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Techno-economic assessment (TEA) of renewables-based hydrogen in Pakistan

Oeko-Institut Working Paper 6/2026

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Techno-economic assessment (TEA) of renewables-based hydrogen in Pakistan

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Acknowledgement: The authors would like to express their gratitude to Christoph Heinemann, Christian Winger, and Johannes Aschauer for their valuable support with the PTX Business Opportunity Analyzer, and to Dr. Vanessa Cook for proofreading.

Working Paper 6/2026 Oeko-Institut e.V

July 2026

Download: www.oeko.de/fileadmin/oekodoc/WP-Impact-of-Methane-Regulation-on-GHG-emissions.pdf

This working paper is a product of the research project funded by Alexander von Humboldt Foundation through its International Climate Protection Fellowship (2025-26) Programme. The authors gratefully acknowledge the opportunity to conduct this research. The views and recommendations expressed in this paper are solely those of the authors and do not necessarily reflect the official position of Oeko-Institut.

Zusammenfassung

Wasserstoff, der auf Basis erneuerbarer Energien gewonnen wird (im Folgenden als „RES-Wasserstoff" bezeichnet), wird zunehmend als zentraler Baustein der globalen Energiewende anerkannt. Um die weltweite Nachfrage zu decken und die Klimaziele zu erreichen, entsteht eine neue Generation energiepolitischer Initiativen. Diese sollen sowohl die Energiesicherheit stärken als auch die Dekarbonisierungsverpflichtungen vorantreiben. Vor diesem Hintergrund plant Pakistan die Entwicklung einer Wasserstoffstrategie als Bestandteil des National Electric Plan (NEP) 2023–2027, um die energiepolitischen Verwundbarkeiten des Landes, geopolitische Abhängigkeiten sowie die gegenwärtige Energie- und Wirtschaftskrise zu bewältigen.

Pakistan steht derzeit vor vielschichtigen energie- und wirtschaftspolitischen Herausforderungen, die eng mit der sich verschärfenden Klimakrise verknüpft sind. Der Energiesektor ist weiterhin stark von importierten fossilen Brennstoffen abhängig, insbesondere von Erdgas, Erdöl und Kohle. Obwohl das Land über ein erhebliches Potenzial an erneuerbaren Energien verfügt, deckten Solar- und Windenergie im Jahr 2024 weniger als 4 % der Stromerzeugung. Die „Alternative and Renewable Energy (ARE) Policy" von 2019 verfolgte das Ziel, den Ausbau erneuerbarer Energien zu beschleunigen und eine heimische Industrie für erneuerbare Energien aufzubauen. Die bisherigen Fortschritte bleiben jedoch deutlich hinter den Zielvorgaben von 20 % bis 2025 und 30 % bis 2030 zurück. Ebenso besteht das Risiko, dass die geplante Wasserstoffstrategie nicht ausreichend mit den nationalen energiepolitischen Prioritäten abgestimmt wird und dadurch ein wenig zielführendes politisches Szenario entsteht. Dies könnte die Entwicklung einer RES-Wasserstoff-Wertschöpfungskette im Land letztlich behindern und die Rolle von Wasserstoff als Wegbereiter der pakistanischen Energietransformation einschränken.

Diese Forschung untersucht die institutionellen und energiewirtschaftlichen Rahmenbedingungen, die die Entwicklung einer grünen Wasserstoffstrategie in Pakistan prägen, und trägt dazu bei, die Lücke zwischen analytischer Evidenz und politischer Entscheidungsfindung zu schließen. Hierfür wird ein Mixed-Methods-Ansatz angewendet, der technologische und ökonomische Analysen mit einer Stakeholder-Mapping-Analyse kombiniert. So lassen sich die wesentlichen Bausteine einer Wasserstoffstrategie identifizieren. Die technische Analyse beleuchtet das Potenzial erneuerbarer Energiequellen, Elektrolysetechnologien, die Verfügbarkeit von Infrastruktur sowie Möglichkeiten der natürlichen Wasserstoffspeicherung. Für agrarisch geprägte Länder wie Pakistan bietet der bereits etablierte Ammoniakmarkt eine solide Grundlage für die inländische Nutzung sowie für Exportperspektiven. Ein besonderes Augenmerk liegt auf der Ausrichtung an den Nachhaltigkeitszielen der Vereinten Nationen (Sustainable Development Goals, SDGs), um sicherzustellen, dass Wasserstoffprojekte zur Verbesserung des Energiezugangs beitragen und Ungleichheiten in ländlichen Regionen verringern können.

Die Ergebnisse zeigen, dass Pakistan über erhebliche Möglichkeiten verfügt, sein Potenzial an erneuerbaren Energien für die Entwicklung einer Wasserstoffwirtschaft in die langfristige Energieplanung zu integrieren. Ein proaktiverer Ansatz bei bilateralen Partnerschaften und der transregionalen Zusammenarbeit ist erforderlich, um Pakistan wirksam in die entstehenden internationalen Wasserstoffentwicklungsstrukturen einzubinden. Darüber hinaus enthält die Studie eine vergleichende Analyse auf Grundlage des PTX Business Opportunity Analyzer (BOA) v3.0.1, indem Pakistan in die Datenbank potenzieller Lieferländer aufgenommen und mit anderen ressourcenreichen Entwicklungsländern verglichen wird.

Ohne eine nachhaltige institutionelle Unterstützung und sorgfältig ausgestaltete politische Rahmenbedingungen, die den anhaltenden politisch-ökonomischen Herausforderungen Pakistans Rechnung tragen, werden die Entwicklungsperspektiven eines Wasserstoffmarktes weiterhin durch tiefgreifende Investitionsunsicherheiten eingeschränkt bleiben. In dieser Studie werden die folgenden zentralen Handlungsfelder identifiziert: Erleichterung unternehmerischer Tätigkeiten, sorgfältige Ausgestaltung finanzieller Fördermechanismen, Schaffung transparenter regulatorischer und rechtlicher Rahmenbedingungen sowie Stärkung institutioneller Transparenz und Governance-Strukturen. Insgesamt wird eine integrierte Analyse technologischer, wirtschaftlicher, politischer und unternehmerischer Aspekte vorgenommen, um die Entwicklung einer tragfähigen Wasserstoffstrategie für Pakistan zu unterstützen.

Abstract

Renewable energy source-based hydrogen (referred to hereafter as RES hydrogen) is increasingly recognized as a critical enabler of the global energy transition. To meet global demand and achieve climate neutrality goals, a new era of energy initiatives is forming to advance energy security and decarbonization commitments. In this window of opportunity, Pakistan plans to develop a hydrogen strategy as part of its National Electric Plan (NEP) 2023–2027. The initiative is crucial for addressing the country's energy vulnerabilities, geopolitical interdependencies, and current energy and economic crisis.

Pakistan currently faces multifaceted energy and economic challenges that are intertwined with a worsening climate crisis. The energy sector remains heavily reliant on imported fossil fuels, primarily natural gas, oil, and coal. Despite strong renewable potentials, solar PV and wind supplied under 4% of electricity in 2024. The 2019 Alternative and Renewable Energy (ARE) Policy aimed to scale up and build a domestic renewables industry, but progress remains far behind targets of 20% by 2025 and 30% by 2030. Likewise, there is an anticipatory risk that the hydrogen strategy will be misaligned, leading to a quixotic policy scenario that may ultimately hinder the development of RES hydrogen value chain in the country and prevent its enabling role in Pakistan's energy transformation. This research examines the institutional and energy context shaping Pakistan's green hydrogen strategy and helps bridge the gap between analytical evidence and policymaking. The research uses a mixed-methods approach, combining technology and economic analysis with stakeholder mapping to identify the key components needed to develop a hydrogen strategy. The technical analysis highlights the resources of renewable energy potential, electrolyzer technologies, infrastructure availability and natural storage possibilities. For agrarian countries like Pakistan, the established ammonia market offers a strong platform for domestic uptake and export opportunities. Emphasis is placed on ensuring alignment with the Sustainable Development Goals with regard to hydrogen project developments that can improve the energy access and reduce inequalities within rural communities.

The research suggests that Pakistan has significant potential to utilise its renewable energy resources for hydrogen development in long-term energy planning. A more proactive approach to bilateral engagement and transregional collaboration is imperative to effectively position Pakistan within emerging international hydrogen development frameworks. The research also provides a comparative analysis based on the PTX Business Opportunity Analyzer (BOA) v3.0.1 by adding Pakistan within its supply country database and comparing it with other resource-rich developing countries.

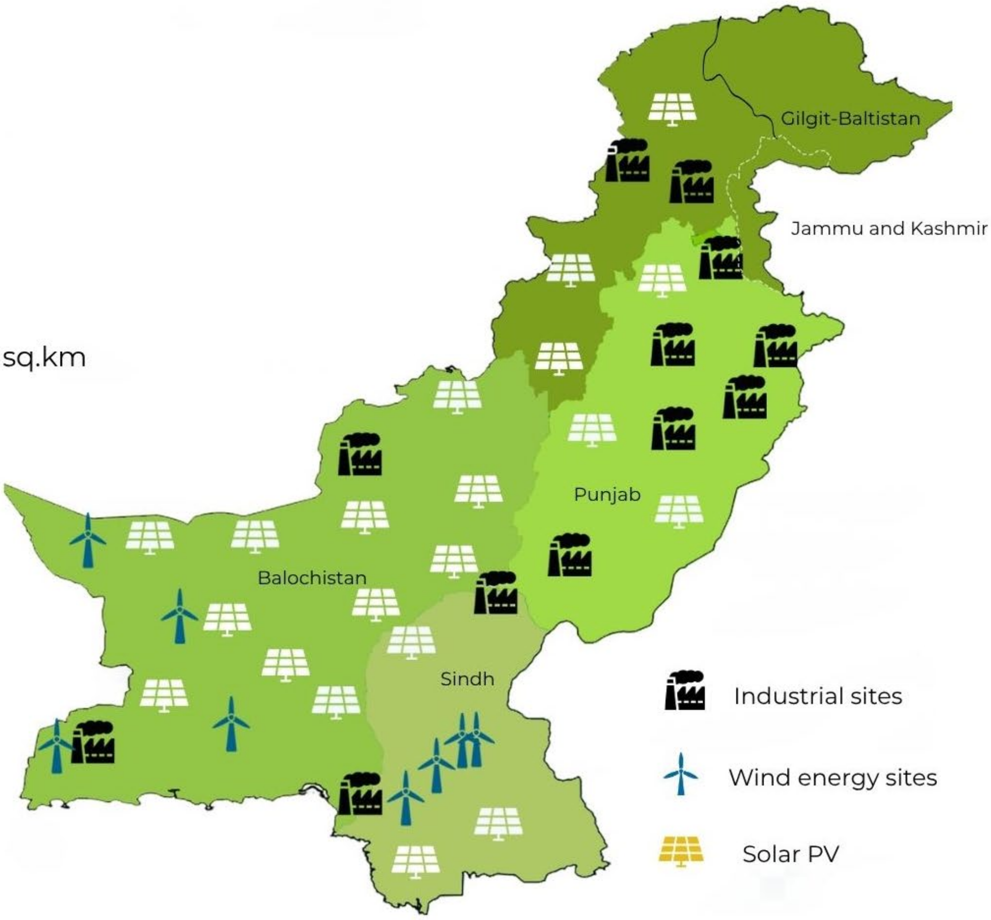
Without sustained institutional support and carefully crafted policy frameworks capable of addressing Pakistan's persistent politico-economic challenges, the prospects for hydrogen market development will remain constrained by deep-seated investment uncertainties. Key areas for intervention in the research mainly include the facilitation of business operations, thorough considerations of financial mechanisms, establishment of transparent regulatory and legal frameworks, and transparency of institutional arrangements. Overall, an overarching analysis of technology, economics, policy and business is carried out to support the formulation of hydrogen strategy.

Pakistan: At a glance

South Asia

Area: 881,913 sq.km

Population
241.5 million



2025 Statistics

Climate Risk Index
(1995-2024)

15

Environmental Performance Index

179 /180

Global Gender Gap Index

148/148

Power Generation Capacity

46 GW

Renewable Energy Potential

Solar PV

2900 TW

Onshore Wind

50 GW

Design courtesy: S.Maham Ali

Sources: World Economic Forum (2025); German Watch e.V (2025); Pakistan Beaurau of Statistics (2025)

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1 Introduction

RES hydrogen is considered one of the key enablers of the global transition towards energy security and decarbonization of hard-to-abate sectors. Global hydrogen demand reached 97 million tonnes per annum (Mtpa) in 2023, with the current production of hydrogen from electrolysis making up only 1% in hydrogen production worldwide (IEA, 2024). Demand for RES hydrogen is expected to surge in the years ahead. Net-Zero Emissions (NZE) energy scenarios project that hydrogen could supply 10–22% of final energy consumption by 2050, making for a RES hydrogen market of approximately 600 million tonnes by 2050 (IRENA, 2022; IEA, 2025).

At present, hydrogen is mainly produced from fossil-based conversion processes, with Steam Methane Reforming (SMR) as the dominant route. Hydrogen and its derivatives produced by renewable electricity is referred to as power to x (PtX), which is explained in more detail in Box 1. Hydrogen use is largely concentrated as a feedstock in fertilizer manufacturing, oil refining, and methanol production. Additional growth opportunities are expected in sectors such as steelmaking, shipping, aviation, and long-haul transport. Since these applications cannot readily run on renewable electricity directly, they are widely considered as 'hard to decarbonize' in NZE scenarios.

Hydrogen enjoyed great momentum in the early 2020s as a versatile decarbonizing agent for hard to abate sector mainly driven by the post Paris Agreement developments on climate commitments. This led to a plethora of hydrogen strategies and industrial decarbonization roadmaps. As global efforts to decarbonize intensify and countries seek greater energy security, hydrogen becomes a strategic option for diversifying energy systems. IEA reports that around 60 hydrogen strategies have been prepared worldwide, targeting hard-to-abate local sectors and tapping into export opportunities of PtX products (IEA, 2024). In parallel, global funding and policy incentives surpassed USD 100 billion in 2024, reflecting a ramp up of RES hydrogen deployment. This surge is enabled by falling renewable energy costs alongside improved risk management to reduce investment uncertainties. However, a significant gap remains between hydrogen project announcements and the implementation of real-world projects.

The trade dynamics of PtX products are also expected to reshape energy geopolitics, creating a clear distinction between hydrogen-exporting and hydrogen-importing countries. Most countries in the Emerging and Developing Economies (EMDEs) hold abundant renewable energy potentials, can produce hydrogen at lower costs and are emerging as exporters, while industrialized and developed economies are likely to become importers (with a few exceptions such as USA, Australia and Canada) (Pepe, Ansari, & Gehrung, 2023). However, it is worth mentioning that geographical market differential is also huge. For example, the cost of Alkaline electrolyzers in Europe/USA is high at 800 USD/kW) as compared to China where the lowest costs are recorded around USD 270-280 /kW and for export it is USD 350/kW (Energy Sector Management Assistance Program (ESMAP), 2026).

For many EMDEs with high renewable energy potentials, hydrogen is increasingly positioned as a strategic export opportunity within national hydrogen plans. Hydrogen developments create a pathway to contribute to their climate mitigation efforts while also gaining revenues through cross-border hydrogen trade. However, realising hydrogen potentials requires more than resource availability alone. A focused hydrogen strategy is essential to guide investment decisions, avoid fragmented infrastructure development, and ensure that limited resources are allocated efficiently. By aligning renewable energy potential, labour capacity, electrolyzer deployment, and sectoral priorities, strategies can help EMDEs capture value from emerging hydrogen markets while supporting domestic energy needs and industrial development.

In line with the global hydrogen progress, Pakistan is considering the formulation of a national hydrogen strategy under its National Electric Plan (NEP) 2023–2027 (MOE, 2023). These developments take place against the background of Pakistan's ambition to diversify its energy mix and international climate commitments. Under the Paris Agreement, the latest Nationally Determined Contributions (NDCs 3.0) pledges to reduce emissions by 17% unconditionally through domestic efforts, and by up to 33% conditionally depending on international support (MOCC&EC, 2025). At the same time, Pakistan's ability to plan and implement major energy transition projects is constrained by longstanding structural challenges in governance and public dept. For more than three decades, the economy has faced persistent strains linked to political instability, state fragility, and socioeconomic crisis. This research contributes to bridging the knowledge gap between literature on hydrogen technology advancements and policymaking by evaluating Pakistan's potential to produce RES hydrogen and outlining the key elements of a possible hydrogen strategy.

With a view to developing a hydrogen strategy, it is important that strategy should be evidence-based with concrete implementation outlook. This paper presents some of the required evidence in the following three areas: technical analysis, economic analysis and hydrogen governance. The technical analysis identifies potential production locations, assesses electrolyzer technologies in terms of performance, scalability, and suitability for national conditions, and examines the availability of large-scale underground storage options. The economic assessment evaluates the viability and extent of local adoption by analyzing cost competitiveness. It also provides a comparative overview of Pakistan’s cost competitiveness with other export-oriented countries. This analysis is carried out by using the **PTX Business Opportunity Analyzer (BOA) v3.03** tool that provides an overview of the trade potential of PtX molecules and was developed by Oeko-Institut e.V and Agora Energiewende for PtX Hub. The third section covers the governance perspective on hydrogen, asking how policy making can take phased approaches to developing a functional hydrogen market.

As a country, Pakistan faces chronically weakened institutional capacity and mounting exposure to external shocks. Climate change is intensifying these vulnerabilities, driving more frequent and severe extreme weather events that threaten economic stability and critical infrastructure alike. The 2022 floods alone caused an estimated USD 30 billion in losses and damages. In June 2025, the country was struck by another flood, fuelled by monsoon rainfall running 15–20% above average, displacing more than 6.9 million people and inflicting widespread damage to agricultural lands, highlighting the growing threat that climate-induced disasters pose to Pakistan's development trajectory (Reliefweb, 2025).

Further, a significant constraint on the economy lies in the energy sector, which is burdened by mounting debt because of fossil-fuels based thermal power generation. Compounding this challenge, more than 60% of the country's energy requirements are met through imports. Domestic reserves of natural gas are in decline, leaving only about a decade's worth of fossil fuel resources (Competition Commission of Pakistan, 2024). Natural gas represents the second-largest fossil fuel used in the country, much of which is imported as Regasified Liquefied Natural Gas (RLNG) via long-term contracts with Qatar, the United Arab Emirates, and Saudi Arabia (World Integrated Trade Solution, 2025).

In this context, exploring indigenous resources becomes inevitable. Hydrogen can play a strategic role in reducing reliance on imported natural gas, particularly in industrial feedstocks such as fertilizer production, where hydrogen could replace natural gas-derived hydrogen used in ammonia synthesis. Beyond decarbonization, hydrogen offers Pakistan an opportunity to strengthen both energy and food security while accelerating the transition to a low carbon future.

For RES hydrogen, Pakistan is well positioned to harness abundant regional renewable resources particularly strong onshore wind and solar photovoltaics (PV) potential along its coastline. The Gharo–Jhimpir wind corridor, extending roughly 60 km along the southern coast, is estimated to offer around 40 GW of exploitable wind capacity (Ghauri, 2023). Wider assessments indicate that Pakistan's overall wind potential could reach 346 GW, with additional hybrid opportunities in Sindh and Baluchistan to combine wind and solar for integrated hydrogen production (Knight, 2025). However, large parts of this renewable resource base remain underutilized. The offshore wind energy production remains unexplored with no existing projects now. There is an operational existing natural gas infrastructure that could possibly enable the local transport of hydrogen (more details in section 2.7). The proximity of industrial hubs to production sites could also help to reduce transportation costs while improving supply reliability, both critical for making hydrogen economically viable at national scale.

It is important that a hydrogen strategy must be informed by a comprehensive assessment of potential end-use applications and market formation pathways. If Pakistan establishes the foundations of a hydrogen market today, it could be well-positioned to meet rising future demand, particularly given that hybrid renewable energy plants offer the potential to achieve a competitive levelized cost of hydrogen (LCOH). However, realising this potential will depend on sound system design, supportive market mechanisms, and government-backed long-term offtake agreements that provide the investment certainty needed to attract and sustain capital. While politico-economic constraints and institutional capacity challenges present significant obstacles, they are counterbalanced by compelling drivers that create a credible pathway toward developing a functional, emission-free hydrogen market in Pakistan.

1.1 Global Hydrogen Strategy Landscape

Global developments in hydrogen landscape are moving from ambitious strategies, with governments using auctions, hubs and incentives to unlock demand and reduce risk for early movers in the industries. The strategies have strong emphasis on increasing "Market-making" instruments (auctions, contracts-for-difference, quotas and hub models) to close the cost gap and create reliable demand, rather than only funding supply of clean hydrogen. However, the strategies span from developed countries to developing countries mainly focused on renewable energy needs, local demand of hydrogen and PtX and decarbonization needs.

Germany provides a strong example of an industry-led hydrogen strategy. Initially a target of 6 GW of electrolysis capacity was set but later the National Hydrogen Strategy was updated in 2023 to increase domestic electrolysis target to 10 GW by 2030, reflecting a stronger commitment to scaling RES hydrogen production. The strategy is also closely linked to EU Green Deal, and Clean Industrial Deal with an explicit expectation that domestic supply will not be sufficient, and imports will therefore be required (BMWK, 2023). In parallel, Germany also published a strategy for importing hydrogen and its derivatives along with prioritising hydrogen infrastructure development, including a national hydrogen network to connect production sites, import hubs, storage locations, and industrial demand centres (BMWK, 2024). Germany also passed a Hydrogen Acceleration Act as a legislative effort to fast-track the development of hydrogen infrastructure by streamlining approvals (NWR, 2024).

The EU has also integrated hydrogen into its climate strategy under the European Green Deal, positioning RES hydrogen as a key tool for decarbonising industry and supporting the shift to cleaner fuels in transport. The EU's Hydrogen Strategy sets ambitious deployment goals, including 40 GW of renewable hydrogen electrolysers by 2030 and production of around 10 million tonnes of renewable hydrogen within the EU. In addition, EU policy promotes hydrogen corridors and cross-border infrastructure development, alongside certification schemes to establish clear standards for what counts as renewable or low-carbon hydrogen (European Commission, 2026).

The United Kingdom's approach also highlights hydrogen as a central element of its net-zero pathway, particularly for industrial decarbonization and the development of low-carbon industrial clusters. The UK's Hydrogen Strategy and subsequent energy security plans set a target of up to 10 GW of low-carbon hydrogen production capacity by 2030, with at least half expected to come from electrolytic (green) hydrogen. The UK's strategy focuses on creating market incentives and investment frameworks to scale supply, while also supporting pilot projects in heating and transport (DESNZ, 2021).

