and volatility under standard conditions. The import-export spectrum requires due diligence regarding cost of hydrogen delivery at the end of use. The importers will be the ones with limited green hydrogen production potential and greater demand use such as Germany, Japan, and South Korea as presented in Figure 23. Exporters are the ones with abundant renewable resources to achieve low LCOH i.e., Sub-Saharan Africa and Australia. However, the method of transportation of hydrogen delivery is connected to the ultimate cost of bilateral contracts and offtake alliances.

The key drivers for choosing the type of delivery mechanism are dependent on distance and intended end-use applications. For shorter distances, the most practical choice is the transportation of hydrogen through pipelines. For long distances, it is either required to be compressed, liquified or converted into another energy carrier. The most favorable option for transporting hydrogen up to 3000 km involves the establishment of dedicated pipelines linking demand centers to nearby production facilities. This is likely to necessitate comprehensive regional and national planning, given that pipelines are long-lasting assets with high upfront investment requirements. The natural gas pipelines can be refurbished up to 7500 km at approximately half of the transportation cost required by other means [41]

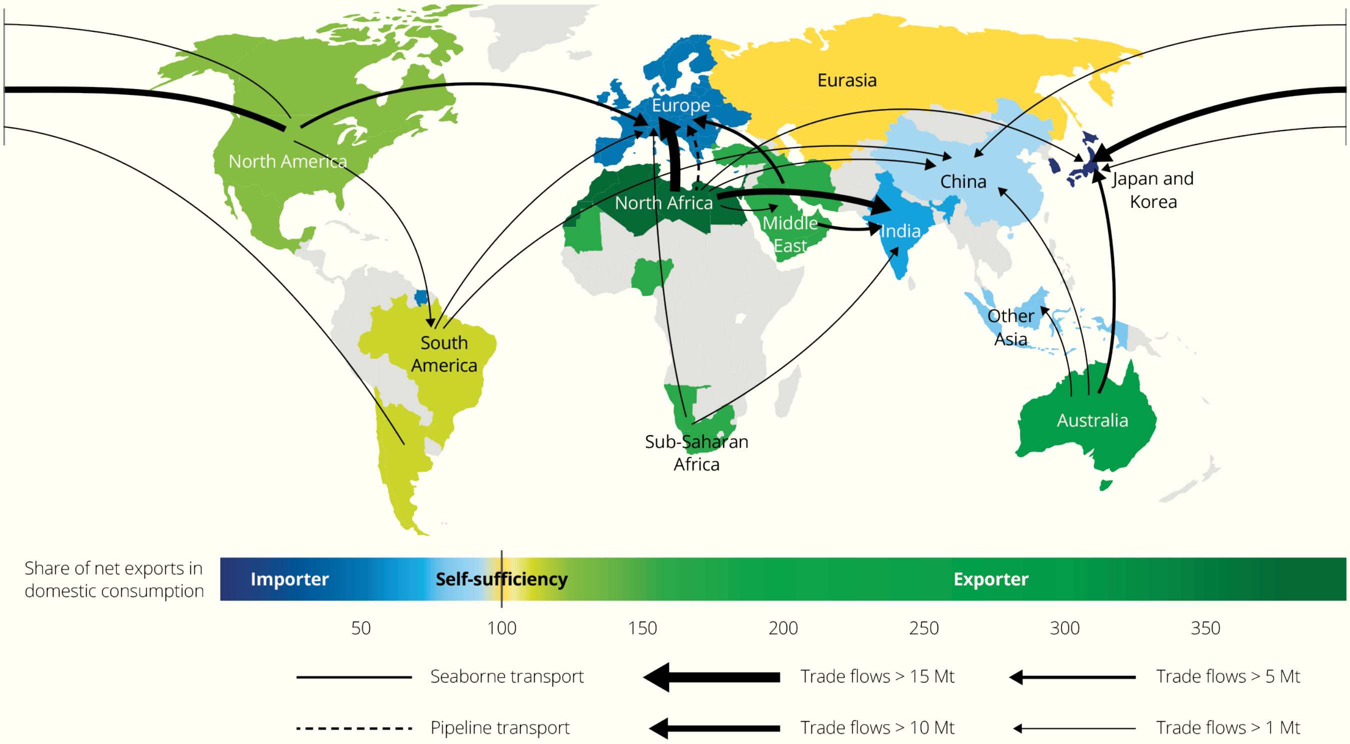


Figure 23 - Anticipated global trade flows by 2030 (Deloitte-2023)