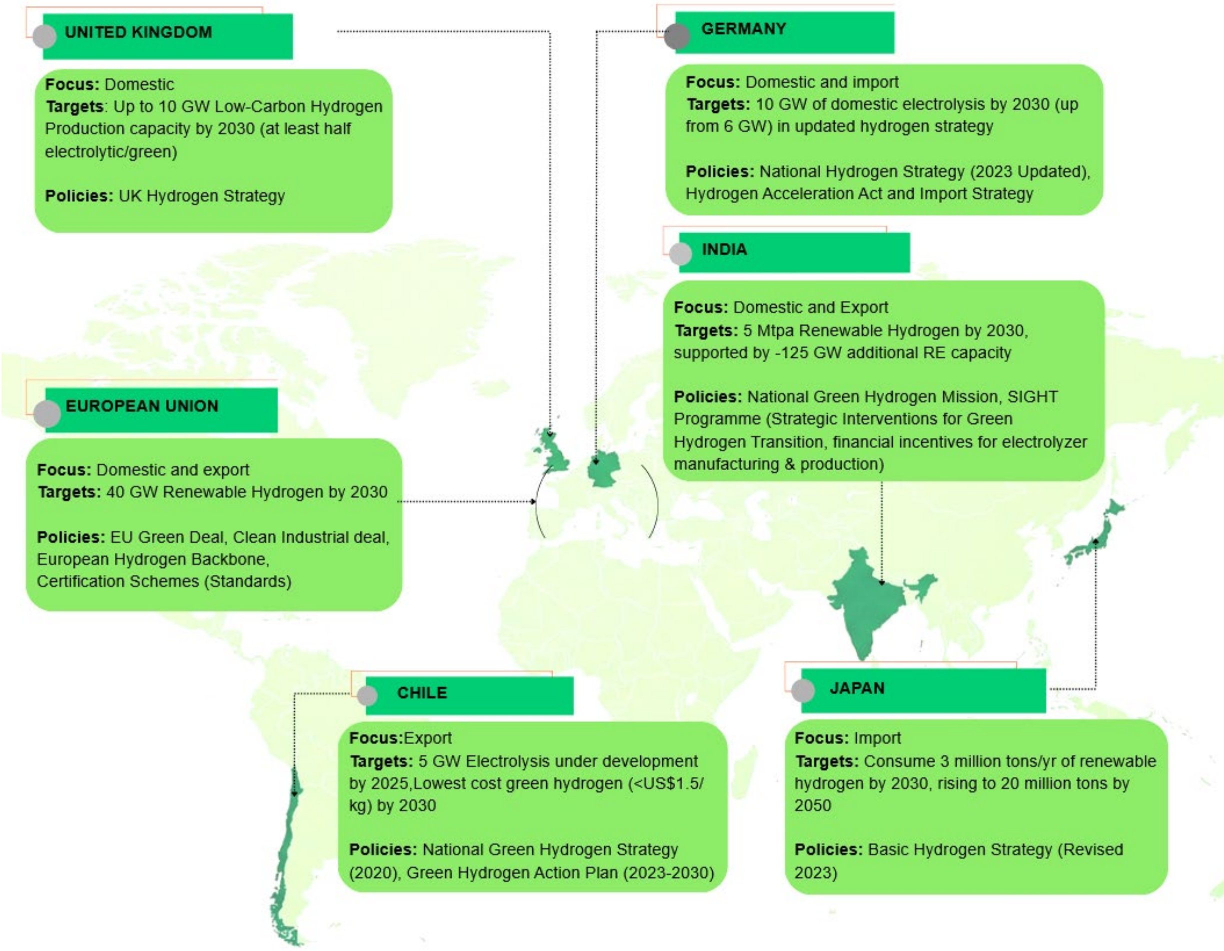
Japan's hydrogen strategy is closely linked to its energy security and import-based supply chains. The revised Basic Hydrogen Strategy (2023) increases hydrogen consumption to around 3 million tonnes/yr by 2030, rising to approximately 20 million tonnes/yr by 2050. Japan also places a strong emphasis on ammonia as a hydrogen carrier and as a fuel, including plans for ammonia co-firing in power generation and industrial applications (The Ministerial Council on Renewable Energy, Hydrogen and Related Issues, 2023).

In the case of EMDEs, Chile has developed its National Green Hydrogen Strategy (2020) solely focused on export markets. The strategy set the target of 5 GW of electrolysis capacity under development by 2025 and to achieve the lowest possible cost green hydrogen by 2030 (target <US$1.5/kg) (Ministry of Energy-Chile, 2020). Building on the strategy, Chile published a Green Hydrogen Action Plan (2023–2030), which lays out a coordinated roadmap across ministries to accelerate permitting, infrastructure planning, standards/certification, R&D, and investment promotion aiming to move from vision to implementation across the full value chain (including derivatives like ammonia) (Ministry of Energy, 2023).

India's National Green Hydrogen Mission (NGHM) targets at least 5 Mtpa hydrogen produced from renewables by 2030, supported by around 125 GW of additional renewable energy capacity, and dedicated finance backed by government. of A key implementation pillar is the SIGHT programme (Strategic Interventions for Green Hydrogen Transition), which provides financial incentives to scale up both domestic electrolyser manufacturing and hydrogen production, aiming to reduce costs and build an indigenous supply chain. The mission focuses on decarbonizing associated industries such as steel, while also laying the groundwork for export-oriented value chains (including green ammonia) (Ministry of New and Renewable Energy, 2023).

Overall, these examples illustrate that hydrogen is being incorporated into net-zero strategies in different ways depending on national circumstances. Countries such as Germany, the EU and Japan frame hydrogen mainly as an industrial decarbonization tool supported by infrastructure expansion and imports. India and Chile are focused on export opportunity while equally building up the local industries. Despite differences, a common theme across strategies is that hydrogen is prioritised for local demand applications.

Figure 1: Overview of hydrogen strategies across the globe



Source: Author's compilation based on National Hydrogen Strategy Germany (2023); UK Hydrogen Strategy (2021); National Green Hydrogen Strategy (Chile, 2020); Basic Hydrogen Strategy (Japan, 2023); (European Commission, 2026) & National Green Hydrogen Mission (India, 2023)

1.2 Key drivers of RES hydrogen developments in Pakistan

The global push to phase out fossil fuels in line with the Paris Agreement's objective of achieving climate neutrality by 2050 is closely tied to the urgent need to identify alternative, carbon emission free energy solutions across all sectors. Within Pakistan's climate and energy context, reliance on fossil fuels, particularly natural gas, can be reduced by replacing it with hydrogen produced from electrolysis, as well as through other PtX applications such as ammonia, methanol, and other synthetic fuels. The key drivers for RES hydrogen developments are highlighted in Figure 1.

Figure 1: Key drivers for RES hydrogen developments in Pakistan

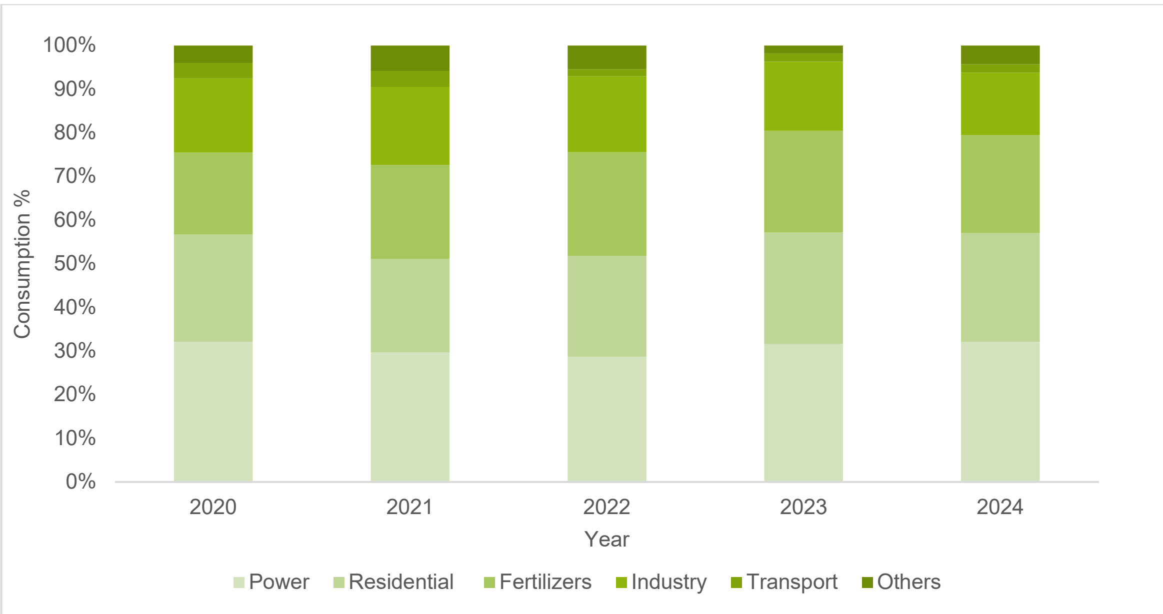
Source: Author's compilation

1.2.1 Energy security and transition

a) Natural gas dependency: Import and declining reserves

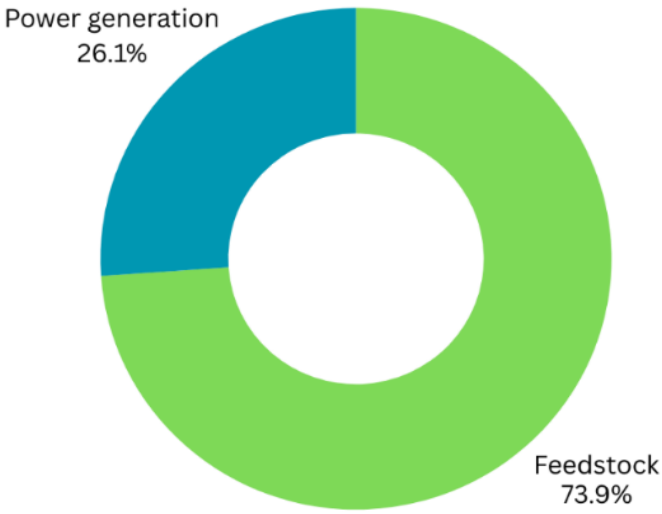
Pakistan's natural gas consumption is approximately 35 bcm (FY'2024) making it the second largest fossil fuel source in the national energy mix. Figure 2 gives the breakdown on consumption across varying sectors from 2020-24 (PACRA, 2025).In FY'2022-23, natural gas accounted for approximately 38.6% of the total primary energy supply (TPES) in Pakistan referring to cumulative supply of energy produced and imported in the country to meet the overall demands. Natural gas consumption within the fertilizer sector is approximately 23% of the TPES that is split between feedstock and fuel for power generation highlighted in Figure 2.

Figure 2: Pakistan's natural gas consumption across sectors in 2020-2025



Source: Author's compilation based on PACRA (2025)

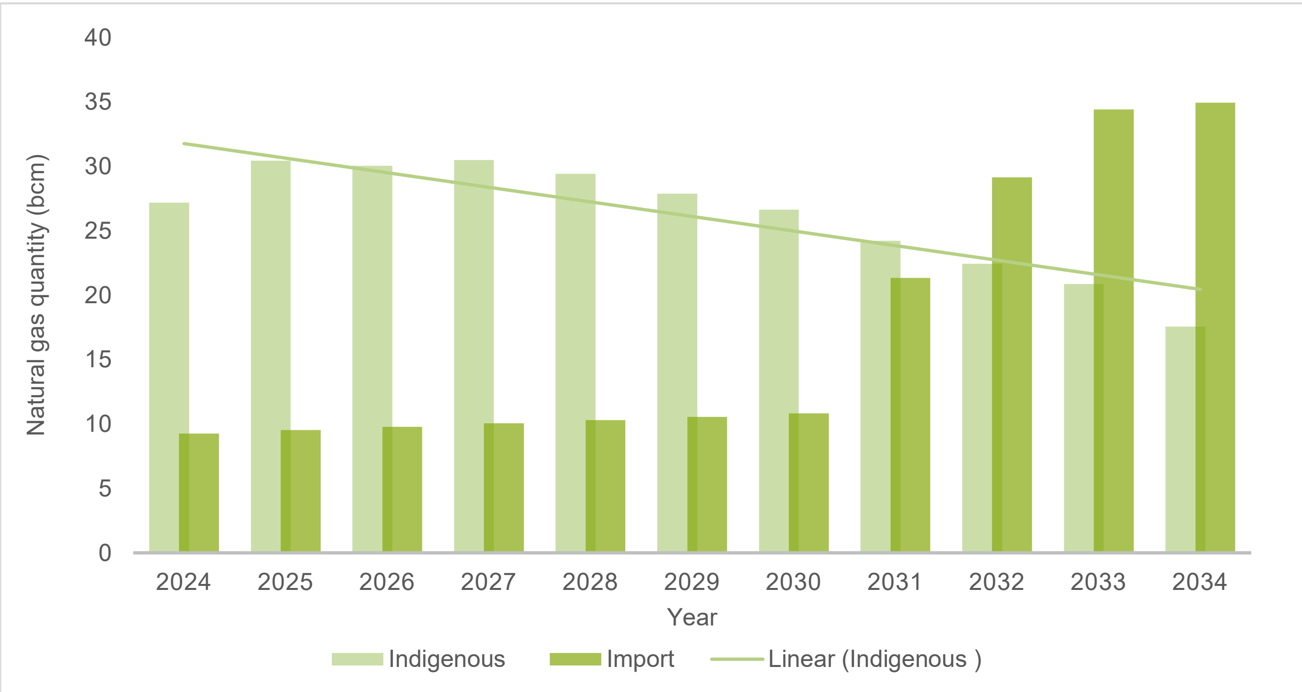
Figure 3: Natural gas usage in fertilizer industry



Source: Competition Commission of Pakistan (2024)

The proven natural gas reserves are reported to be 535 bcm, with no recent discoveries in place. From domestic supply perspective, the domestic natural gas output has been on a persistent downward trajectory (Competition Commission of Pakistan, 2024). A significant production decline of 9% is reported from the production rate in 2015 to 2020. Figure 4 represents the demand growth and supply through imported and local natural gas, huge import influx is expected by 2032.

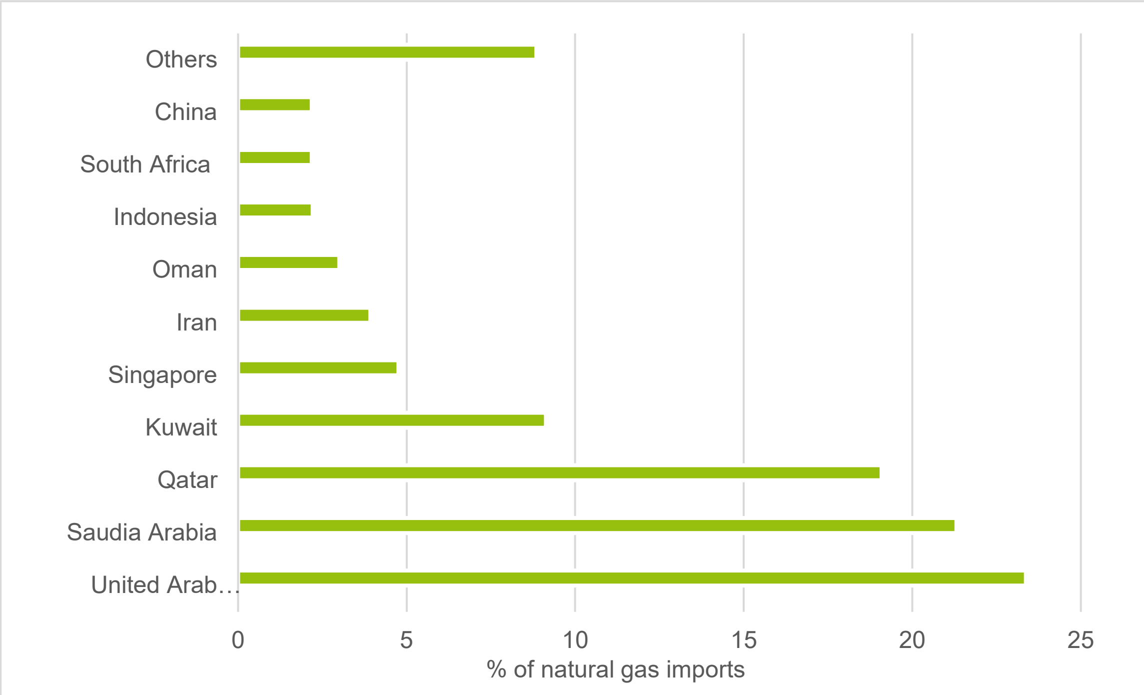
Figure 4: Demand growth of natural gas: Local natural gas production vs imported (2024-2034)



Source: Author's compilation based on OGRA (2024); PACRA (2025)

Figure 5 provides an overview of Pakistan's natural gas import sources by country (World Integrated Trade Solution, 2025).The figure helps assess the diversity of supply and the extent to which Pakistan's energy system depends on external producers, which has important implications for supply security, price volatility, and long-term energy planning (OGRA, 2024). Overall, the situation emphasizes on the need for immediate prioritization of alternative supply options to meet the country's needs, while ensuring energy security.

Figure 5: Pakistan's natural gas import partners globally (FY'2023)



Source: Author's compilation based on WITG-World Bank (2023)

Addressing the projected supply gap will require a nearly twofold increase in LNG imports by 2034 as highlighted in Figure 4. Moreover, Oil and Gas Regulatory Authority (OGRA) sets the LNG price on a weighted-average basis, factoring in import volumes, DES (Delivered Ex Ship) prices[1],importer margins, terminal charges, retainage and T&D loss adjustments, pipeline supply costs, and distributor margins (Competition commission of Pakistan, 2024). At present, LNG imports are handled through only two terminals, with a combined handling capacity of approximately 12–14.5 bcm. As import volumes increase, current LNG infrastructure will be insufficient, requiring new terminal capacity and placing additional cost burdens on consumers (PACRA, 2025).

1.2.2 Economic growth and sustainable development

a) Resource utilization

As mentioned in above section, the depleting fossil reserves, and economic depreciation entangled with the use of fossil fuels, makes a switch to renewables a necessary particularly to reach climate neutrality goals. Globally the momentum of phasing down fossil fuels is an essential criterion for

[1] The delivery price of LNG is calculated using an agreed percentage of crude oil prices, averaged over the last three months. This gives a price in US dollars per unit of energy (USD/mmbtu) for each shipment. These individual shipment prices are then combined into a single average price for the two importers, Pakistan state oil (PSO) and Pakistan LNG Ltd (PLL), based on how much LNG each one imported.

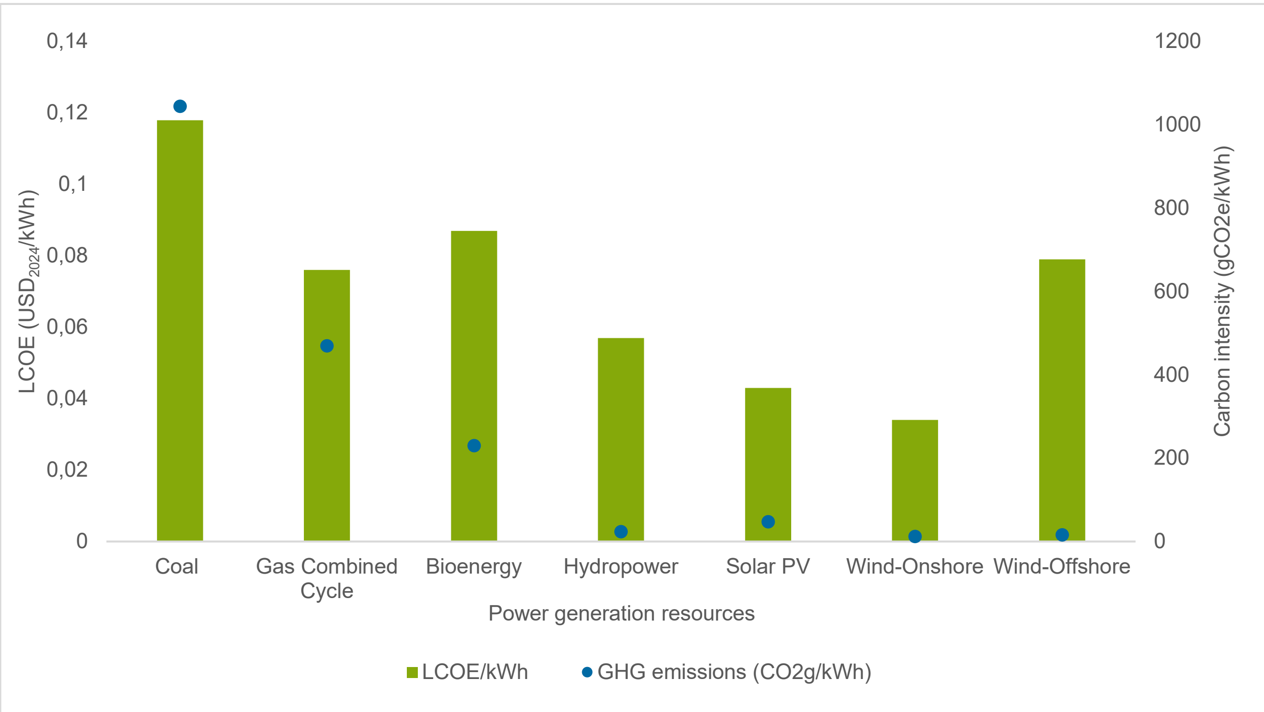
advancing energy transition and industrial transformation. At COP-26, the Glasgow Climate Pact also put ambitious limitations to phase down unabated coal and to deal with fossil fuel subsidies that are impacting developing world more than ever (UNFCCC, 2025).

Further, many Development Finance Institutions (DFIs) have limited the financing of further fossil-based energy projects particularly for coal and are more focused to help countries to retire coal power plants (Kachi, 2024). Mechanisms such as Asian Development Bank's (ADBs) Energy Transition Mechanism (ETM) are currently helping Asian coal-based power plants be retired or replaced with clean energy projects. It is planned that the ETM will be extended to Pakistan, Kazakhstan and the Philippines, however nothing concrete is yet on table (ADB, 2026).

While Pakistan's energy policy explores expanding the Thar coalfield to reduce reliance on imported fossil fuels, the project faces a trifecta of financial, technical, and environmental barriers. Financially, high capital costs are exacerbated by a global banking shift away from coal, making foreign investment nearly impossible to secure. Technically, the low quality of Thar coal necessitates expensive beneficiation and precludes the use of high-efficiency supercritical technology, resulting in a higher specific emission factor per unit of electricity. Consequently, renewable energy has emerged as the least cost alternative with a minimal carbon footprint. Figure 6 shows the levelized cost of electricity (LCOE) of different power generation technologies and associated average lifecycle GHG emissions (Ember, 2024).

Pakistan's coal power generation is relatively recent with most of its coal projects constructed under China Pakistan Economic Corridor (CPEC). In the further development of fossil fuel-based power generation and industrialization, it is expected that carbon capture and storage (CCS) will be employed. CCS is still an expensive avenue in terms of capital expenditure, while having associated carbon footprint.

Figure 6: LCOE of different technologies with respect to GHG emissions



Source: Author's compilation based on Ember (2024)

Long-term energy security scenarios increasingly favour a rapid transition to renewables over fossil fuels. The economic rationale is clear: solar energy has achieved cost-parity and now represents the least-cost option among all available power generation technologies. The uptake of residential solar PV in Pakistan - 46 GW between 2023 and 2025 - was driven by large-scale panel imports and serves as a market-led proof of the technology's cost-competitiveness against rising grid tariffs (Transition Zero, 2026).