Hydrogen derivatives, such as ammonia, methanol, or Sustainable Aviation Fuel (SAF), may present advantages in terms of containment and transportation compared to the pure hydrogen compound. The need for further conversion to an alternative carrier is unnecessary for these derivatives. For extended distances and cross border trade, conversion into alternative energy carriers like ammonia and methanol is the most effective option.

The industrial applications of these chemical feedstocks have an established presence in the market already. The safest commodity chemical to transport hydrogen is ammonia if the end-use application is in fertilizers or other relevant industries. However, in other cases, the reconversion of ammonia to hydrogen again leads to 15-34% energy loss. Liquefaction is another method to enhance the volumetric density of hydrogen; however, it is energy intensive with elevated cost, also leading to a loss of 30-36% final energy during conversion. Liquid Organic Hydrogen Carriers (LOHC) is also an emerging technology for the safe transportation and storage of hydrogen, involving the absorption of hydrogen in organic molecules, but due to its limited technological advancement and elevated costs, the option remains in the research and development phase [41].

Gas infrastructure in Pakistan

In the national context, the gas transmission and distribution networks are well established to connect production sites with demand centers. The country possesses an expansive infrastructure of 13,737 km for transmission and 203,625 km for the distribution of gas pipelines, catering to the needs of domestic, industrial, and commercial sectors by delivering natural gas. There are two integrated entities, one, addressing the demand centers in the South (SSGC) and the other in the North (SNGPL).

Pakistan's existing natural gas infrastructure can be significant to deliver green hydrogen to local demand centers through dedicated pipelines and upgradation of current facilities. The geographical distance between the northern and southern regions spans approximately 1,500 km, which is well within the recommended threshold of 3,000 km for utilizing pipelines in hydrogen transportation, as specified in Annexure II [43].