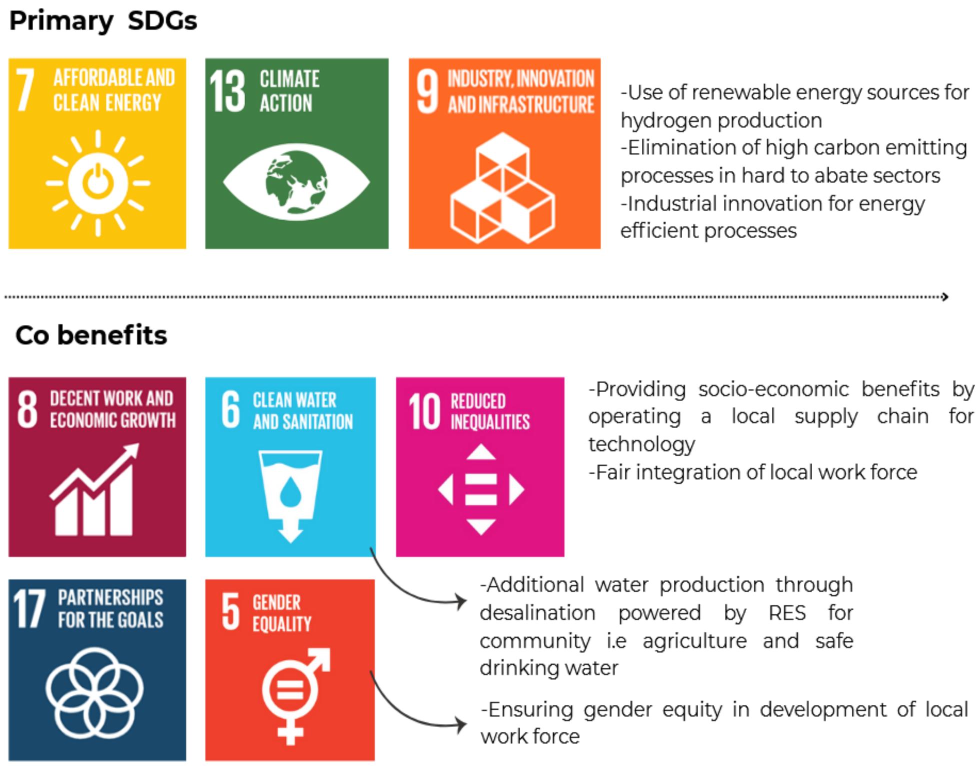
This transition is a pragmatic response to the high cost of traditional electrification. In this context, extending renewable energy applications to industrial sectors through hydrogen production is a logical next step for long-term reliability.RES hydrogen is essential for the 'deep decarbonization' by replacing fossil fuels in of heavy industries.

b) Addressing Sustainable Development Goals and co-benefits

RES hydrogen is evidently becoming a strong enabler of sustainable development in EMDEs due its cross-cutting nature of addressing multiple Sustainable Development Goals (SDGs). These are presented in Figure 7. A primary SDG that it directly supports is 'Climate Action' (SDG 13) by cutting carbon emissions linked to producing hydrogen from natural gas and by enabling decarbonizing.

Another relevant primary SDG is SDG-7: 'Access to Clean Energy' since it addresses renewable energy requirements for hydrogen developments. RES hydrogen is expected to be produced in remote regions particularly in Pakistan, that lack access to electricity despite having enormous renewable energy potential. Hence, adding additional renewable energy capacity can enhance electrification rates by creating a "co-benefit" for nearby communities that may be struggling to meet their electricity needs (Martins, 2024).

Figure 7: Sustainable development goals and co-benefits across RES hydrogen



Source: Author's compilation based on Öko-Institut e.V(2024)

RES hydrogen can also be useful in terms of enhancing industrial infrastructure by incorporating net zero industry and innovation, thus addressing SDG-9 of 'Industry, Innovation and Infrastructure'. The RES hydrogen demand can drive innovation across electrolysers production, catalysts, storage, and transport infrastructure, while developing clean industries that are essential for economic growth.

Water sourcing for electrolysis must be managed sustainably. Although electrolysis does not require very large volumes of water, RES hydrogen project design should explicitly address SDG 6 'Clean Water and Sanitation' (IRENA, 2023). Pakistan, where water scarcity is a critical challenge, hydrogen projects should prioritize sustainably sourced water, such as treated wastewater or carefully managed desalination. Where feasible, water infrastructure developed for hydrogen production could also contribute to improving access to clean water for nearby communities, thereby delivering additional social co-benefits while ensuring responsible resource use (Heinemann & Mendelevitch, 2021).

The importance of co-benefits is beyond addressing the climate change – it is a matter of the sustainable transition of energy and industries. The development phase of renewable energy projects creates both short- and long-term economic co-benefits, offering diverse employment opportunities across construction, installation, and ongoing operations and maintenance. Long-term industrial transformation through the manufacture of electrolysers and peripheral equipment can boost economic growth by creating employment opportunities, which essentially addresses SDG 8 'Decent Work and Economic Growth'. Sustainability must be ensured when developing hydrogen projects which may include transparent land allocation, clear permitting processes, and strong community engagement can help ensure that new infrastructure does not place an unfair burden on local communities but rather creates inclusive opportunities for economic development and sustainable growth.

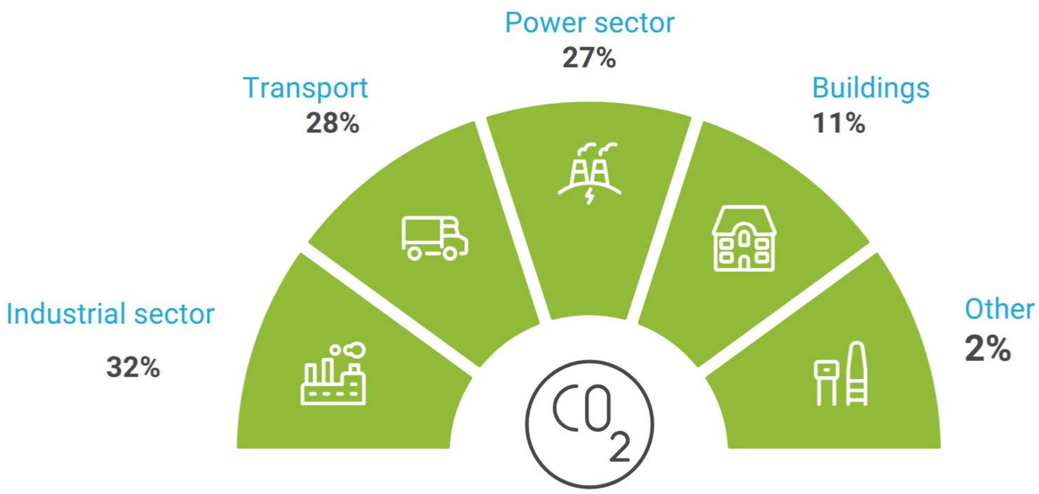
1.2.3 Industrial decarbonization and reaching net-zero pathways

Hydrogen has become a prominent feature in many countries' net-zero strategies as a climate mitigation component, primarily because it offers a pathway to decarbonize sectors where direct electrification is difficult or costly. Across national plans, hydrogen is typically positioned as a strategic fuel and industrial feedstock for sectors such as steel, chemicals, refining, and heavy transport, while also being explored as a tool for long-term energy storage and energy system flexibility. However, most strategies emphasise that hydrogen should be used selectively on priority sectors, given its high cost, infrastructure requirements, and the efficiency losses associated with converting electricity into hydrogen and then back into energy.

Pakistan's emissions have seen an increase of 140% (land use emissions are not considered) from 1990-2017, driven mainly by CO_2 emissions from fuel combustion. Industry is the largest contributed to energy related emissions (32%), followed by transport (28%) and electricity generation (27%) presented in Figure 8 (Climate Transparency, 2020).From 2010 to 2022, overall GHG emissions have also increased in both the energy and industrial sectors presented in Figure 8.

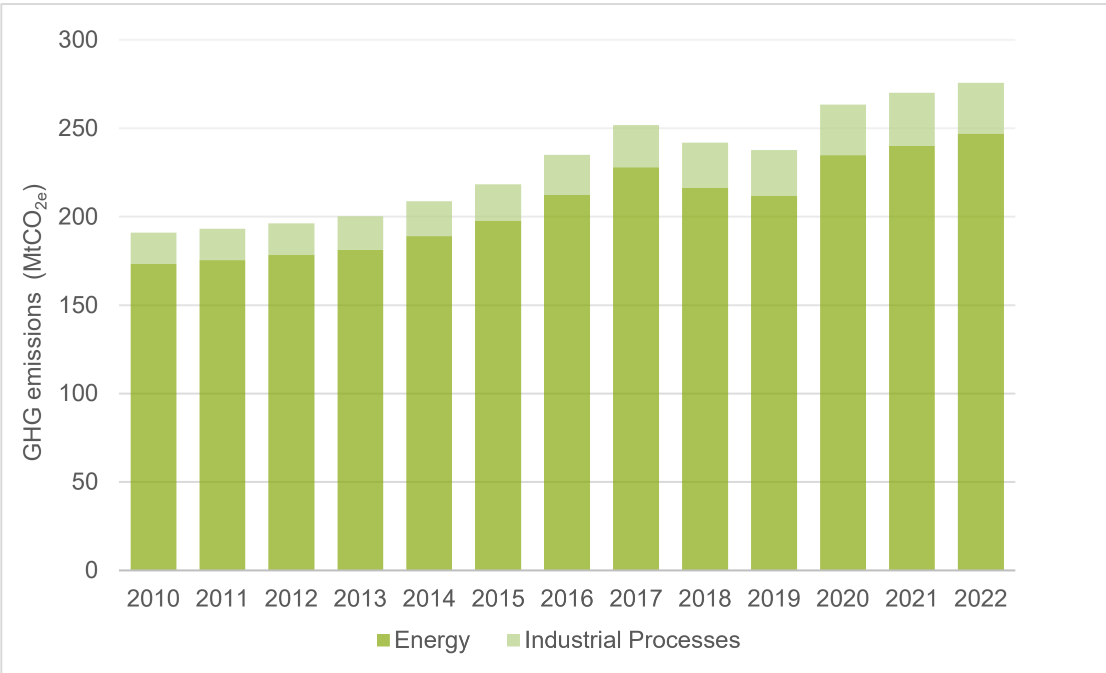
Energy-sector emissions increased by about 30%, reflecting growing energy demand was met by an increase in fossil-fuel based generation mainly RLNG, oil and coal while industrial process emissions increased around 38% indicating expanding production (Climate Watch, 2026).

Figure 8: Annual CO_2 emissions from fuel combustion in Pakistan ($MtCO_2$/year) by sector



Source: Author's compilation based on Climate Transparency (2024)

Figure 9: GHG emissions trend (2010-2022) for energy and industrial processes

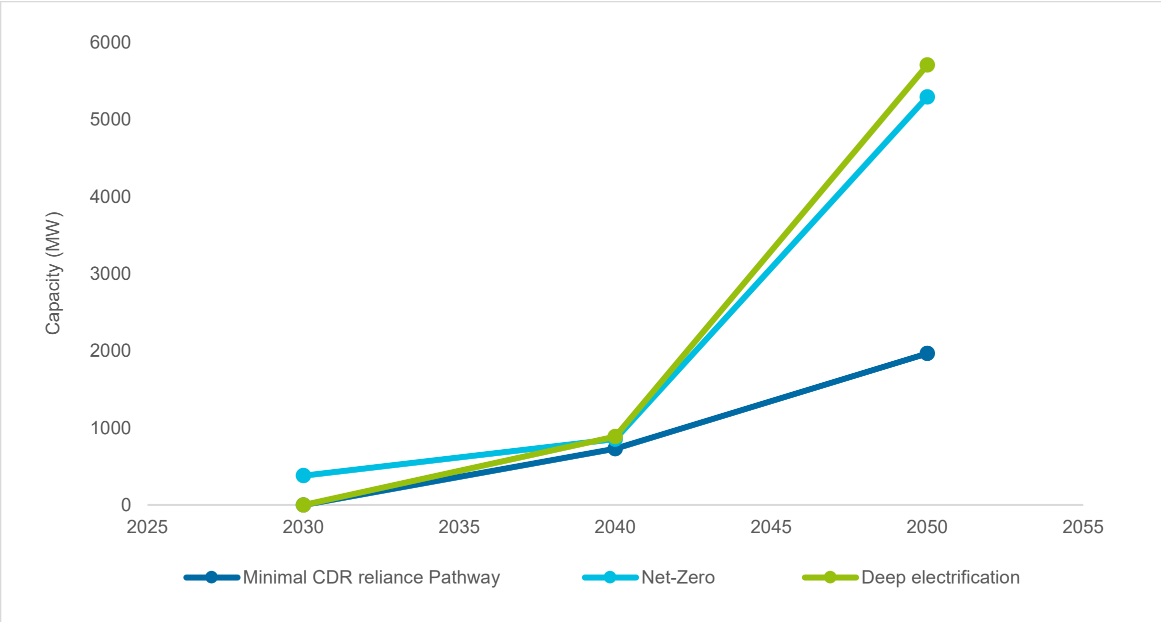


Source: Author's compilation based on Climate Watch (2022)

In relation to mitigation strategies for industrial emissions, Climate Analytics assessed multiple decarbonization pathways for Pakistan. Under the Minimal Carbon Dioxide Removal (CDR) Reliance pathway, industrial energy emissions are reduced by 95% below 2021 levels by 2050, enabled by a full coal phase-out by 2040 and a steep decline in oil and gas use. Over the same period, renewables-based electrification increases from 13% of industrial energy demand in 2022 to 53% by 2050. Clean hydrogen requirements differ by pathway. The CDR pathway implies a need for approximately 730 MW by 2040 and up to 1,965 MW by 2050 as shown in Figure 10. More stringent net-zero and deep electrification pathways require earlier and higher scale-up, rising from around 380 MW by 2030 to approximately 5,000–5,700 MW by 2050 (Climate Analytics, 2025).

To achieve its climate mitigation objectives, Pakistan's hydrogen strategy must connect near-term NDC implementation with the deeper structural transformations needed to reach net-zero. To follow a 1.5°C-compatible pathway and meet its conditional NDCs, Pakistan would need GHG reductions of up to 90% by 2050 (Climate Analytics, 2025), implying deep domestic emissions cuts alongside limited, credible removals. By prioritising hydrogen deployment in the industrial process, energy, and transport (long haul), use of hydrogen could be pivotal for achieving these reductions.

Figure 10: RES hydrogen capacity needs in industry for 2030, 2040, 2050 scenarios



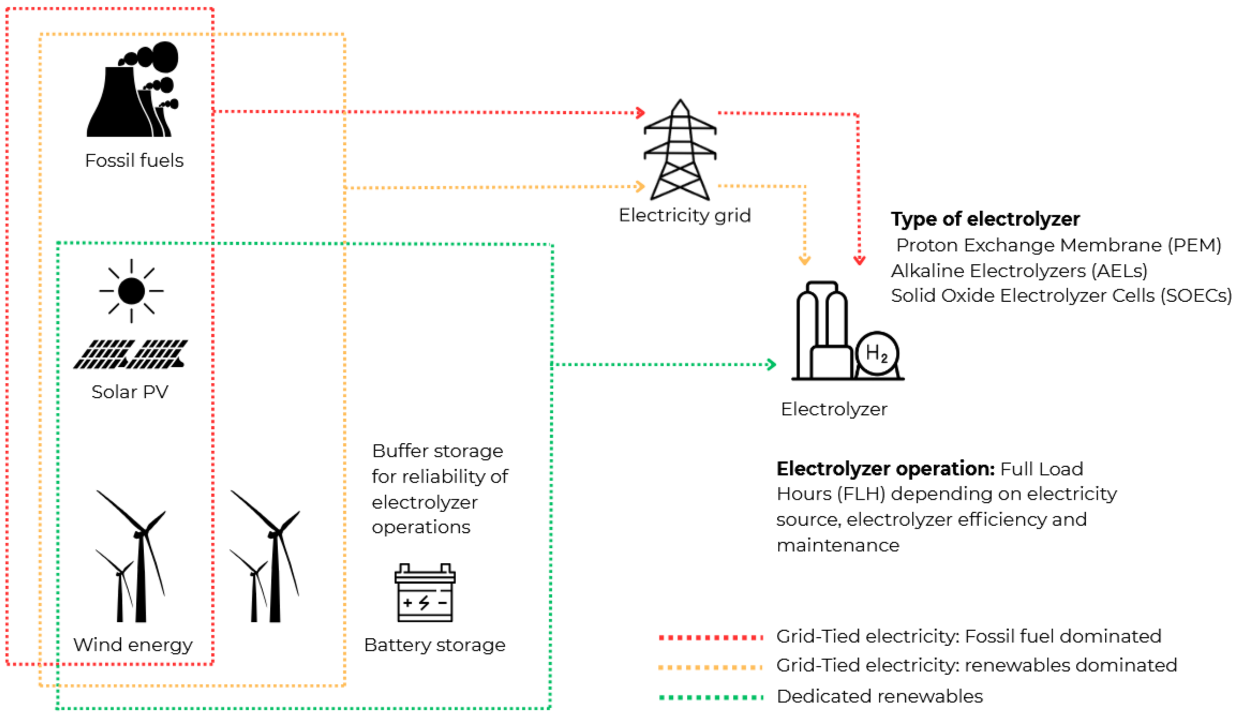
Source: Author's compilation based on 1.5º National Pathway Explorer (Climate Analytics, 2025)

This widening ambition gap suggests that a coherent hydrogen strategy can strengthen Pakistan's ability to implement its NDCs while establishing a credible pathway towards an economy-wide net-zero. It can also guide investment by coordinating infrastructure planning and aligning hydrogen production with renewable energy expansion in the country. This reduces the risk of fossil fuel lock-in and can ensure that hydrogen contributes effectively to emissions reductions.

2 Technical analysis

RES hydrogen is produced through the use of renewables-based electricity for splitting water into hydrogen (H_2) and oxygen (O_2) in an electrochemical reaction known as electrolysis. The final electricity consumption is typically 50–55 kWh per kilogram of hydrogen production from electrolysis dependant on the efficiency of electrolyzer technology (Telsche Nielsen, 2024).The optimal RES hydrogen production depends on several factors starting from electricity supply (grid-tied vs off grid), system design i.e. (renewable profiles, and energy and hydrogen storage options, and economic optimization (considerations full-load hours vs. CAPEX of RES-E and electrolyzer), usually defined as the technical parameters of hydrogen production plant assembly. Broadly the technical analysis of RES hydrogen potential is categorized into: Production, transport and storage.

Figure 11: Schematics of electricity supply options for electrolyser operation



Source: Author’s compilation

2.1 Production

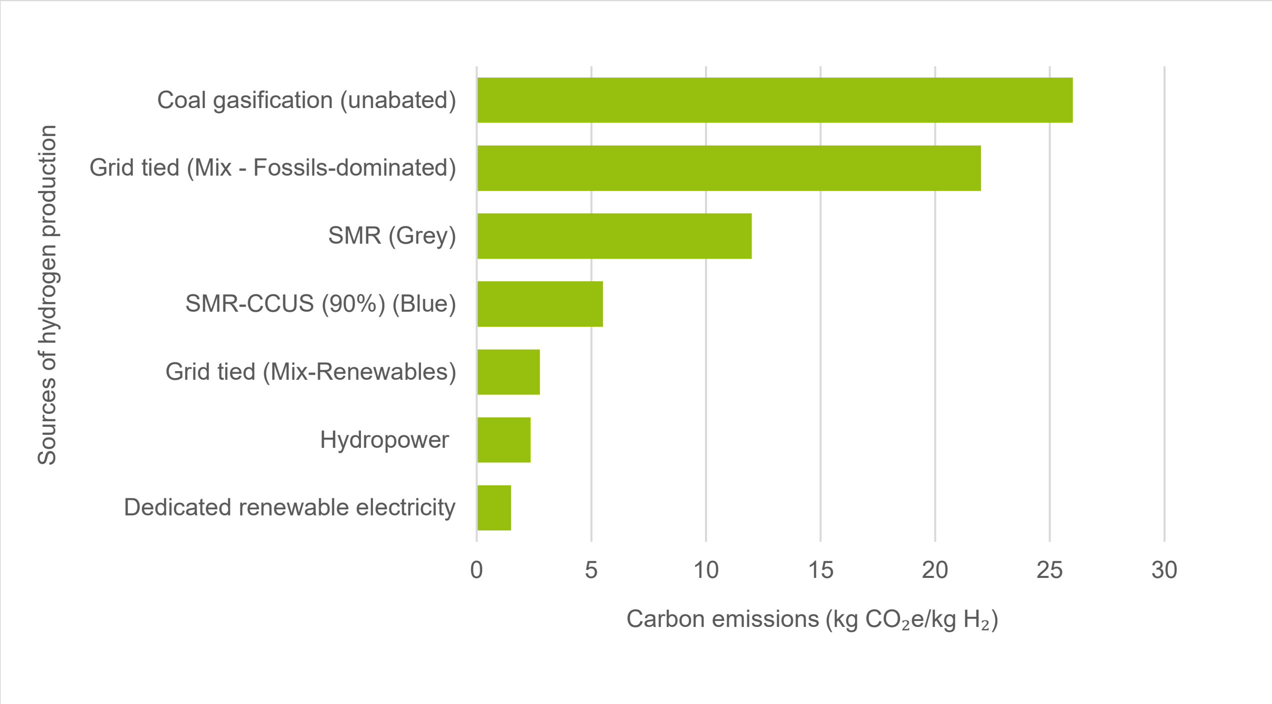
2.1.1 Sources of electricity

a) Grid-tied hydrogen

The grid-tied hydrogen refers to producing hydrogen from electricity sourced through the main or national grid. Figure 12 defines the categorization of electricity supply source considering that grid electricity often comes from a mix of multiple energy resources. The carbon footprint of grid-tied hydrogen depends strongly on how that electricity is produced and then grid becomes a defining factor on the emissions associated with hydrogen production. Grid tied electricity can be cleaner if renewable energy is dominated or solely used within the grid.

If the grid uses mainly fossil fuels i.e natural gas, oil or coal, the electricity has a high emission factor of 400–900 grams of CO_2 equivalent per kWh of utilization highlighted in Figure 12.If the grid is dominated by renewable or nuclear energy, the emission factor can fall below 100 g CO_2e/kWh. However, IEA reports that emissions should be less than 200-240 g CO_2/kWh for emissions to be lower than steam methane reforming (IEA, 2024).