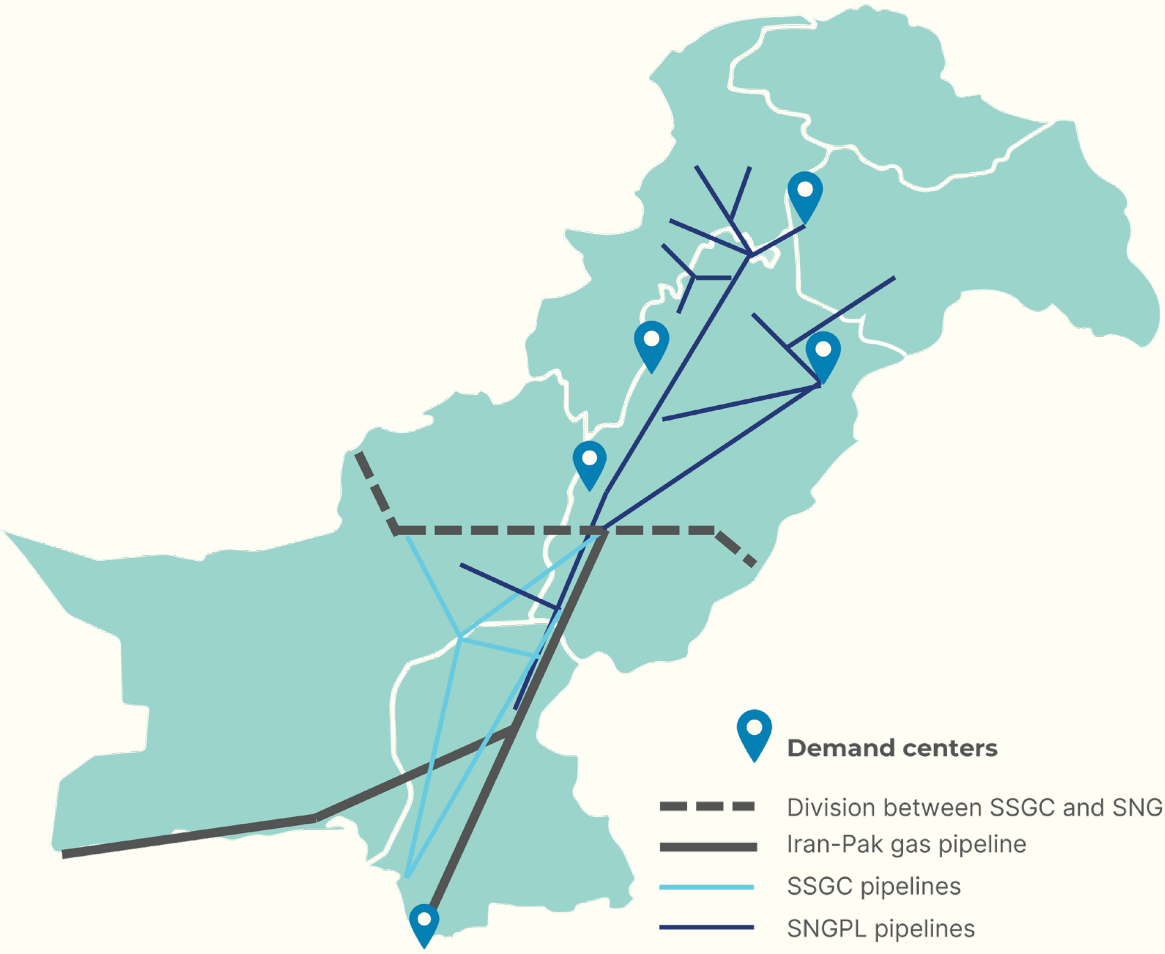


Figure 24 - The natural gas transmission and distribution infrastructure in Pakistan (Source: Petroleum exploration 2012) [44]

The green hydrogen production potential sites in Sindh and Balochistan are strategically situated along the coastal regions, presenting a lucrative avenue for leveraging bilateral trade flows. The Southern coasts of Pakistan have two well-established ports in Sindh—Port Qasim and Karachi Port providing robust infrastructural support. Moreover, Gwadar Port, strategically positioned in Balochistan, is poised to play a pivotal role as the exclusive deep-sea port for the region. This confluence of developed ports and geographically advantageous production sites underscores Pakistan's potential to develop trade frameworks for economic development.

Regional hydrogen cooperation

The countries with high green hydrogen requirements, low self-sufficiency and limited access to seaports share common geographical proximity as neighboring countries with Pakistan as presented in Figure 23. Similarly, China's demand for green hydrogen utilization exceeds its domestic resources, creating an opportunity for Pakistan to explore bilateral trade. The well-established intra-country (Figure 24) gas infrastructure can be utilized for this purpose as it spans all over the country.

The projects for regional energy security and cooperation such as the Turkmenistan-Afghanistan-Pakistan-India (TAPI) present intercontinental regional trade opportunities by developing a pipeline. The pipeline presented in Figure 25 that is spanning over 1,814 km is anticipated to connect Turkmenistan's Galkynysh gas fields passing through Afghanistan and Pakistan before reaching India. The length of the pipeline is adequate for transporting green hydrogen within the regional network for import and export purposes within the Central Asian region [45].

While regional cooperation projects like TAPI can contribute to economic prosperity, they are susceptible to political instability. Nevertheless, adopting a long-term strategic vision necessitates encompassing all aspects of existing and new infrastructure for bilateral trade focused on green hydrogen.

Figure 25 - Route of the Turkmenistan Afghanistan Pakistan India TAPI pipeline

Insight 7 - An effective green hydrogen strategy demands a dynamic policy overhaul that dives deep into addressing the diverse needs of all stakeholders.

The increasing trends of green hydrogen demand by 2050 remain uncertain due to the evolving need to decarbonize hard-to-abate sectors. Considering the dynamic landscape, it is vital to seek an adaptable approach that considers both the potential scale of demand and supply. To achieve this, national governments must thoroughly assess business cases supporting the creation of a hydrogen market before initiating the development of a strategy. By laying the groundwork for a flourishing hydrogen economy now, Pakistan could be well-positioned to meet the surging global demand for green hydrogen expected by 2030, leveraging an early-mover advantage in the Asian regional context [38].