Figure 12: Carbon emissions (kg CO_2e/kg H_2) of different hydrogen production



Source: Author's compilation based on IEA (2024)

b) Additionality

Additionality refers to construction of dedicated renewable energy projects to supply electricity to electrolysis. This ensures the origin of electricity and helps to mitigate any emissions associated with the supply of electricity. Many countries require measures to ensure additionality, largely because grid-supplied electricity still carries higher emissions. These measures also help verify the renewable origin of the electricity used (Martín, 2024).

c) Temporal correlation

Temporal correlation refers to the obligation to match hydrogen production activity with renewable electricity generation within the same time typically on an hourly basis. This means that the renewable electricity used to produce hydrogen must be generated and consumed within the same hour, establishing a direct relation between production and renewable energy use. In a renewables-dominated grid, hourly fluctuations in electricity output from sources such as Solar PV and wind power directly influence the carbon intensity of the grid, meaning that electricity consumed at different times of the day can carry vastly different emissions profiles. Temporal correlation requirements therefore try to push hydrogen producers to align their operations with periods when renewable energy generation is abundant and grid carbon intensity is at its lowest, ensuring that the hydrogen produced can be genuinely and verifiably classified as green. The parameters impacting temporal correlation are highlighted in Table 1 (Flávia Pereira Pinheiro, 2025).

Table 1: Parameters impacting temporal correlation in RES hydrogen production

Time-of-Use of renewable electricity	Temporal flexibility and co-location	Optimization of Energy Consumption
Renewable electricity from Solar PV and wind resources is intermittent with high fluctuations based on time and weather conditions i.e. solar peaks at mid-day and wind fluctuations throughout the day. Electrolyzers can be optimized by scheduling to operate when the grid's electricity mix includes a higher share of renewable electricity, which will have less carbon footprint compared to fossil fuels.	Temporal control mechanisms can include real-time carbon tracking, and electricity market signals that help electrolyzer adjust their operational hours based on carbon intensity forecasts or renewable generation patterns.	From an operational perspective, ensuring that hydrogen production occurs at times when renewable energy sources are available helps reduce overall energy costs and minimizes GHG emissions. Energy storage or grid balancing solutions (like battery storage or power-to-gas systems) can be integrated to shift hydrogen production to off-peak renewable times.

Source: Author's compilation based on Pinheiro (2025)

2.2 System design for optimized RES hydrogen production

a) Full load hours (FLHs)

In electrolyzer operation, FLHs are a key metric that reflects how many hours per year the plant operates at its nominal capacity. Many EU and IEA hydrogen roadmaps assume around 4,000–5,000 FLH for green hydrogen electrolyzers as a "typical" benchmark. Hydrogen plants using wind energy-based electricity have reported around 4,000–4,500 FLHs, for standalone Solar PV projects FLHs range from 2000-3500 due to the daily intermittency of solar availability. To maximize operational efficiency, electrolyzer operation through hybrid energy system of both solar PV and wind energy is considered optimum. However, there is no universally agreed-upon standard for full load hours (FLHs); instead, typical ranges are commonly derived from feasibility studies, energy system models, and policy assessments, highlighted Table 2 (Kost, 2024).

Table 2: Full Load Hours (FLHs) in reference to the renewable energy source

Low utilization: renewables-only, variable supply	Medium utilization: dedicated renewable mix, hybrid sourcing	High utilization: grid-connected, baseload-oriented
Around 2,000–3,500 full load hours per year. This corresponds to using surplus renewable energy such as solar PV or wind, which is intermittent.	Around 4,000–5,000 hours per year. This can be achieved when combining solar and wind resources, or when Electrolyzers are partially grid-connected but still prioritizing renewables.	Up to 6,000–8,000 full load hours per year. These values assume access to low-carbon baseload electricity (e.g. constant grid supply). However, such high utilization is often less aligned with the idea of "hydrogen from surplus renewables."

Source: Author's compilation based on Kost (2024)

b) Provision of energy storage-BESS

Use of Battery Energy Storage Systems (BESS) is an important component for the operational reliability of electrolysis. BESS acts as a buffer between intermittency of renewable energy and the electrolyzer operation. When renewable electricity exceeds the electrolyzers capacity, excess electricity can be stored in the battery. During a low renewable output period, electricity from BESS can be used to maintain stable operation. Economically, BESS adds capital costs, however, it can lower overall hydrogen production cost by optimising electricity use and reducing curtailment losses (Patrick Mößle, 2025). Overall, integrating BESS into hydrogen production plants can enhance operational flexibility and efficiency through enhancing capacity factors.

2.3 Type of electrolyzer Equipment

The electrolyzer is the central component of hydrogen production facility where electrolysis is conducted. An electrolyzer is essentially composed of a basic electrochemical cell that integrates an electrode–electrolyte assembly. When an electric current is applied to water within this cell, hydrogen is generated at the cathode and oxygen is produced at the anode. Electrolyzer technologies are distinguished primarily by the electrolyte material they employ, leading to their classification into Alkaline Electrolyzers, Proton Exchange Membrane (PEM) Electrolyzers, and Solid Oxide Electrolyzer Cells (SOECs) (IEA, 2025).

Alkaline and PEM electrolyzers are the most mature technologies (TRL-9), with Alkaline offering the lowest costs for large-scale industrial use while PEM provides higher pressure and a longer stack lifetime of up to 80,000 hours. In contrast, the Solid Oxide Electrolyzer (SOEC) achieves a superior 78% efficiency but requires extreme temperatures (500-800°C) and suffers from a shorter lifespan and higher complexity. Meanwhile, Anion Exchange Membrane (AEM) technology operates at the lowest temperatures (50-60°C) but remains in the research and development phase (TRL-7) with limited data on cost and long-term durability (IRENA, 2020). Brief overview of electrolyzer comparison is given in Table 3.

Table 3: Comparison of electrolyzer technologies

Electrolyzer type	Alkaline	PEM	SOEC	AEM
Operating temperature (°C)	60-80	70-90	500-800	50-60
Operating pressure (Bar)	30	70	-	-
Efficiency %	61	59	78	62
Stack Lifetime (h)	60,000	50 000-80 000	< 20 000 hours	> 5 000
Technology Readiness Level (TRL)	TRL-9 Market uptake	TRL-9 Market uptake	TRL-8 Demonstration	TRL-7 Demonstration
Pros and cons	They are slightly inexpensive as compared to other types making them suitable for large-	They offer high efficiency, low-temperature operation, and a compact design,	They operate at very high temperatures (up to 850 °C) and use a ceramic solid-oxide electrolyte, and the	They operate at lower temperature but still are in research and development phase. The electrode is like

	scale industrial use. However, they are sensitive to impurities and raise maintenance requirements.	but rely on precious metal catalysts such as platinum, which increases their cost.	systems remain more complex, costly, and less technologically mature than other electrolyzer types.	PEM but is composed of Anion exchange ionomer.

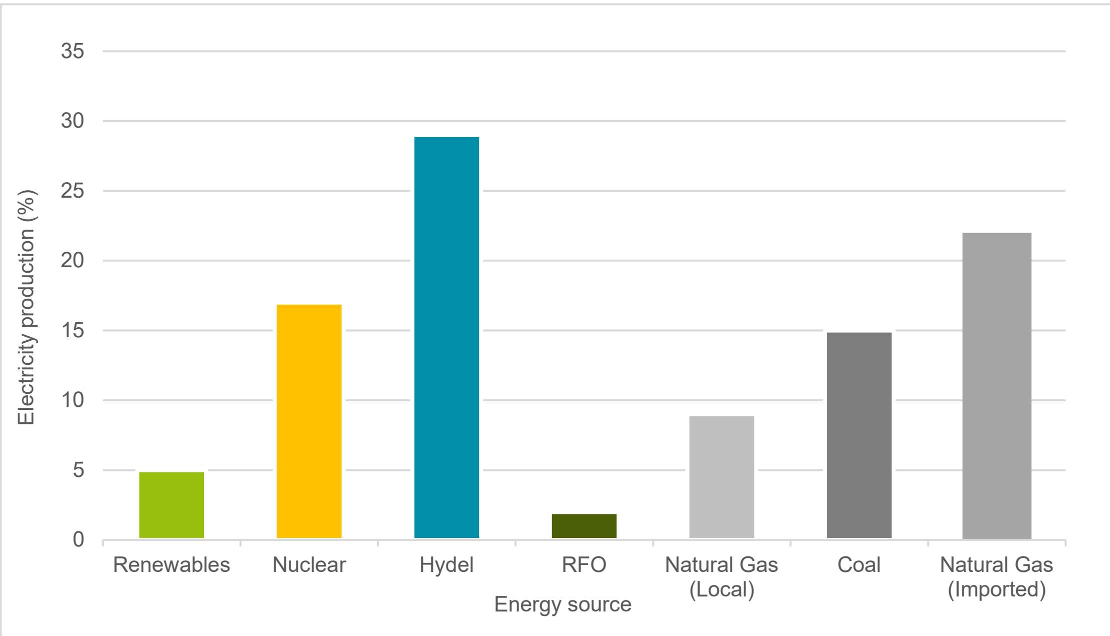
Source: Author's compilation based on IRENA (2020)

2.4 Pakistan's electricity resources for RES hydrogen production

Pakistan holds abundant resources to produce renewable electricity through solar PV and wind energy. World Bank estimates that if only about 0.071% of Pakistan's land were used for solar PV installations, it would be sufficient to supply all the country's present electricity needs (World bank, 2020).It also holds several prominent onshore wind corridors, with the top 10 % of its windiest regions recording average wind speeds of around 7.87 m/s (World bank, 2020). Initial feasibility studies for offshore wind potential also present optimistic potential, however the potential currently remains untapped (Nadeem, Naqvi, Saad, Malik, & Ahmed, 2025)

Despite having high-RES potential, the electricity mix of the country is dominated by fossil fuels elaborated in Figure 13. Currently renewables-based electricity is only 5 % (6.85 TWh) of the centralized grid corresponding to 3 GW (1.3 GW Solar and 1.8 GW Wind) out of 46 GW of dispatchable installed capacity (Renewables First, 2025).This situation makes the grid tied renewable electrolysis questionable as it might emit more than SMR process (see Figure 12:). However, for remote regions without access to electricity, the development of dedicated renewable energy infrastructure for hydrogen production could serve as an additional co-benefit; nevertheless, even in such cases, the electricity source must remain exclusively renewables based.

Figure 13:Pakistan's electricity mix (FY'2024)



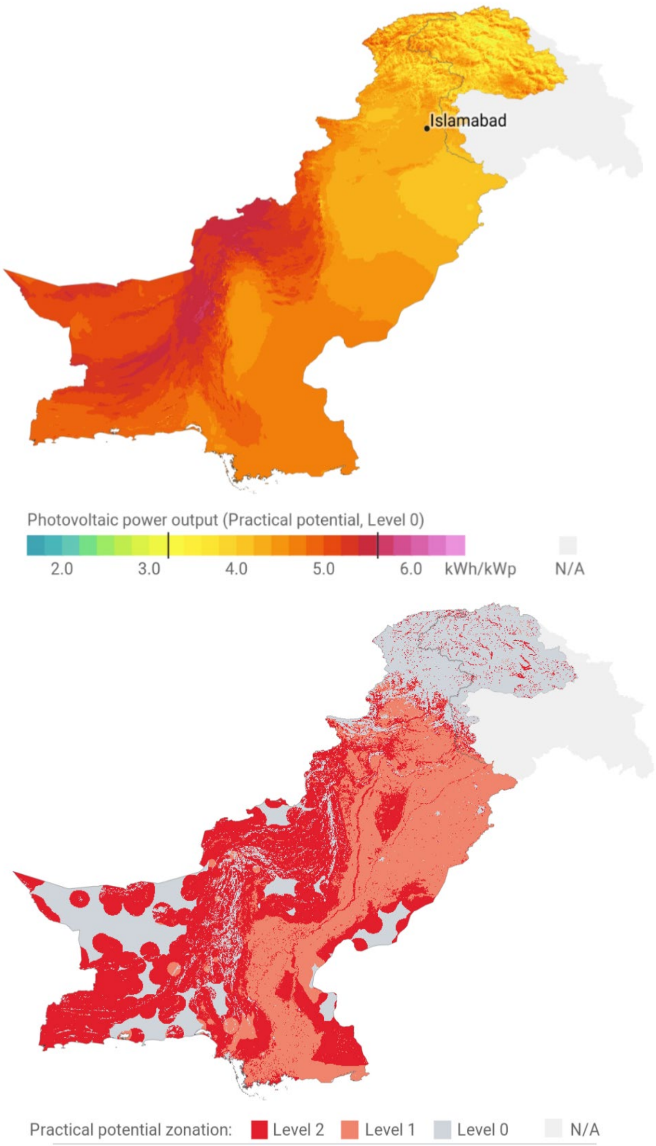
Source: Author's compilation based on Renewables First (2025)

2.4.1 Solar PV potential in Pakistan

The solar PV potential is by far the most readily accessible source for electricity generation in Pakistan, with an average daylight duration of about 8.5 hours, estimates suggest geographical potential of solar PV in Pakistan around 32,900 TWh/year (Khatri, Harijan, & Uqaili, 2022). Most solar resource assessments indicate that both Direct Normal Irradiance (DNI) and Global Horizontal Irradiance (GHI) are high across much of the country. The highest values are recorded in the southwestern region, particularly in Balochistan exhibited in Figure 14 .Majority of locations present level 2 of solar PV potential according to ESMAP.

On a provincial scale, Balochistan exhibits the greatest solar PV potential nationwide, with values reaching around 5.8 kWh/day. This is followed by Sindh and southern Punjab, where PV potential ranges from 4.5 to 5.4 kWh/day shown in Figure 14. In contrast, northern Punjab, Khyber Pakhtunkhwa, and Gilgit-Baltistan have comparatively lower potential, between 3.4 and 4.4 kWh/day (ESMAP, 2020).

Figure 14: Solar PV potential by Global Solar Atlas by ESMAP



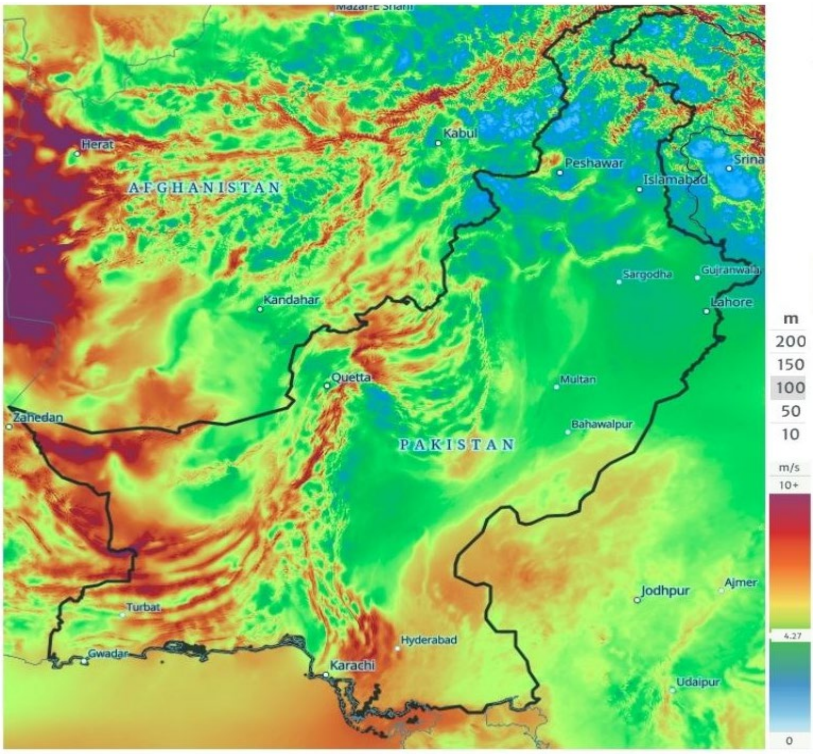
Source: ESMAP (2020)

2.4.2 Wind energy potential in Pakistan

a) Onshore wind

Cumulatively, Pakistan has 349 GW of exploitable wind energy potential based on geographical assessment of wind energy resources (Raza et al, 2022). However, currently only 1.8 GW of wind power plant have been installed (Renewables First, 2025). In the early 2000s, extensive data was collected by Pakistan Meteorological Department that covered coastal locations in Sindh and Balochistan and reported 11 GW of exploitable potential in Gharo Corridor (PMD, n.d.). Figure 15 shows the wind energy potential highlighted by Global Wind Atlas (ESMAP, 2026)

Figure 15: Wind speed (m/s) mapped all over country at 100 m by Global Wind Atlas



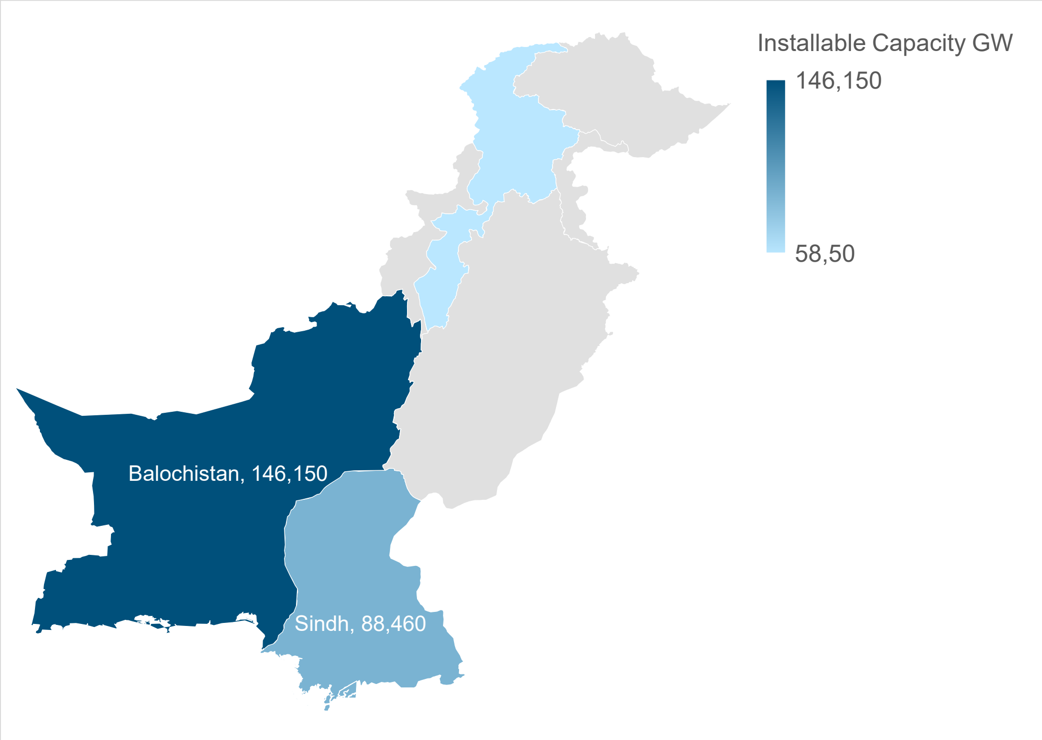
Source: Global Wind Atlas (GWA 4.0; accessed 22/07/2026)

Sindh's wind resource has been strategically developed through the establishment of the Gharo–Jhimpir corridor, which now hosts most the province's wind power installations. Within this zone, land was allocated for 18 Independent Power Producers (IPPs), each with a planned capacity of 50 MW, across sites including Gharo, Jhimpir, Lakha, Kuttikun, and Bhambore. However, Sindh is not the only province with adequate wind energy potential, Balochistan and Khyber Pakhtunkhawa also hold exploitable potentials.

Provincial distribution

Literature suggests that mainly south-eastern and western zones of Sindh and Balochistan constitute the country's most promising corridors for installing wind power plants. Sindh has approximately 12% of land area classified within the moderate-to-good wind category. Balochistan's classification is mostly in good to excellent category having the highest estimated yield of 146 GW covering only 8.4% of land area of the province. For Khyber Pakhtunkhwa, roughly 16% of the selected territory falls into the moderate-to-excellent wind class, corresponding to an estimated potential of 58 GW (Shami, 2016). Figure 16 presents the province-based distribution of installable wind energy capacity.

Figure 16: Provincial distribution of installable wind energy potential (GW)

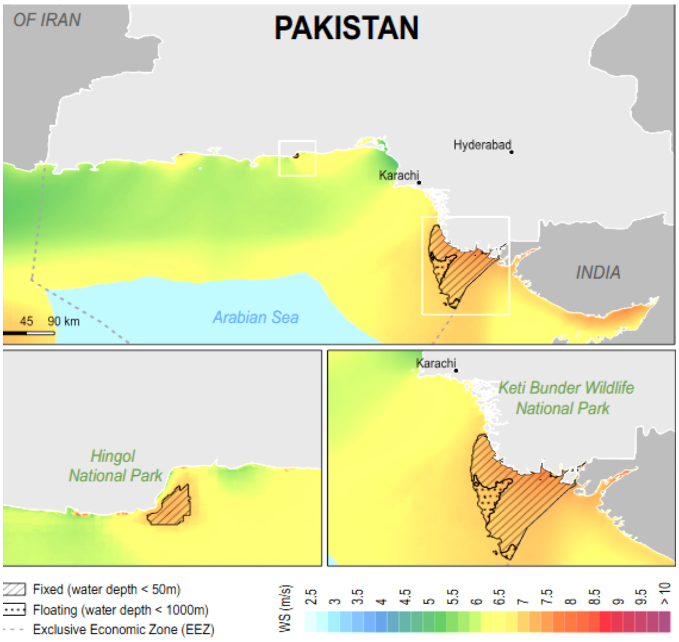


Source: Author's compilation based on Shami et al (2016)

b) Offshore wind

Discussions about offshore wind are relatively new, and Pakistan is still in the process of mapping its offshore wind energy potential. However, the World Bank Group, in its 'Going Global: Exploring offshore Wind in Emerging Markets,' has presented two suitable locations for offshore wind with a potential of 17 GW of fixed (depth < 50 m) and 3 GW of floating offshore wind (depth <1000 m) as highlighted in Figure 17 (World bank, 2024). Another literature resource refers to a capacity factor of up to 36% of exploitable offshore wind potential at Omara beach in Balochistan (Nadeem, Naqvi, Saad, Malik, & Ahmed, 2025).