The shift towards a green hydrogen economy will not happen overnight. It involves overcoming various challenges that span multiple dimensions of market creation. To successfully navigate this transition, it is essential to adopt a long-term vision while developing the green hydrogen strategy. This approach should involve active collaboration from a diverse range of stakeholders, including developers, private investors, development finance institutions (DFIs), and multilateral international organizations dedicated to creating an impact in upscaling the hydrogen ecosystem. Support from all stakeholders is necessary to scale up the green hydrogen market.

Most countries including Pakistan, with high potential for establishing green hydrogen projects, are typically located in the global south, often classified as economically developing with high political and climate risks. To attract private investors and lenders who seek increased returns to offset the heightened political risk, there is a crucial need for accessible financing mechanisms that effectively address and mitigate the risks associated with developing green hydrogen projects. Establishing a hydrogen market relies on strategic planning and securing access to financial mechanisms, facilitating a decrease in production costs for green hydrogen. DFIs play a crucial role in catalyzing climate finance and mitigating risks through the creation of financial tools that foster fair competition, thereby aiding in a just energy transition.

The path towards an inclusive national hydrogen strategy

The government has the responsibility of rafting a hydrogen strategy by utilizing various approaches to encourage the growth of the green hydrogen market. The most substantial impacts are expected in the initial stages of implementation. Pivotal actions, such as regulating the market and providing financial assistance, become essential as the market develops and expands. The government should maintain an adaptable approach, regularly assessing strategies and objectives to align with the latest advancements crucial to its strategy formulation. Exhibit 6 emphasizes the key elements involved in formulating a strategy at a national level. Green hydrogen's successful growth relies on market creation and offtake alliances, with policy development and collaboration among stakeholders playing a key role. Strategic partnerships are crucial for scaling up production and addressing challenges, ensuring the success of developing a hydrogen economy.

Key dimensions for consideration

Policy support and incentivization

Developing a green hydrogen economy requires supportive national policies, enacting strategies, implementation plans and incentives to hasten the shift towards a net-zero carbon future. Before venturing into the market, it is essential to integrate the policy into the demand requirements. The strategies may entail imposition of viable mechanisms such as financial incentives, tax credits, research funding, and regulatory structures aimed at advancing the production and utilization of green hydrogen. By cultivating a conducive environment, policymakers can stimulate investment, upscale innovation, and facilitate the widespread integration of green hydrogen value chains in regular market scenarios.

Geopolitics and bilateral trade cooperation

As countries position themselves in this new energy landscape, the geopolitics of hydrogen will be crucial in shaping diplomatic ties and economic partnerships on a global scale. It is increasingly intertwined with bilateral trade dynamics and energy independence as the strategic importance of emerging markets is gaining significance. The countries planning to get engaged in the production and export of green hydrogen are keen on cooperation alliances and partnerships to secure their positions in the emerging global hydrogen market. These alliances are catered by signing bilateral trade agreements enabling the technology and knowledge transfer to collaboratively address the supply and demand parameters.

Value chain creation and bi-products market

Hydrogen economy will require careful consideration of supply chain dynamics to avoid any bottlenecks. Acquiring mineral resources to meet the demand in the electrolyzer sector before strategizing could prove beneficial in utilizing indigenous mineral resources. Forming bilateral agreements with China could also facilitate the initiation of this industry, considering China's leading position in electrolyzer production. The strategy should focus on the right electrolyzer technology choice. Moreover, the feasibilities on water uptake are necessary prior to developing green hydrogen strategy as the concerns are already raise for water scarcity. The bi-products of the process such as oxygen also presents an opportunity to generate revenue.

Market creation and offtake alliances

Green hydrogen's growth relies on market creation and offtake alliances. Market creation involves policy and incentive development, while offtake alliances secure consistent demand through long-term agreements with the consuming industry. Collaboration among government, industries, and stakeholders is crucial for establishing a supportive market framework. This collaboration facilitates the scaling up of production capacities and the development of an integrated green hydrogen value chain. The success of the green hydrogen sector relies on working together to create a favorable market and ensuring reliable offtake agreements.