Figure 17: Pakistan's offshore wind potential mapped by ESMAP



Source: ESMAP (2024)

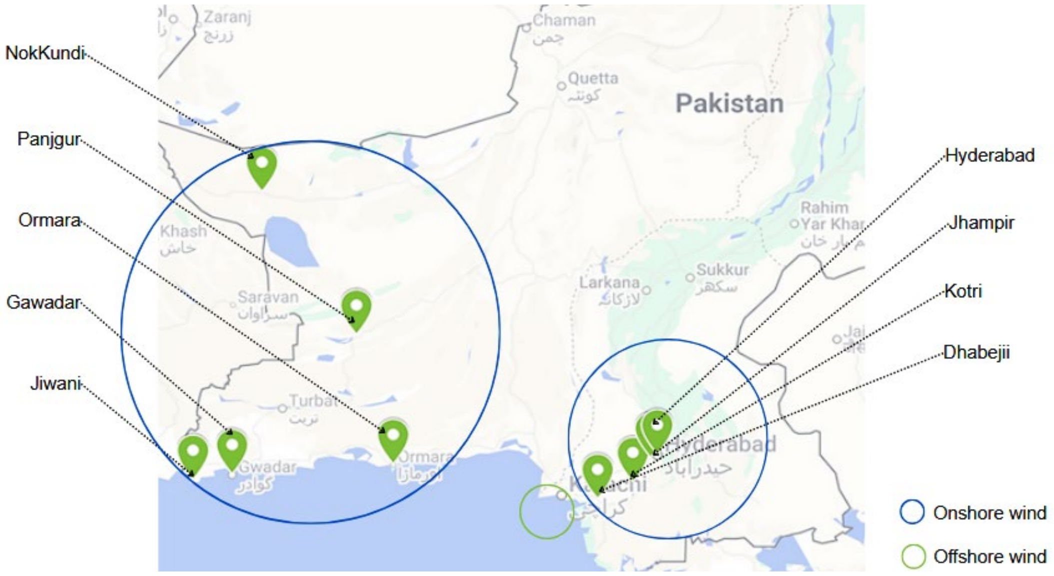
2.5 Suitable locations for RES hydrogen

This section identifies a set of promising locations in Sindh and Balochistan for renewable energy system (RES)-based hydrogen production, with particular emphasis on their suitability for solar PV and wind hybrid power plant development. These two provinces are consistently recognized in the literature as resource-rich regions for renewable energy, owing to their high solar irradiance, favourable wind regimes, large tracts of sparsely populated land, and relatively low competing land-use pressures. Building on the locations highlighted by Shami et al (2016), eight sites presented in Figure 18 across Sindh and Balochistan are selected for detailed assessment of renewable resource availability and their potential to support integrated solar-PV-based energy systems.

The rationale for focusing on these areas is that hybrid renewable configurations can provide a more stable and higher-utilization electricity supply, which is especially important for hydrogen production through electrolysis. This literature-based site selection is correlated with Renewables. Ninja simulations (Staffell, 2016), which provide hourly modelled solar PV and wind generation profiles for specific coordinates. Renewables. Ninja is designed for site-based simulation of hourly PV and wind output, and its custom simulations currently extend through the end of 2024, making it useful for comparing seasonal and diurnal generation variability across candidate sites.

Such correlation helps to verify whether the locations identified in earlier literature still exhibit strong characteristics for renewable generation under recent meteorological datasets. It also enables a more rigorous comparison of expected capacity factors, complementarity between solar and wind resources, and the overall feasibility of using these sites for continuous renewable hydrogen production.

Figure 18: Selected locations for solar PV and wind energy assessment for RES hydrogen production



Source: Author's compilation

Table 4: Constant parameters for the profile generations

Baseline year:2024		
Wind	Hub height	100 m
	Turbine model	VESTAS 100-2000
Solar	PV panel tilt	20 degrees
	Azimuth	180 degrees
	Losses	10 % (built in)
	Tracking structure	No

Source: Author's compilation based on selected parameter in Renewables Ninja

2.5.1 Locations in Sindh

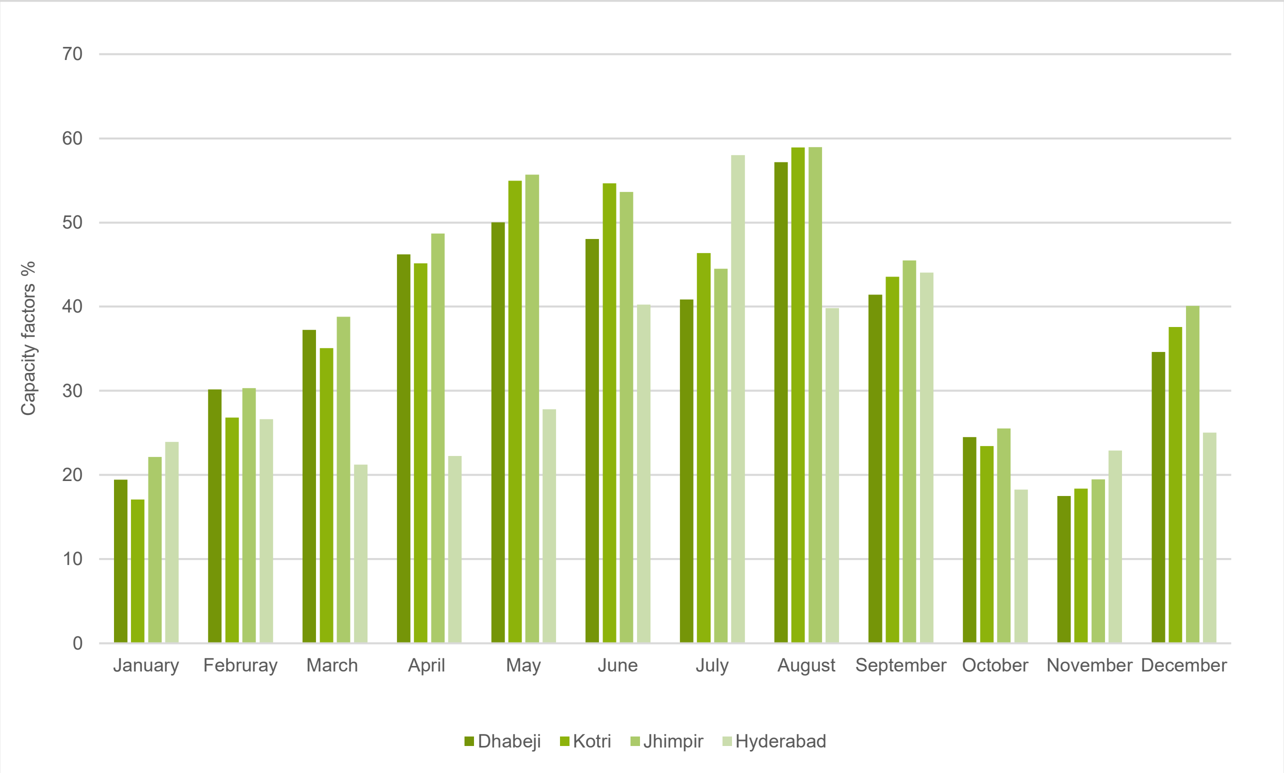
Sindh holds 12.5 % of the area in the windiest location, presenting 88.5 GW of exploitable wind energy potential. Table 5 provides information on the four selected locations i.e. Jhimpir, Kotri, Dhabeji, Hyderabad. The average capacity factor for wind in this location lie between 30-40% which indicates moderate to good potential certainly above the global average. For solar PV, they also have a capacity factor of between 17-22%, which indicates a good potential. However, the data presented is provided solely as approximate values and is not indicative of the actual site conditions.

Table 5: Coordinates for locations in Sindh

Location	Coordinates
Jhimpir	Latitude: 25.0246º; Longitude: 68.0137º
Kotri	Latitude: 25.3668º; Longitude: 68.2983º
Dhabeji	Latitude: 24.8127 º; Longitude: 67.5012º
Hyderabad	Latitude: 17.3606º; Longitude: 78.4741º

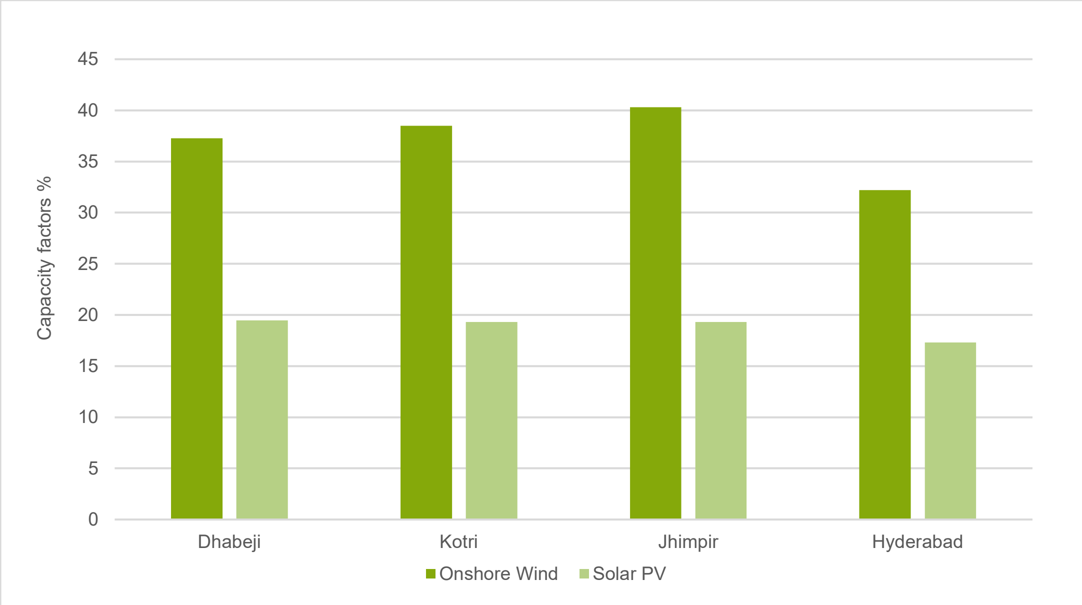
Figure 19 shows a comparison of the locations in terms of capacity factors for wind energy location. It is interesting to note that three of four locations have similar patterns of wind distributions corresponding to the monthly production of wind. However, Hyderabad shows an exception in the monthly profiles, for which there is no explanation in the literature. Figure 20 shows the comparisons of yearly average capacity factors between solar and wind power production from these selected locations in Sindh.

Figure 19: Comparison of wind energy capacity factors across the locations listed in Table 5



Source: Author’s compilation based on Renewables.Ninja

Figure 20: Average capacity factors for solar PV and wind energy for locations in Sindh



Source: Author's compilation based on Renewables.Ninja

2.5.2 Locations in Balochistan

Balochistan is Pakistan's largest province in terms of land area. However, it is also the least electrified with the lowest population density. It also has the highest wind energy potential; however, most of the potential sites are remote, inland, and unpopulated. Table 6 highlights the selected locations for their wind and solar PV energy generation profiles.

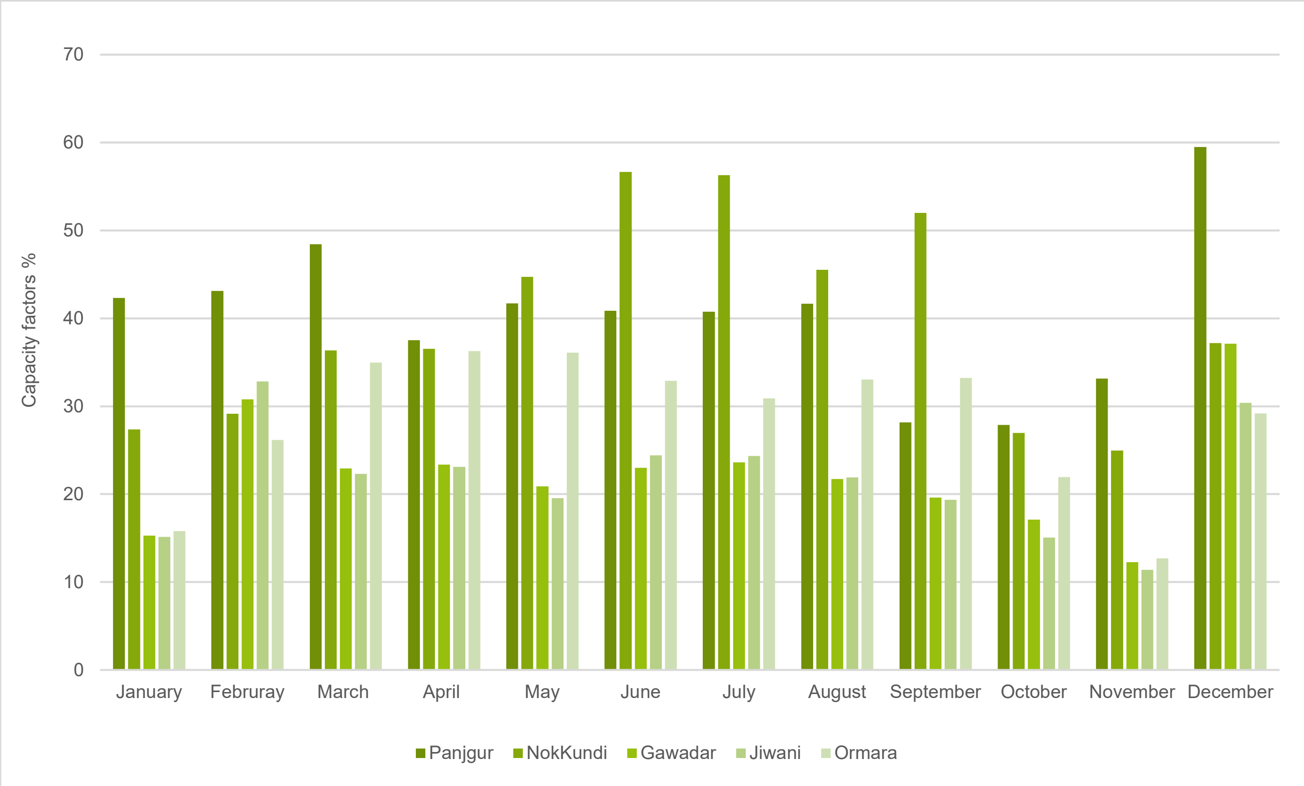
Table 6: Coordinates for locations in Balochistan

Location	Coordinates
Ormara	Latitude: 25.253º; Longitude: 64.6319º
Gwadar	Latitude: 25.14º; Longitude: 62.3255º
NokKundi	Latitude: 28.8257º; Longitude: 62.7455º
Panjgur	Latitude: 26.9616º; Longitude: 64.1153º
Jiwani	Latitude: 26.9616º; Longitude: 64.1153º

Source: Author's compilation based on Renewables.Ninja

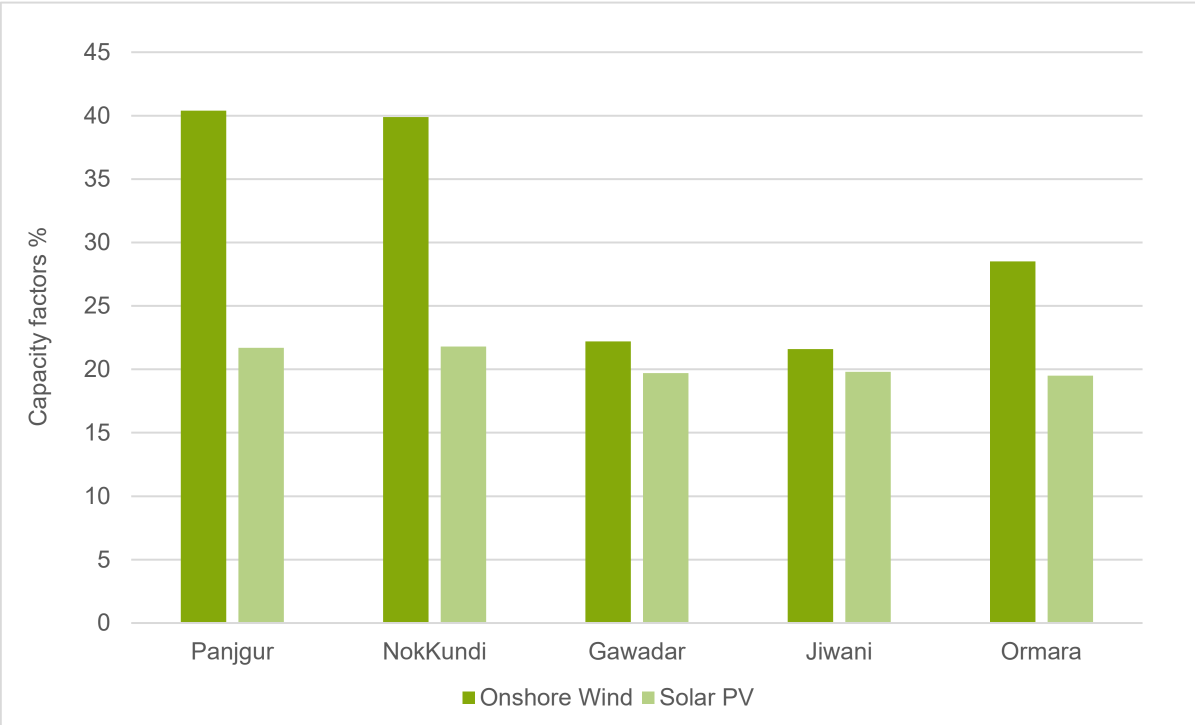
The inland regions of NokKundi and Panjgur show higher capacity factors for wind and solar. NokKundi's recorded average wind speed of 6.4 m/s at a height of about 50 m throughout the year (Hussain, Hussain, & Khan, 2021). The coastal locations at Jhimpir and Gwadar show limited potential for onshore wind. Figure 21 shows the comparison of solar PV and wind power capacity factors in the selected locations.

Figure 21:Yearly wind energy capacity factors for locations in Balochistan



Source: Author's compilation based on Renewables.Ninja

Figure 22: Average capacity factors for solar PV and wind energy for locations in Balochistan



Source: Author's compilation based on Renewables.Ninja

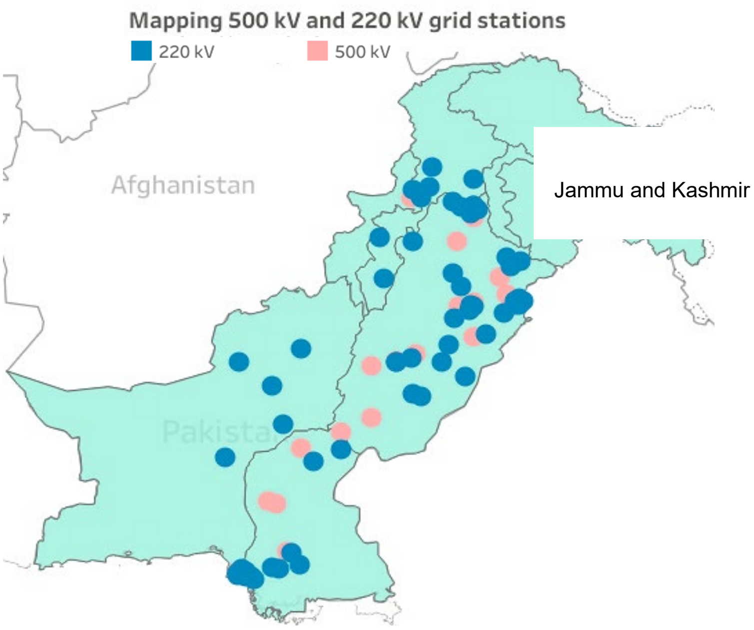
In conclusion, most of the selected sites have strong wind and solar PV resources and are well positioned for cost-effective RES hydrogen production. High renewable potential enables continuous, low-carbon electricity supply for electrolysers, improving efficiency and lowering overall costs. Abundant wind and solar PV can provide stable generation through hybrid power plant in which solar PV offers high daytime output, and wind produces reliable electricity. Together, these resources support scalable hydrogen production with minimal emissions.

2.6 Availability of grid Infrastructure

Large-scale renewable energy deployment depends on efficient grid transmission systems, particularly dedicated high voltage transmission lines, i.e 132 kV, 220 kV and 500 kV lines highlighted in Figure 23 (Renewables First, 2026).However, in many of the locations mentioned above, the availability of adequate grid and transmission infrastructure remains limited at present. The Gharo and Jhimpir areas previously underwent rehabilitation of several 132 kV lines and the installation of additional 220 kV infrastructure to support the integration of wind power plants (IRENA, 2018).

Pakistan also has the highest transmission and distribution losses, estimated at about 20.5% significantly above the global average, that further strain an already outdated and overloaded grid, worsening overall system stability. This presents a challenge and leads to the consideration of establishing dedicated renewable energy plants directly connected to electrolyzers, along with other reliable power solutions such as BESS, to enhance security of supply.

Figure 23:Grid Stations of 220 kV and 500 kV available in Pakistan



Source: Renewables First (2026)

2.7 Hydrogen transport and storage

Hydrogen is a highly volatile, flammable, and light weight molecule having density of 0.089 g/l at normal temperature and pressure at STC. That makes hydrogen extremely prone to leakage, embrittlement, and storage becomes quite challenging. For hydrogen trade, storage is a critical enabler of a reliable hydrogen market, providing flexibility between production, transport, and end use. As storage needs vary by scale and application, no single technology is suitable for all use cases. Pressurized tanks are the most practical solution for storing smaller volumes of hydrogen. Liquid Organic Hydrogen Carriers (LOHCs) offer the advantage of utilizing existing oil transport infrastructure, but they require additional energy for hydrogenation and dehydrogenation processes and periodic replacement of degraded carrier materials. For large-scale, long-duration storage, salt caverns are currently the most mature option, although their deployment requires suitable geological conditions, significant upfront investment, and long development timelines.

The German experience in hydrogen infrastructure demonstrates the importance of integrating hydrogen transport and storage planning to ensure an efficient and reliable infrastructure network. Coordinated development helps avoid bottlenecks and optimizes investments across the value chain. The Governments should address first-mover disadvantages by introducing risk-sharing mechanisms, financial incentives, or regulated cost-recovery frameworks. Such policy measures can reduce investment uncertainty, accelerate infrastructure deployment, and support the development of a competitive and resilient hydrogen market.

Currently, there are multiple methods for hydrogen storage, and the most popular one is high pressure gaseous storage. Other methods include low-temperature liquid hydrogen storage, liquid organic hydrogen carriers and solid hydrogen storage, summarized in Table 7. All these methods have their own limitations, challenges and cost differences (Xinrong Yan, 2024).

Table 7: Hydrogen transportation and storage methods

Method	High pressure storage	Low-temperature liquid hydrogen storage	Liquid Organic Hydrogen Carriers LOHC	Solid hydrogen storage
Description	The density of H_2 is increased through compression to pressures in the range of 350–700 bar. It is again categorized as low pressure (≤350 bar) and high-pressure storage (>350 bar) maximum up to 700 bar.	Hydrogen is liquefied to increase its density. At around –253 °C, hydrogen transitions from a gas to a liquid, and it must be maintained at this cryogenic temperature during storage and transport to prevent it from vaporizing	It operates on the principle of reversible chemical reaction in which hydrogen is stored in aromatic hydrocarbons to facilitate long distance transport. Upon use on consumer end, H_2 is release via dehydrogenation reaction	H_2 is stored in efficient solid state storage materials that have higher energy storage densities. Currently, most are based on metal alloys commonly known as metal hydrides.
Pros	It is the widely used technology in refuelling stations around globe. Simple equipment structure and fast filling and releasing speeds	Low cost of transportation as compared to high pressure over high distances.	Hydrocarbon carriers offer high stability and safety Beneficial for long distance transportation	The method offers high safety, recyclability and efficient transport options as compared to other methods.
Cons	The biggest disadvantage is the gaseous nature of H_2 in this method which	High energy consumption for liquefication, volatility and complex conversion mechanism	High energy requirements on the input side	High sensitivity to external conditions. High performance of solid-state materials,

	poses safety risk of leakage and explosion.	-Manufacturing difficulty and high cost	Low efficiency and low purity due to side reactions. High reconversion losses.	fast H_2 absorption/ desorption. No large-scale applications have been reported yet.
Transport mode	Trailer Pipelines	Liquid hydrogen ships	Standard crude oil tanker and other crude oil infrastructure	Trucks

Source: Authors compilation based on Yan (2024)

2.7.1 Gas pipeline infrastructure

A well-integrated pipeline infrastructure is crucial for delivering hydrogen reliably and at scale from production regions to demand hubs, i.e industrial clusters. Although natural gas and hydrogen differ significantly, modifications to meet pressure needs by adding compressors can make existing systems suitable for hydrogen transport. At present, gas pipelines provide the most efficient and cost-effective mode of delivering hydrogen in gaseous form in high volume up to 6000-10,000 km (NWR, 2021). However, transporting hydrogen could require pipeline refurbishments, including the installation of compression components and other necessary upgrades. Overall, the cost of retrofitting existing gas pipelines is approximately 10-35% of the cost of constructing new gas infrastructure (DNV, 2023). The assessment around “European hydrogen backbone infrastructure” reported that transporting hydrogen over 1,000 km on a typical onshore section can cost up to €0.11–€0.21 per kg of hydrogen. Figure shows the difference in terms of LCOH between new and repurposed pipelines for hydrogen transmission. For small pipelines, distances of up to 200 km are considered and the remaining distances are between 200 km and 1000 km. The pipe sizes are referenced as: small (20 inch), medium (36 inch) and large (48 inch) respectively (European Hydrogen Backbone, 2023).

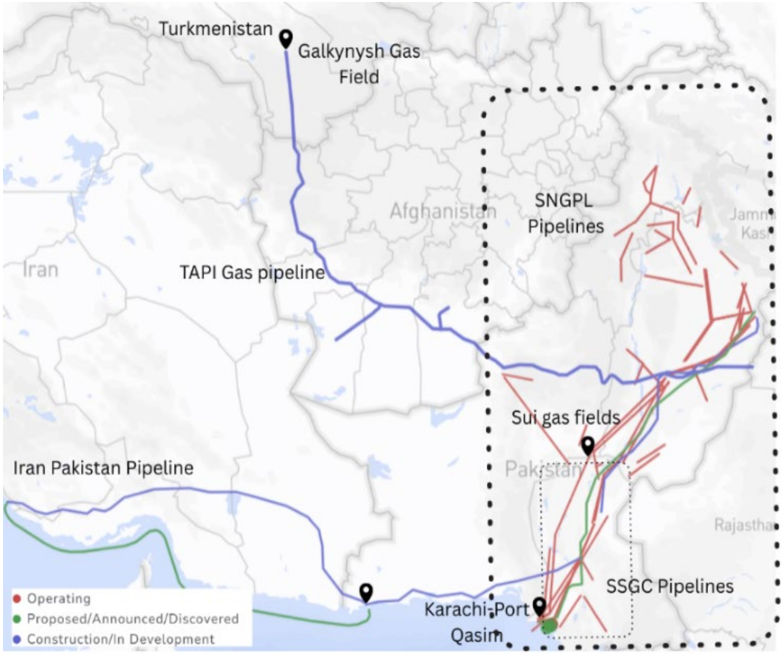
Figure 24: Cost comparison between new and repurposed pipelines

Pipeline specifications		GW[28]	Pipeline Capex	Compression Capex	LCOH	Unit
Small	New	1.2	1.5	0.09	0.16	€/kg/200km
	Repurposed	1.2	0.3	0.09	0.05	
Medium	New	4.7	2.2	0.32	0.35	€/kg/1000km
	Repurposed	3.6	0.4	0.14	0.12	
Large	New	13	2.8	0.62	0.19	
	Repurposed	13	0.5	0.62	0.09	
Offshore Medium	New	4.7	3.7	0.54	0.60	
	Repurposed	3.6	0.4	0.23	0.15	
Offshore Large	New	13	4.8	1.06	0.32	
	Repurposed	13	0.5	1.06	0.14	

Source: European Hydrogen Backbone (2022)

Pakistan has an established gas pipelines infrastructure, spanning over 13,737 km for transmission and 203,625 km for the distribution of gas pipelines, as shown in Figure 25. The gas pipelines are used to deliver natural gas from local and imported sources for domestic and industrial consumers. There are two integrated entities: one, addresses the demand centres in the South called the Sui Southern Gas Company (SSGC) and the other is located in the North and is called the Sui Northern Gas Pipeline (SNGPL). Pakistan's current natural gas network offers strong potential for transporting hydrogen to local demand hubs by converting existing systems and developing dedicated pipelines.

Figure 25: Pakistan's gas transmission infrastructure



Source: Global Energy Monitor (2025)

Regional energy security initiatives like the Turkmenistan–Afghanistan–Pakistan–India (TAPI) pipeline further demonstrate the role of infrastructure in enabling inter-regional energy trade. The planned 1,814 km pipeline in Figure 26, connecting Turkmenistan's Galkynysh gas fields with markets in South Asia, can offer a future-oriented pathway for expanding hydrogen transmission capabilities within the wider Central and South Asian region. While these expansive regional cooperation projects are inherently exposed to political and security risks, they remain strategically valuable for long-term energy transport and trade (Asian Development Bank, 2020). In the current scenarios, integrated infrastructure networks, upgrading priority corridors, and aligning new development projects with emerging regional demand centres can help Pakistan's position as a regional energy partner and enable participation in future green hydrogen value chains through mutually beneficial bilateral and regional trade frameworks.

2.8 Discussion

Pakistan's renewable energy assessment shows strong potential for RES hydrogen, particularly regarding solar and wind resources concentrated in Balochistan and Sindh. The identified locations exhibit high solar irradiance and reliable windy regions, making them strategically valuable for utility-scale projects. Some locations in Jhimpir-Gharo corridor are already in the infrastructure development phase to develop hybrid wind and solar PV projects. The strategic utilization of this renewable energy potential can reduce dependence on imported fuels, enhance energy security, and support long-term economic resilience. This is further elaborated in the economic analysis.

However, successful deployment requires strengthened grid infrastructure, streamlined permitting and regulations, and supportive policy landscape to safeguard investor interests. Key considerations must also address the regional instability in Balochistan, where despite its strong renewable energy potential, many communities remain in remote areas that still lack reliable access to electricity. Community engagement and environmental consideration must also be considered to ensure equitable sustainable development. Overall, Balochistan and Sindh offer potential sites for developing Pakistan's RES hydrogen that can accelerate energy transition in country.

3 Economic analysis

This section presents an in-depth analysis of the cost of RES hydrogen production in Pakistan and export to other countries using the BOA tool v3.0.1. The tool assesses the delivery costs of hydrogen and derived PtX molecules, i.e. green ammonia, Fischer Tropsch (FT) e-fuels, methanol and green iron from 35 export countries to six import destinations. The tool provides a cost-breakdown comparison between a supplier country of PtX molecules and a demand country that requires the imports. The BOA includes default datasets for selected countries to provide a pre-feasibility-level overview, while allowing users to adjust key variables based on local conditions. Further information on the BOA is available in the accompanying documentation (Oeko-Institut, 2024). Overall, BOA supports techno-economic analysis by linking electrolyzer technology choices and renewable energy resources (solar PV/wind/hybrid) to the cost of hydrogen production and its associated export evaluation.

From an economic perspective, RES hydrogen remains significantly more expensive than fossil fuels on an energy-equivalent basis. This cost gap is driven primarily by the capital cost for RES-E generation and electrolysis, and the need for new transport and storage infrastructure for the smooth development of hydrogen supply chain. Fossil fuel energy systems, by contrast, have benefited from over a century of investment, infrastructure buildout, and economies of scale, advantages that any emerging alternative will take considerable time to overcome.

A further structural barrier is that the environmental costs of fossil fuel combustion are largely absent from market pricing, meaning that current energy price signals do not reflect the true cost of using these fuels in terms of their climate change impact. The inclusion of a carbon price, combined with strict emissions regulations and the continued decline in renewable energy costs, could significantly improve the cost competitiveness of RES hydrogen in the years ahead. Ultimately, however, achieving cost parity with fossil fuels will require more than market signals alone, it will depend on supportive policy frameworks, enabling infrastructure, and sufficient scale of deployment to drive costs down to commercially competitive levels.

3.1 Cost of hydrogen production

The price of RES hydrogen production is mostly indicated in the levelized cost of hydrogen (LCOH $/kg). Major cost contributors to LCOH are the: LCOE ($/kWh) from the deployed renewables, electrolyzer CAPEX ($), stack replacement costs, other balance of plant (BoP) components including engineering, procurement, and construction (EPC) costs. Additional minor cost components include water treatment plants, compression requirements, and land acquisition costs. It is important to note that there will always be a cost gap between desk-level estimates of LCOH and costs calculated based on actual project-based conditions. Assessments for formulating strategies and policy papers should therefore pay particular attention to avoid optimistic costs. (Agora Energiewende, 2021).

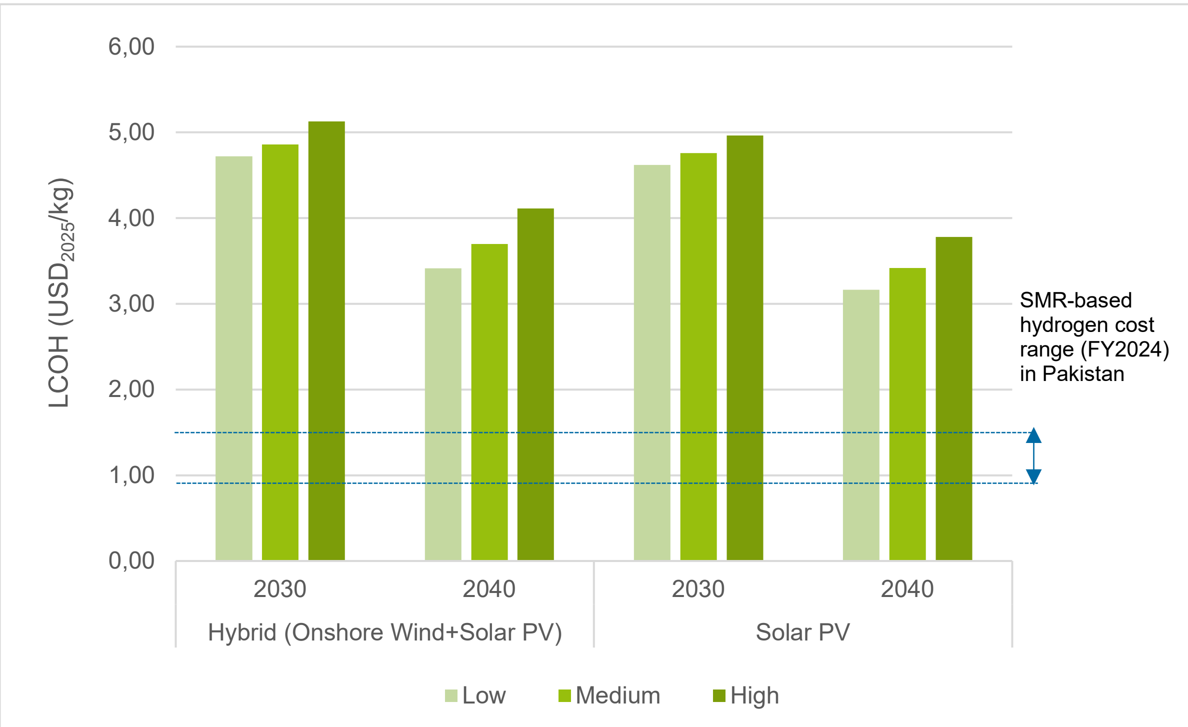
LCOH determines the economic competitiveness of RES hydrogen production as compared to other fossil-based alternatives, and it is lower in regions with strong renewable energy potentials. However, in EMDEs the cost of financing, often expressed as the weighted average cost of capital (WACC) (%) has a major influence on LCOH, since financing costs are typically higher in EMDEs compared to developed countries. The WACC represents the average financing costs of a hydrogen project, combining the cost of equity and debt, weighted by their share in the project's capital structure. WACC is not fixed and varies with broader financial market conditions: investor expectations, risk appetite, inflation and interest rate expectations, and overall market conditions influence both the cost of equity and debt. In hydrogen projects, additional factors such as policy and regulatory certainty, technology maturity, and offtake risk also have a significant impact on WACC.

3.1.1 Levelized cost of hydrogen (LCOH) in Pakistan

Pakistan shows potential for high renewable energy availability (2.4), which provides a solid foundation for producing hydrogen. However, despite favourable renewable energy landscape, LCOH is driven by high WACC; in Pakistan's case it has been between 13–18% from 2020 to onwards (Damodaran, 2026). The high WACC increases the overall project costs disproportionately, as the elevated WACC reflects underlying risks, mainly due to persistent political and economic instability. Even though the country has renewable resources, high WACC can offset much of the expected cost reduction, making hydrogen projects less competitive unless financial and fiscal conditions improve or targeted policies intervene.

An overview of the estimated LCOH based on solar PV-wind hybrid power plants is provided in Figure 26. Three cost scenarios (high, medium and low) are shown for 2030 and 2040. These scenarios are based on the renewable energy costs of 2024 and the scenario projections are extracted from Annual Technology Baseline (ATB) by NREL (2024); more details on the methodology can be found in the BOA documentation (Oeko-Institut, 2024).The three scenarios related to the advanced to conservative cost assumptions for 2030 and 2040, based on actual cost in 2024 reported by IRENA (IRENA, 2025). For hybrid (solar PV+ onshore wind) power plants, the cost estimates in Figure 26 show production costs in the range of USD 4.80–5.10/kg in 2030 and USD 3.30–4.10/kg in 2040. The cost of hydrogen produced from natural gas via SMR in Pakistan is estimated at USD 0.90–1.35/kg H_2 based on natural gas prices (PACRA, 2025). In comparison, the LCOH in both scenarios (2030 and 2040) remains substantially higher than that of conventional fossil-based hydrogen. For production only based on solar PV, the cost estimates are more favourable in 2040, ranging from USD 3.20–3.80/kg. It should be noted that LCOH extracted from BOA excludes transport costs to demand countries, reconversion costs of PtX molecules, storage needs and other losses associated with distribution.

Figure 26: LCOH (USD/kg) in Pakistan from solar PV and hybrid power plants



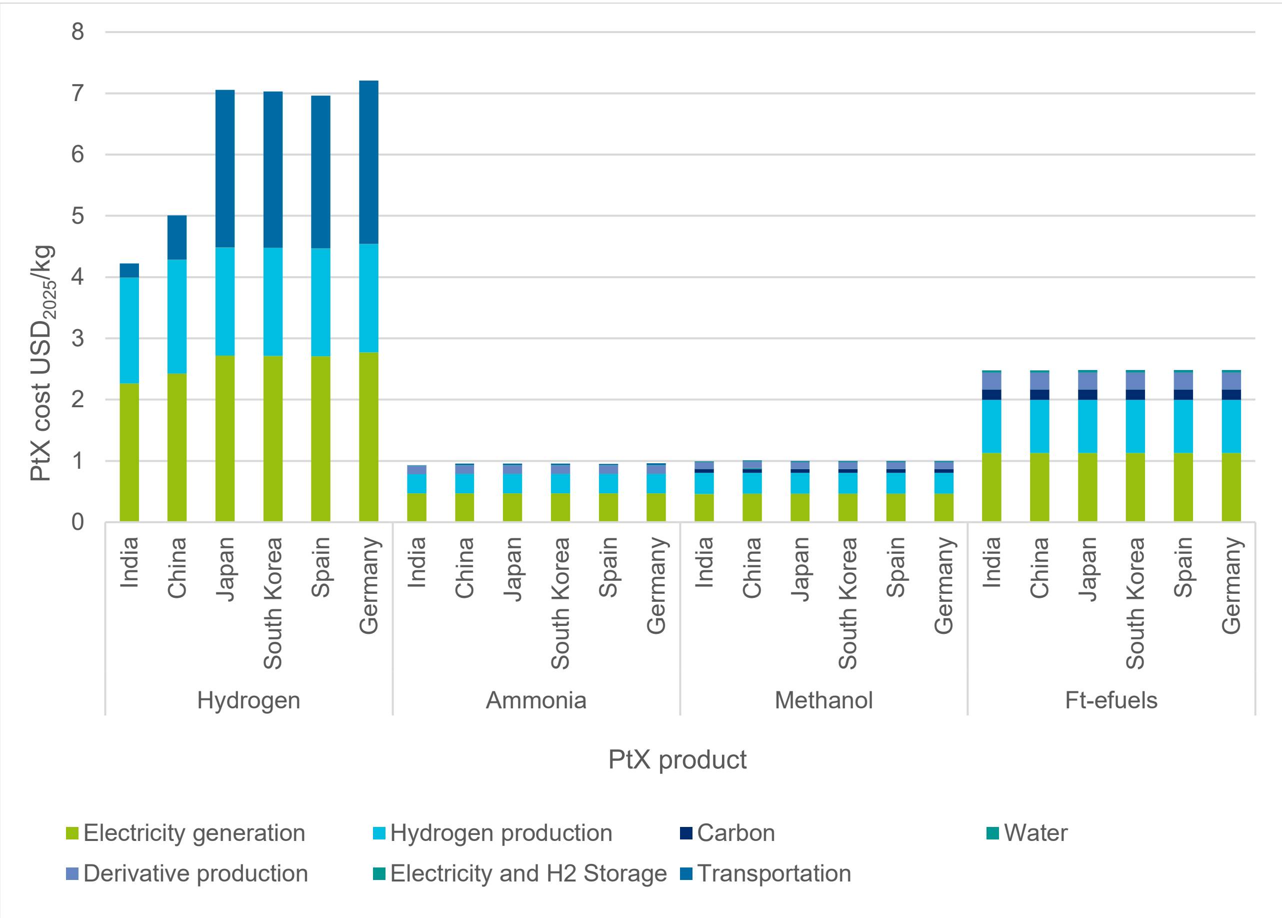
Source: Author's compilation based on BOA v3.0.1(2026); electrolyzer type: AEL; WACC:15.72%; final product: hydrogen

3.1.2 Export of PtX molecules

Delving into further PtX cost assessment, compares the export costs of PtX molecules across six prospective export markets: China, India, Spain, Germany, South Korea, and Japan. All values are expressed in USD per tonne. The import costs for hydrogen from Pakistan range roughly between USD_{2025} 4.2/kg (USD_{2025} 4,200/tonne) in India to about USD_{2025} 7.1/kg (USD_{2025}7,100/tonne) in Germany, reflecting the high costs associated with transporting hydrogen and further step involved such as liquefaction, compression and storage. For European and East Asian destinations: Germany, Japan, and South Korea, transportation adds approximately USD_{2025} 2.50–2.70/kg, which poses significant competitiveness challenges against hydrogen produced locally or from other exporters that are in proximity. By contrast, Pakistan's regional neighbours India and China benefit from substantially lower transportation costs via a possible pipeline. By comparison, hydrogen derivatives are considerably less costly to export, with ammonia and methanol each costing roughly USD 1,000/t. This indicates that handling of these products is comparatively mature, and transport costs are insignificant.

Converting hydrogen into carriers like ammonia or methanol before export is a far more practical and cost-efficient approach to tap into long-distance markets in Europe and East Asia. However, it will ultimately hinge on bringing shipping costs down and scaling up transport infrastructure.

Figure 27: Cost of exporting PtX molecules to selected countries under 2040 scenario



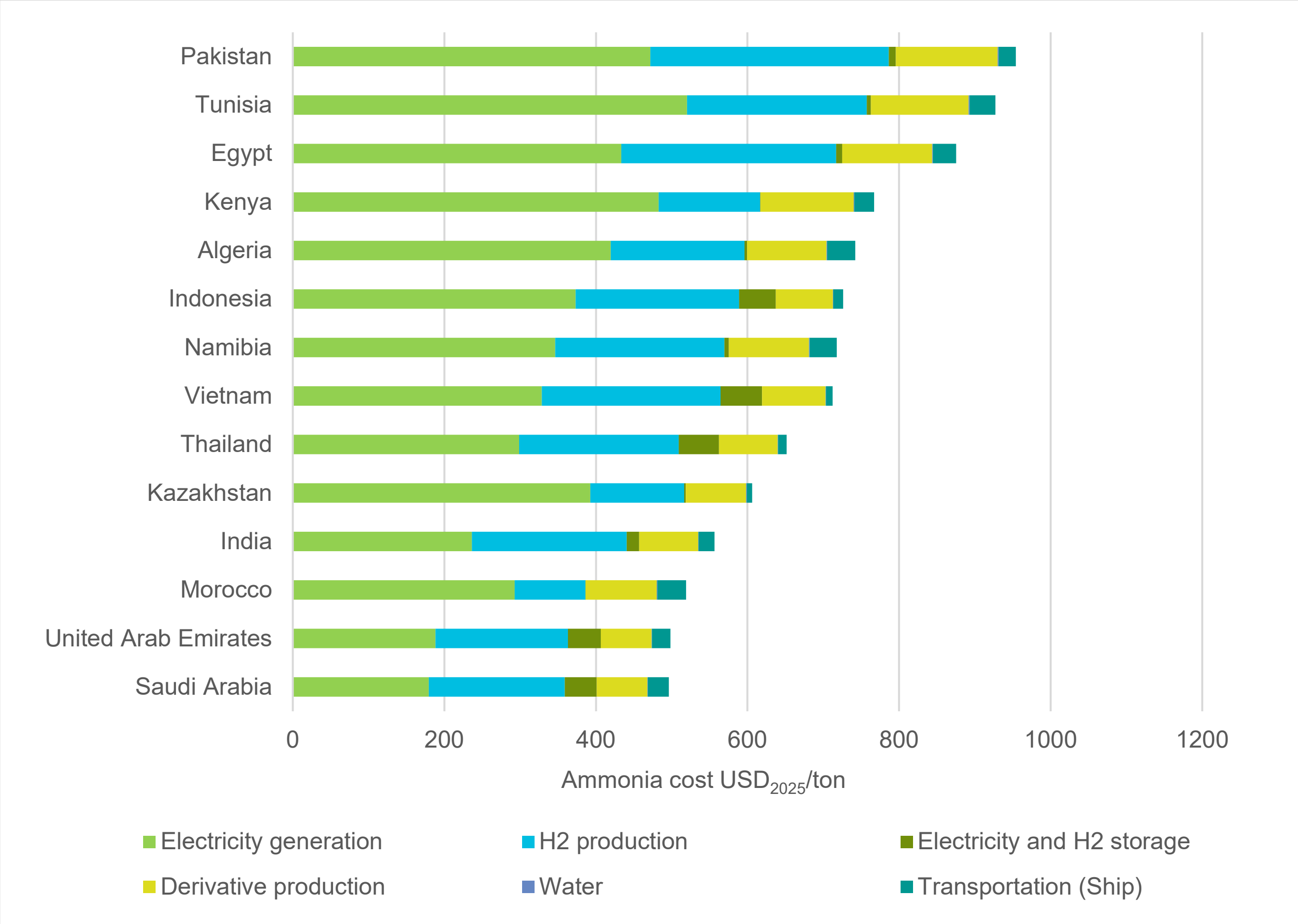
Source: Author's compilation based on BOA v3.0.1(2026); electrolyzer type: AEL; WACC:15.72%; RES (hybrid), 2040 scenario (medium)

Note: This graph is based on PtX prices; however, since energy density and conversion efficiency vary across PtX molecules, these fuels cannot be meaningfully compared on a weight basis alone but should instead be assessed in terms of energy density.