Regulatory framework and standardization

A robust regulatory and standardization framework will be required to develop the green hydrogen market in early stages of development as it will act as the foundation of the effective implementation plans overarching the strategy goals. The hydrogen needs to meet specified standards, adhering to global requirements, to address bilateral trade agreements and support decarbonization efforts. Standardization ensures industry consistency and interoperability, aiding technology adoption. International collaboration on regulatory standards promotes global cooperation, leveling the playing field for investment.

Financing mechanisms and de-risking

The cost competitiveness of green hydrogen projects is heavily influenced by financing costs, given the considerable capital intensity that requires significant debt and equity. Financial mechanisms and de-risking strategies will play a crucial role in achieving the Final Investment Decisions FIDs for green hydrogen projects. Attracting investments can be achieved through innovative financing avenues like public-private partnerships and green bonds. De-risking strategies, such as government guarantees and insurance, could be implemented to reduce uncertainties and enhance the attractiveness of developing projects for investors. These efforts can expedite the development of green hydrogen projects and gain investors trust.

Exhibit 6 - Key dimensions for developing a strategic roadmap for developing green hydrogen ecosystem

Box 1.4

Opportunity for Pakistan – Global H_2 foundation's procurement in EU

The Global Hydrogen Foundations' procurement initiative in the EU could be a game-changer for Pakistan to tap into the global green hydrogen market. This market-driven approach, akin to Contracts for Difference (CfD), ensures long-term purchase contracts, compensating for the difference with grants.

The Auctions are centered on the intermediatory HINT.CO that concludes long term purchase agreements of green hydrogen and its derivatives i.e. green ammonia, methanol, and e-fuels to give producers security on investments. Then H2 Global will take on lowest cost to sell in the EU market for highest bidder and will plunge in the difference. The whole initiative has been granted €6 billion in subsidized grants. The successful completion of its initial auction is anticipated by early 2024, that will mobilize €900 million for importing the Hydrogen and PtX to the EU market.

This innovative approach, reminiscent of Contracts for Difference (CfD), presents a transformative opportunity. The initiative focuses on securing 10-year term purchase contracts for hydrogen, coupled with grants that compensate for any price differences. By adopting a market-driven strategy like this, Pakistan can position itself to actively participate in the global green hydrogen landscape. As Pakistan explores avenues for collaboration and engagement in bilateral trade market, leveraging insights and considering engagement in these successful global models like the one implemented by the Global Hydrogen Foundation can pave the way for the future.

Annexures

Annexure-I-Chinese auction prices (Source : Hydrogen insights)