3.1.3 Cost comparison across other supplier countries

The landscape of green ammonia production costs varies substantially across countries, Figure 28 presents the import cost of ammonia to China. Regional cost estimates range from approximately USD 490/tonne for Saudi Arabia and the UAE to nearly USD 950/tonne in Pakistan. This gap indicates that Pakistan's PtX derivative production remains considerably more expensive than its regional neighbours even though its relative proximity to China keeps transport costs low. Gulf states benefit from low electricity generation costs, giving them a clear competitive advantage, while countries like Pakistan, Tunisia, and Egypt face significantly higher costs due to the elevated costs of financing. Storage, derivative production, and transportation add further costs but play a comparatively minor role. Overall, access to cheap renewable electricity appears to be the decisive factor separating low-cost and high-cost green ammonia producers.

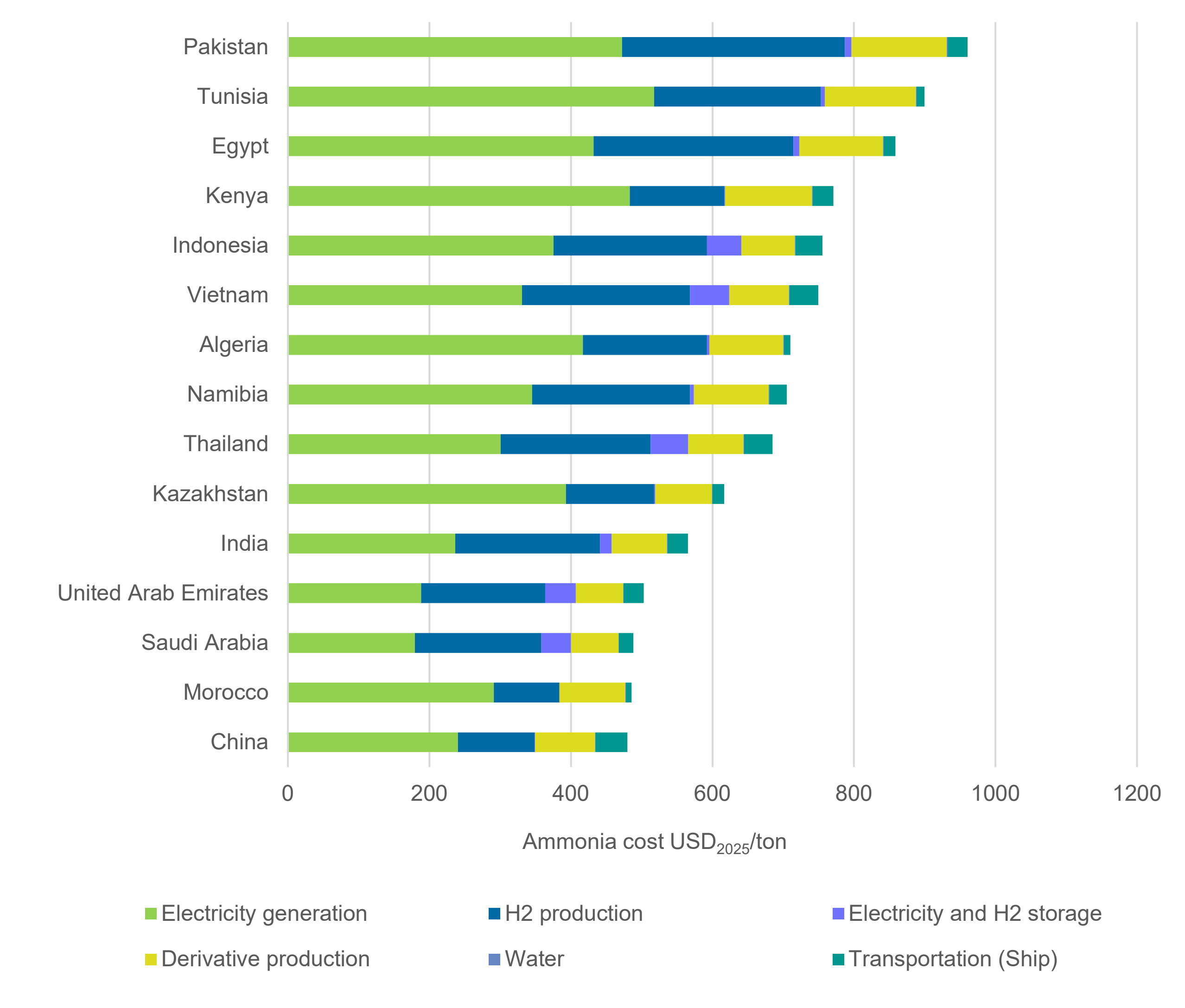
Figure 28: Cost of ammonia imports to China from selected countries



Source: Author's compilation based on BOA v3.0.3(2026); electrolyzer type: AEL; WACC for Pakistan:15.72%; RES (hybrid), scenario:2040(medium); final product: ammonia

A similar pattern emerges when comparing ammonia import costs to Germany presented in Figure 29, with Pakistan again showing no competitive advantage. Total landed costs range from roughly USD 480-488/tonne for China, Morocco, and Saudi Arabia to nearly USD 960/tonne for Pakistan. Pakistan also fares worse than Vietnam and Indonesia in this respect. Both Vietnam and Indonesia face comparable regional constraints, however, to maintain lower costs (~USD 760/ton) despite having higher transportation costs.

Figure 29: Cost of ammonia imports to Germany from selected countries

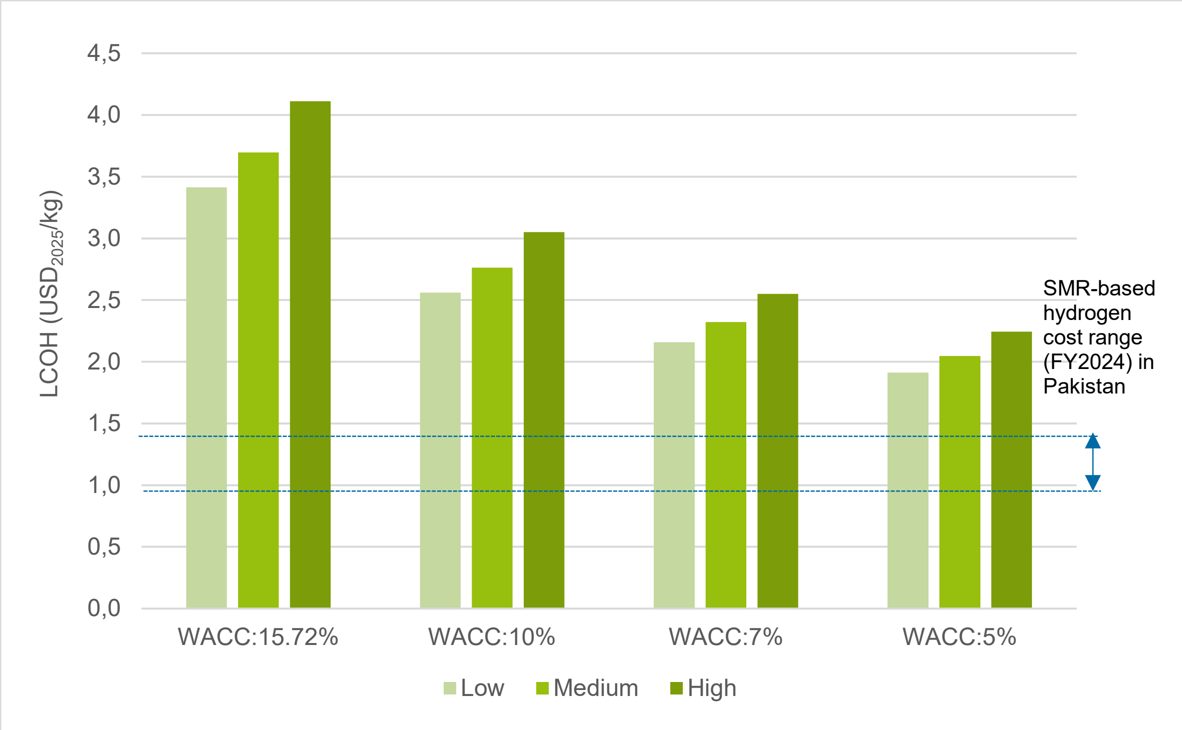


Source: Author's compilation based on BOA v3.0.3(2026); electrolyzer type: AEL; WACC for Pakistan:15.72%; RES (hybrid); scenario:2040(medium); final product: ammonia

3.2 Sensitivity analysis: Impact of WACC

WACC plays a decisive role in shaping the economics of RES hydrogen production. As the 2040 LCOH projections clearly demonstrate, financing conditions are among the most influential drivers of cost competitiveness. Currently, Pakistan has a relatively high WACC of 15.72% (2025), reflecting the country's elevated investment risk profile. At this WACC, the LCOH ranges from USD 3.40/kg to USD 4.10/kg across the Low to High scenarios, resulting in production costs that would struggle to compete in international hydrogen markets. Lower WACC shows a remarkable decline in costs. At a WACC of 10%, the LCOH falls to USD 2.60–3.05/kg, while at 7%, it decreases further to USD 2.10–2.60/kg. At a WACC of 5% (typically for developed countries) the LCOH can reach as low as USD 1.90–2.20/kg. The cost gradient across WACC scenarios makes a compelling case for reducing the cost of capital through targeted policy interventions. Measures such as sovereign risk guarantees, blended finance structures, and preferential climate finance could significantly improve Pakistan's competitiveness in RES hydrogen production.

Figure 30: Impact of WACC (%) on LCOH (USD/kg)



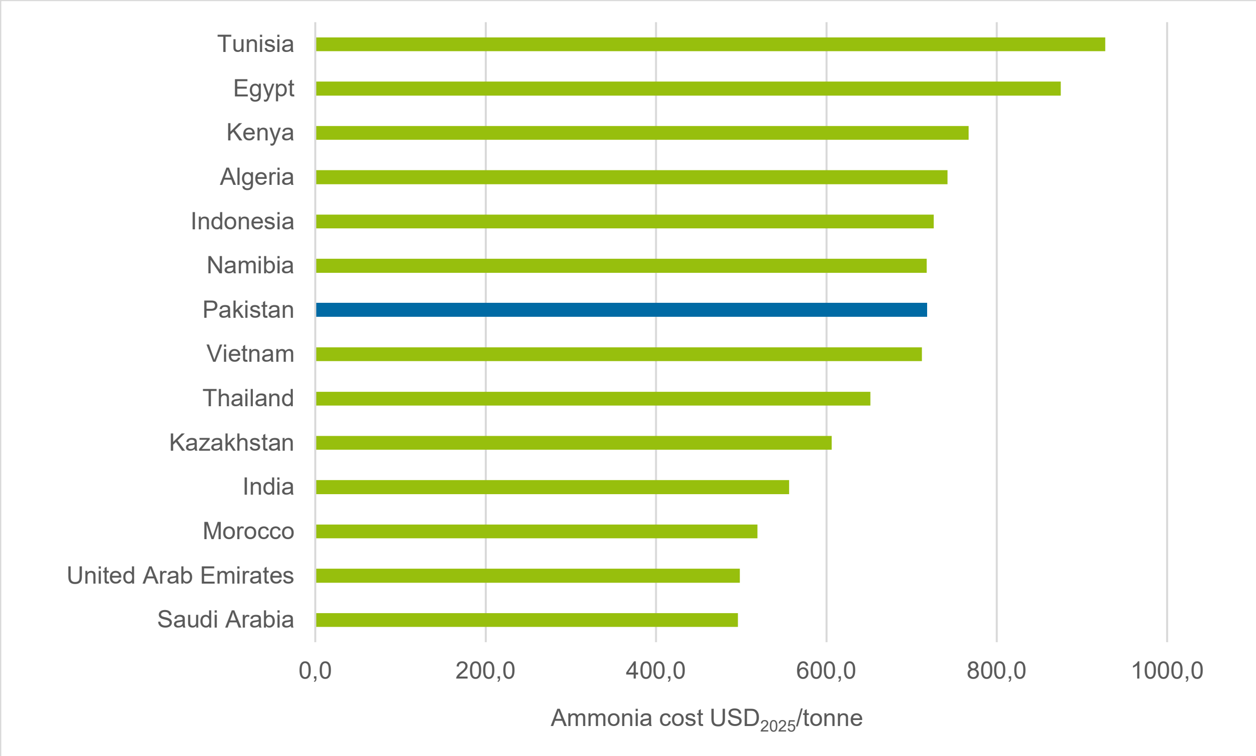
Source: Author's compilation based on BOA v3.0.3(2026); electrolyzer type: AEL; WACC: own variations; RES (hybrid), scenario:2040(medium); final product: hydrogen

Similarly, the WACC has a significant effect on Pakistan's competitive positioning relative to other countries in the region. As shown in Figure 31, under the medium 2040 scenario, a lower WACC brings Pakistan's green ammonia production costs significantly closer to those of Vietnam and Indonesia, narrowing the competitive gap between these countries when exporting to China.

At a WACC of 10%, the cost of green ammonia for imports to China is estimated at USD_{2025} 718/tonne. However, as the WACC is further reduced to 7% in Figure 32, reflecting a lower cost of capital and reduced financial risk, the cost declines to around USD_{2025} 600/tonne. It is important to note that this analysis isolates the impact of WACC specifically; all other parameters including renewable energy costs, CAPEX, and transportation costs are held constant across assessment. This allows for a clearer understanding of how financing costs alone influence Pakistan's relative competitiveness in the green ammonia export market.

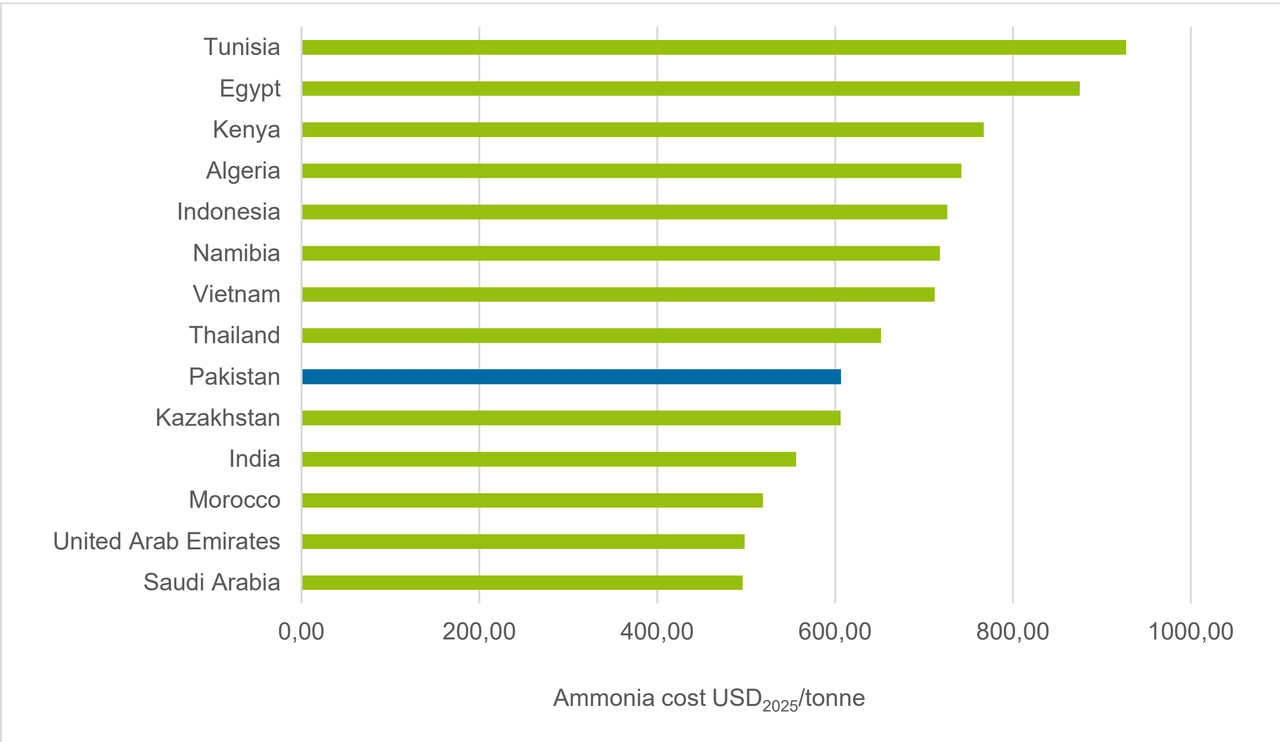
The cost of financing can be reduced through targeted policy interventions that de-risk hydrogen investments and provide guaranteed offtake mechanisms. Measures such as government-backed guarantees and concessional financing can help to lower investment risk and the associated cost of capital, while guaranteed offtake agreements together, these interventions may improve the bankability of hydrogen projects and reduce overall WACC.

Figure 31: Cost of ammonia imports to China from different countries with a 10% WACC



Source: Author's compilation based on BOA v3.0.3(2026); electrolyzer type: AEL; WACC for Pakistan:10.0%; WACC for other countries remain as it is; RES (hybrid); scenario:2040(medium); final product: ammonia

Figure 32: Cost of ammonia imports to China from different countries with a 7% WACC



Source: Author's compilation based on BOA v3.0.3(2026); electrolyzer type: AEL; WACC for Pakistan:7.00%; WACC for other countries remain as it is; RES (hybrid); scenario:2040(medium); final product: ammonia

3.3 Discussion

This section has explored the main determinants of production costs for hydrogen and PtX products in Pakistan and assessed the competitiveness of exports from Pakistan compared to other potential competitors in the emerging international market. Pakistan does not have a considerable advantage in the export of PtX molecules based on the evaluation presented in this PtX assessment, as compared to other regional counterparts, as shown in Figure 29 (export to China) and Figure 30 (export to Germany). Hydrogen remains a challenging vector in terms of transportation. Other molecules, particularly ammonia and methanol do present near-term opportunities; however, given the current high cost of financing, Pakistan's competitiveness with other countries remains limited.

This does align with broader literature consistently identifying ammonia as the most scalable hydrogen carrier for long-distance trade and local demand needs. If hydrogen is the final energy carrier required by the end user, the reconversion process back to hydrogen incurs additional costs and efficiency losses, making the overall supply chain significantly more expensive. The risk of demand-side uncertainties in potential import markets regarding industrial decarbonization pace and PtX certification frameworks may introduce market challenges that cost projections alone cannot capture.

The export cost comparison also reveals a fundamental challenge in the hydrogen sector: the high cost of transporting pure hydrogen. As shown in Figure 32, the cost premium of transporting pure hydrogen to European and East Asian markets is nearly 60% of the production costs, significantly reducing its competitiveness compared with geographically closer exporters in the Middle East and North Africa.

Perhaps most critically, the WACC analysis (Figure 27) demonstrates that financial de-risking could deliver cost reductions for hydrogen that are comparable to a decade of technological progress. There can be a 25% cost decline for a 5% reduction in the WACC. Furthermore, a reduction in WACC can also shift Pakistan's competitiveness regarding ammonia relative to other regional counterparts. At 10%, Pakistan has a cost basis like that of Vietnam and Indonesia, and eventually, at 7%, it becomes one of the top 10 cheapest import options for China. The WACC also highlights a structural inequity whereby emerging economies with weaker institutional frameworks are systematically at a disadvantage in terms of benefiting from green transitions as compared to global north countries. Addressing this financing gap through multilateral mechanisms such as sovereign risk guarantees, blended finance and innovative policy instruments for hydrogen developments could make it more competitive in the global market.

At the same time, demand stimulation and implementable policy design is essential for commercially self-sustaining markets. As an example, the European Hydrogen Bank is explicitly designed to bridge the gap between renewable hydrogen production costs and what buyers are willing to pay through competitive support schemes which directly target the early-stage cost premium that hinders the market development (European Commission, 2022).Policy-driven offtake certainty is therefore essential, given that many hydrogen projects have faced cancellations or delayed implementation due to cost competitiveness constraints and an uncertain policy environment. Furthermore, large-scale market deployment will depend significantly on demand-side policies and the availability of supporting infrastructure.

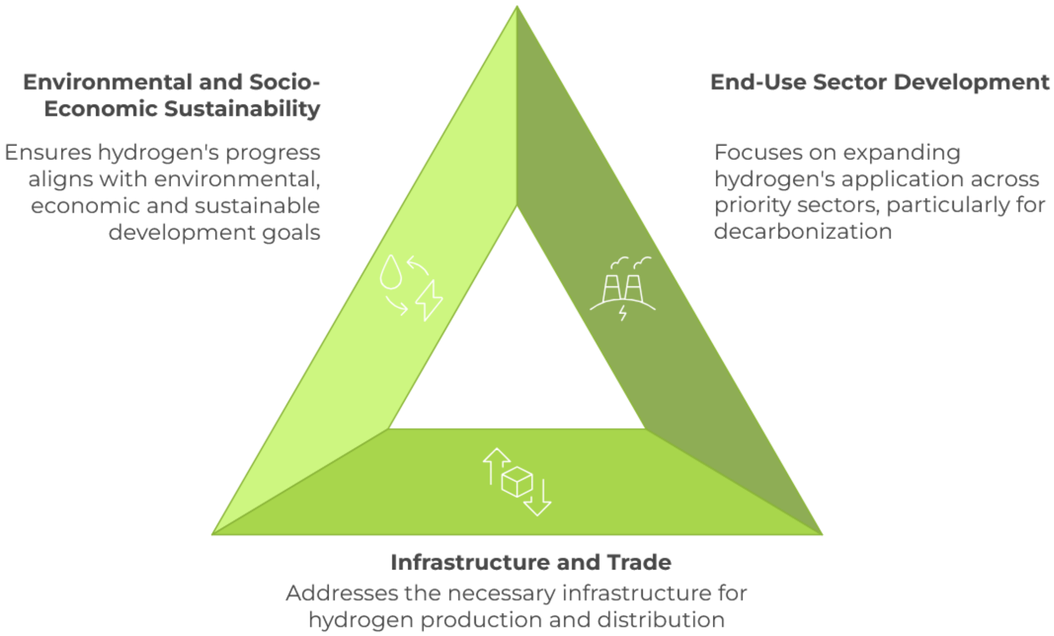
4 Hydrogen governance

The governance segment in hydrogen developments is complex and transitioning away from fossil-based hydrogen production should be understood as a multi-dimensional process. As fossil fuels are phased out, renewable electricity and clean technologies expand. Together, these changes drive a broader restructuring of the associated energy systems and value chains.

4.1 Key considerations for hydrogen strategy developments

RES-based hydrogen development shares many barriers familiar from wind and solar roll-outs, yet it also introduces key challenges that require international and local coordination: building reliable demand across end-use sectors, establishing infrastructure and trade networks, and ensuring that hydrogen supply chains meet environmental and socio-economic sustainability goals highlighted in Figure 33 (Lentschig, Patonia, & Quitzow, 2025).