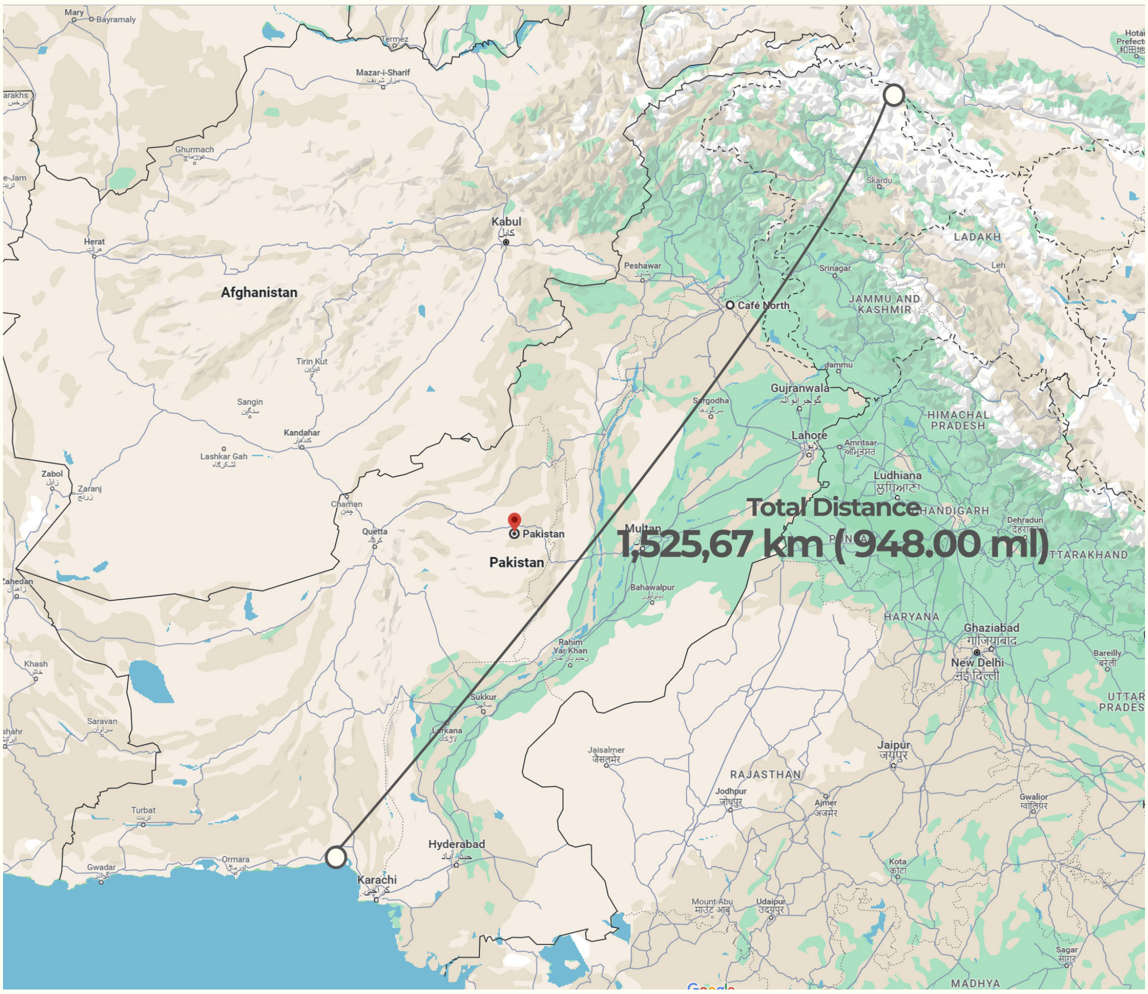
Chinese Auction prices Dec, 2023

Alkaline electrolyzers		
	Total USD/5 MW	USD per kW
Sungrow	961,504.0	192
Wuxi Huaguang	992,758.0	199
Guangdong Shengquing	994,830.0	199
Trina solar hydrogen	1,004,681.0	201
Biejing Power	1,041,786.0	208
Tianjin	1,053,900.0	211
Shanghai electric	1,072,423.0	214
Cockerill Jingli Hydrogen	1,081,812.0	216
Shuangliang Group	1,090,042.0	218
Peric	1,100,000.0	220
Longi hydrogen	1,112,256.0	222
	Average USD/kW	**209**

PEM electrolyzers		
Shanghai Electric	484,000	484
Sungrow Hydrogen	567,209	567
Bri Hy Nergy	626,741	627
SPIC Hydrogen	728,858	729
Cummins Enze	750,418	750
	Average USD/kW	**631**

Reference: https://www.hydrogeninsight.com/electrolysers/auction-results-reveal-that-chinese-hydrogen-electrolysers-are-two-to-five-times-cheaper-to-buy-than-western-machines/2-1-1570717

Annexure-II- The tentative distance from north and south. (Source : Google maps)



Annexure-III Levelized cost of hydrogen (Source: Agora Energiewende) [40]

$$LCOH = \underbrace{\frac{LHV}{\eta_{sys,LHV}}}_{\text{specific energy demand}} \left(\left(\underbrace{\frac{\frac{i}{100} \cdot \left(1 + \frac{i}{100}\right)^n}{\left(1 + \frac{i}{100}\right)^n - 1}}_{\text{annuity}} + \frac{OPEX}{100} \right) \frac{CAPEX}{\tau} + E \right)$$

LCOH	levelised cost of hydrogen [€/kgH_2]	$\eta_{sys,LHV}$	system efficiency related to the LHV
LHV	lower heating value [kWh/kgH_2]	τ	full load hours [h]
i	discount rate [%]	OPEX	operational expenditures [% CAPEX/a]
n	lifetime [a]	CAPEX	capital expenditures [€/kW]
E	electricity costs [€/kWh]		

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