Figure 33: The overlapping dimensions of building hydrogen ecosystem



Source: Author's compilation adapted from Lentschig (2025)

4.1.1 Focus on end-use sector development

End-use sector development for RES hydrogen is currently characterized by a strong near-term focus on substituting fossil-based hydrogen in existing markets (feedstock for fertilizer industry, hydrogen as a reducing agent in steel industry and refining) eventually solidifying the PtX market. While demand expansion into new sectors such as shipping and aviation e-fuels remains constrained by cost gaps, infrastructure readiness and limited long-term offtake commitments. The IEA highlights that demand is still concentrated in traditional uses and stresses the need to both decarbonize existing hydrogen consumption and expand into hard-to-abate applications such as heavy industry and long-distance transport. Shipping is emerging as a dynamic early adopter through e-methanol and e-ammonia, supported by multiple initiatives to decarbonize the sector, whereas road transport expectations have seen a decline compared to earlier forecasts.

Pakistan’s fertilizer sector, accounting for roughly 17% of national gas demand, offers a compelling entry point for developing an end-use case for RES hydrogen, particularly via developing green ammonia value chains (Competition Commission of Pakistan, 2024).

Overall, the demand growth of natural gas by 2030 is expected to fall short of stated policy targets unless stronger demand-side incentives and infrastructure development accelerate shaping the market (MOE, 2021). In parallel, the hydrogen project pipeline is growing but only a few projects reach the final investment decisions as producers struggle to secure offtake agreements for RES-produced hydrogen. During the transition towards cost competitiveness with the natural gas-based hydrogen, it is becoming increasingly important to stimulate the end use demand.

4.1.2 Infrastructure and trade

RES hydrogen developments are reshaping industries and trade by reorganizing value chains based on cost competitive advantages across regions. It is anticipated that new clusters of industrial activity around ports will be created along with industrial hubs in renewables dominated regions. Further, a new paradigm of importing and exporting is on the horizon. In this paradigm, low-cost renewable players are the exporters, while import-dependent regions seek secure supply chains and diversified sourcing like today’s fossil fuel markets but with different infrastructure requirements and sustainability concerns.

At the same time, traditional fossil fuel sectors (oil and gas companies, utilities, chemical producers) are also repositioning themselves in developing RES hydrogen across its value chain: producers, carriers, or infrastructure operators. This indicates that hydrogen is not merely an add-on technology: it is a politically and economically contested restructuring of industrial strategies, investment flows, labour markets, and geopolitical relations (IRENA, 2022).

4.1.3 Socio-technical transition and sustainability

Framing global decarbonization as a socio-technical transition is particularly helpful for understanding the development needs. Hydrogen offers a system-level innovation that depends on simultaneous change in technology, market formation, infrastructure investment and governance. Its scale-up would fundamentally reshape energy use by enabling decarbonization in hard-to-abate sectors such as chemicals, steel, and long-distance transport fuels, while driving new demand for hydrogen-derived products such as ammonia, methanol and synthetic aviation fuels (Essi Laitinen, 2024).

A socio-technical perspective therefore implies that hydrogen policy must move beyond supply support and adopt integrated measures that jointly stimulate end-use uptake, coordinate infrastructure deployment, ensure credible sustainability standards, and manage distributional impacts and public legitimacy at national and international levels. Hydrogen development has implications for water use, land use, biodiversity, local communities, and employment. A socio-technical approach requires policies that proactively address distributional effects. These incudes who bears the costs and who captures the benefits through social safeguards, just transition measures, community engagement, and transparent environmental governance (Cotton, Cooper, Milner, & Towers, 2025).

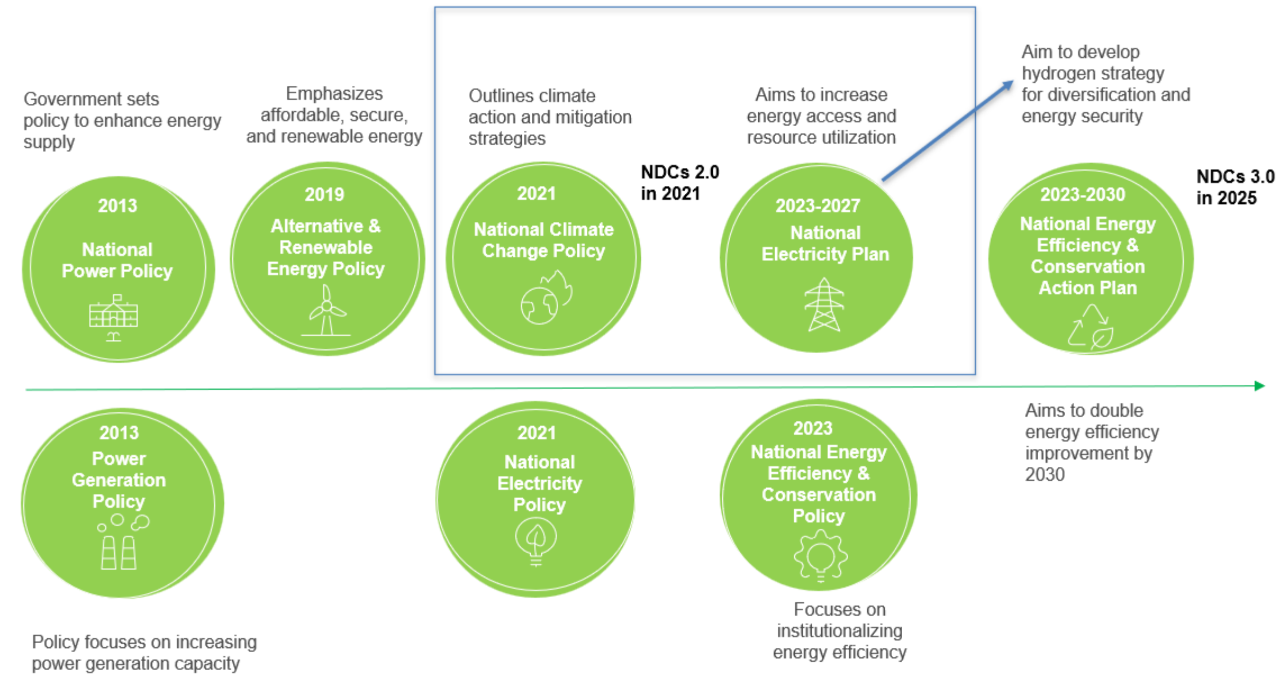
4.2 Existing energy policy landscape

Pakistan's energy policy landscape has been continuously evolving in response to rapid population growth, ongoing economic development, and the resulting increases in energy demand. Given the country's limited domestic fossil fuel resources, a significant share of fuel used in thermal power generation as well as in industrial processes is imported. This reliance on external energy sources has shaped policy decisions, pushing the government to reassess its energy strategies to ensure the affordability and reliability of supply.

Pakistan's first electricity policy, introduced in 1994, focused on expanding generation capacity, mainly through thermal power plants. While this increased overall capacity, it also led to high fixed costs in the form of capacity payments to power producers, even when demand growth lagged. Alongside significant transmission and distribution losses and weak revenue collection, these factors have placed persistent fiscal and political strain on the sector. This ongoing crisis is commonly described as 'circular debt,' which remains a major barrier to financial sustainability and sector reform (Malik, 2024).

On the fuel side, Pakistan remains heavily exposed to global commodity price volatility because of the import dependence on LNG, oil, and coal. Major policies have increasingly focused on flexibility in LNG procurement for industrial competitiveness and affordability reasons. The broader energy policy challenge is that Pakistan's fuels and power policies cannot be separated: decisions on gas pricing, LNG contracting, or fuel import strategy directly affect electricity costs and the circular debt trajectory, while electricity market reform affects how efficiently fuel costs are passed through.

Figure 34:Timeline of electricity generation policies in Pakistan



Source: Author's compilation based on policy documents

Policies promoting renewable and alternative energy emerged in the early 2000s, but they did not significantly advance variable renewable energy (VRE). Instead, they largely concentrated on small hydropower and cogeneration in biomass-based power plants. Later, the Alternative Renewable Energy Policy (ARE) was launched in 2019 with targets, incentives and opportunities for growing local renewable energy industry. ARE 2019 set the target of increasing the share of renewables to 20% by 2025 and 30% by 2030 in the electricity mix (AEDB, 2019).

In 2021, the National Electricity Policy (NEP) was launched and focused on Pakistan's medium-term roadmap to make the power sector more efficient, financially sustainable, and consumer-focused by moving from a traditional single-buyer model towards a more competitive electricity market through Competitive Trade Bilateral Contract Markets (CTBCM) (MOE, 2021).Another strategic instrument shaping long-term energy decision-making is the Integrated Generation Capacity Expansion Plan (IGCEP), a ten-year capacity planning roadmap that is published on recurring basis with its latest version published in 2024 (NEPRA, 2024).The IGCEP is meant to guide least-cost investment, and has been publicly framed by Pakistan's government as a tool for large-scale savings through the rescheduling or cancellation of electricity generation projects.

Further, the National Electricity Plan (NEP) 2023–27 is Pakistan's five-year strategic roadmap for improving the efficiency of the power sector, developed under the broader direction of the National Electricity Policy 2021 (MOE, 2023). It is relevant to hydrogen because it explicitly places hydrogen on the medium-term policy workplan via the development of a hydrogen strategy. It emphasizes integrated energy planning, decarbonization, and market/open-access reforms building on IGCEP considerations and stakeholder processes including UNIDO-linked engagements and discussions on a national green hydrogen policy/action plan.

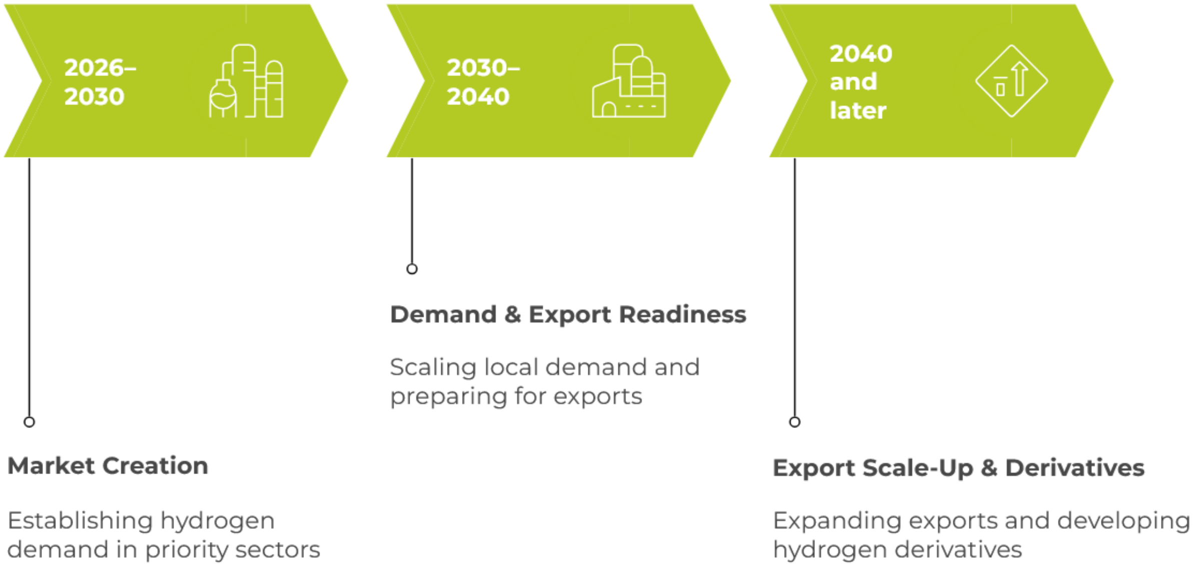
Pakistan's largest recent shift has been the rapid growth of distributed rooftop solar, driven largely by high electricity tariffs that consumers seek to avoid by installing inexpensive imported solar equipment on the rooftops. This 'solar surge' in 2025 became a central policy debate, particularly in correspondence to thermal power generation. While it strengthens energy security by reducing imported fuel dependence for consumers facing outages and price instability. However, it threatens the cost-recovery model of distribution utilities and may shift a larger share of grid costs on to the grid connected consumers. Policymakers have therefore explored reforms such as changing net metering compensation and adjusting taxation rules around solar imports (Financial Times, 2025)

Overall, Pakistan's energy policy landscape is defined less by a lack of strategies and more by the challenge of implementation under fiscal and economic challenges. The government has outlined policy directions, including market reforms, least-cost planning, and increased use of renewable energy. However, governance challenges particularly gaps in capacity and slow policy implementation have limited their effectiveness. The next phase of policy debate is likely to revolve around whether Pakistan can modernize its electricity market and manage decentralised solar growth without worsening inequality or undermining the financial stability of the centralized energy systems.

4.3 The phases of planning a hydrogen strategy

Developing a hydrogen strategy typically follows a phased planning pathway that progresses from early strategy and pilots to large-scale deployment and later to market maturity stages. In the first phase, countries focus on establishing the enabling environment by defining national targets, developing regulatory and safety frameworks, introducing certification and verification systems, and launching pilot projects supported by public finance and policy incentives. Once this foundation is in place, the second phase centres on market ramp-up, where proven pilots are scaled into hydrogen hubs and industrial clusters, early infrastructure such as storage and pipelines are developed, and demand is stimulated through tools like long-term offtake contracts and industrial decarbonization policies (Ali, 2024).

Figure 35: Phases of planning a RES hydrogen ecosystem



Source: Author's compilation

In the final phase, hydrogen becomes a fully integrated component of the energy and industrial system, with expanded infrastructure networks, mature certification and carbon accounting for domestic and cross-border trade and decreasing reliance on subsidies as markets become more competitive. This phased approach is widely reflected in major international roadmaps such as the EU Hydrogen Strategy and the IRENA's toolkit, which emphasize the importance of sequential planning, coordinated infrastructure development, and adaptive policy support to accelerate transition from early demonstration to a functioning hydrogen market.

Table 8: Phases of developing hydrogen landscape in Pakistan

Phase	Focus
Phase 1 (2026–2030)	Market creation in priority end use sectors
Priority actions	-Creation of a focused hydrogen strategy indicating concise targets and development timelines for local and export orientation. -Link RES hydrogen to renewable deployment objectives already laid out in ARE Policy 2019 -Strategic incentivization to promote hydrogen demand and decarbonization -Focus on ammonia for fertilizer as the lead market. -Identifying or dedicating a "Hydrogen Hub "on coastal/port-adjacent or industrial cluster sites where renewable resources, grid integration, water options, and offtake can be bundled. -Establish hydrogen governance through clear certification mandates, lifecycle emissions methodology, water safeguards, and regulatory frameworks -Strategic hydrogen partnerships on achieving economic growth through technology transfer and hydrogen exports.
Phase 2 (2030–2040)	Scaling up local demand and export readiness
Priority actions	-Expand hydrogen use into chemicals, iron and steelmaking and other selected priority sectors -Focus on building an investment ecosystem that is investor-friendly with long-term offtake contracts

	-Enable multi-user infrastructure focused on storage, conversion, and port handling -Creation of local industries focus on decarbonization technologies -Using financial mechanisms and carbon-linked incentives to close the price gap
Phase 3 (post-2040):	Export scale-up and wider derivatives
Priority actions	-Scale export corridors only after robust certification compliance, contracted buyers, proven system efficiency -Achieving the national net-zero targets and industrial decarbonization initiatives -Focus on economic growth and sustainable development through the opportunity by net-zero technologies

Source: Author’s compilation

4.4 Elements of hydrogen strategy

4.4.1 Transparent regulatory and legal framework

Legislative and regulatory measures are an important dimension to incubate Hydrogen and PtX developments. A clear and consistent regulatory framework can ensure market certainty during the national-scale ramp-up of hydrogen projects. While many countries are still developing such legislation, a few have taken more ambitious steps, positioning regulation as a key component for the on-the-ground project implementation. Beyond policies and strategies, legislative and legal clarity provides a solid foundation, particularly for developing large-scale projects. An overview of global such initiatives is provided in Table 11 below.

Table 9: Legislative and regulatory measures regarding hydrogen around the globe

Country	Mechanism	Details
Germany	Wasserstoff-beschleunigungsgesetz / Hydrogen Acceleration Law	The Act is intended to significantly accelerate the market ramp-up of hydrogen in line with climate neutrality goals and the National Hydrogen Strategy. It is focused on addressing issues on regulations, administration and permitting bottlenecks across hydrogen value chain. It covers both, hydrogen from renewables-based electrolysis, and hydrogen from natural gas with carbon capture (BWE, 2023).
France	Public-private partnerships (PPPs)	Government–industry contracts and commitments reduce administrative hurdles for hydrogen projects and support the initiation of new initiatives (France Hydrogène, 2023).
Chile	Land use regulations	Streamline land use and permitting processes to ease hydrogen development, focusing on identifying and utilizing public lands suitable for green hydrogen production. A national task force will guide green hydrogen developers through permitting and pilot processes, ensuring coordination across public sectors to minimize uncertainty.
	Power market regulations	Chile intends to update power market rules to integrate hydrogen technologies into energy and capacity services and streamline related environmental and industrial licensing processes.

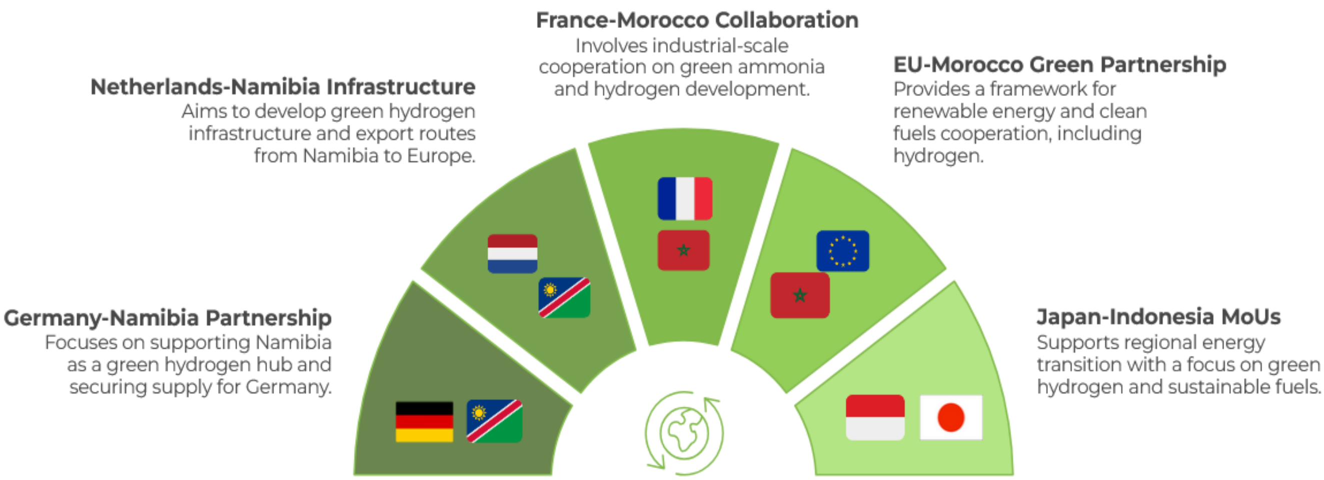
South Korea	Hydrogen Law	Establishing the legal framework to promote hydrogen through initiatives that include developing educational programs, compiling hydrogen-related statistics, setting safety standards, and regulating fuelling systems and installations

Sources: Author's compilation based on BWE (2023); France Hydrogène (2023); Ministry of Energy-Chile (2020); Green Hydrogen Organisation (2026)

4.4.2 Bilateral trade relations and development cooperation

Countries with high natural gas and coal demand in industrial processes and heating and limited and unfavourable domestic capacity to produce low carbon and green hydrogen, are increasingly seeking to establish long-term cooperative agreements with nations that possess strong hydrogen production potentials based on renewable energy. Most industrialized countries like Germany that will be meeting 50-70% of its hydrogen needs through imports (Oeko-Institut, 2024), have already taken concrete steps by developing an import policy and other strategic partnerships on hydrogen and PtX with developing countries such as Namibia, as highlighted in Figure 36 (BMWK, 2024). The Netherlands has also signed a cooperation to develop green hydrogen-related infrastructure and supply chains, building a future export route from Namibia to the Netherlands and wider Europe through its Rotterdam–Lüderitz corridor (Port of Rotterdam, 2023). Similarly, France has signed a collaboration with Morrocco and Japan with Indonesia for regional cooperation on hydrogen and its derivatives.

Figure 36: Hydrogen cooperation agreements across the globe



Source: Author's compilation based on Port of Rotterdam (2023); BMWK (2024)

RES hydrogen developments in EMDEs, in the form of feasibility studies, pilot projects, and early-stage investments, are rapidly becoming central to both developing and industrialized economies today. This approach is valuable because it not only helps to secure future hydrogen demand but also enables partner countries to benefit economically and technologically by establishing and scaling up their own industrial growth, creating opportunities for investment and employment. In this sense, green hydrogen opportunities are no longer confined to advanced economies: a global market is evolving in which EMDEs will play a critically important role, if investment conditions, infrastructure development, and supportive policy environments continue to improve (Oeko-Institut, 2024).

As an EMDE, Pakistan's strategic geographic position, combined with access to a deep-water seaport, offers a growing opportunity to become an important player in future low-carbon energy trade corridors. A key potential partner in this context is China, which has already emerged as a global leader in hydrogen development, hosting more than half of the world's large-scale hydrogen projects (IEA, 2024).

i. Engagement with China

Building on the long-standing and cooperative relationship between the two countries, Pakistan could benefit from establishing a RES hydrogen partnership with China under the ongoing Belt Road Initiative (BRI). Such a collaboration could support technology transfer, investment, and infrastructure development, while also strengthening Pakistan's role as a regional hub for clean energy production and exports. Few points for potential linkages are:

1. Integrate hydrogen cooperation into priority development areas: Pakistan should explicitly include green hydrogen within its strategic cooperation frameworks with China, especially under CPEC and other bilateral initiatives under the BRI. This ensures that hydrogen infrastructure (electrolyzers, renewable power integration, transport applications) is prioritized alongside energy transition and industrial modernization projects.
2. Leverage China's rapidly expanding hydrogen ecosystem as technology transfer opportunity, from low-cost electrolyzer manufacturing to renewable energy technologies. This could include establishing a Hydrogen Innovation Centre or demonstration corridor co-financed by Chinese and Pakistani partners.
3. Encourage Chinese investors already active in Pakistan's renewable sector (solar, wind, and battery manufacturing) to extend into RES hydrogen and ammonia production, ensuring technology localization and domestic skill development.
4. Inviting Chinese investment in electrolyzer manufacturing in Pakistan could provide a strong starting point while ensuring the active involvement of local partners.

ii. Engagement with European Union

Given the EU's strong commitment to advancing renewable-based hydrogen and building sustainable energy partnerships, Pakistan should adopt a structured and strategic approach to engaging with the EU, particularly Germany and Denmark, to establish itself as a credible partner in emerging hydrogen value chains. Establishing early partnerships with European utilities and hydrogen off-takers will enhance Pakistan's investment attractiveness and market access.

1. Strengthening cooperation with the German Corporation for International Cooperation (GIZ) by aligning national hydrogen development priorities with ongoing European hydrogen initiatives. This includes collaboration under frameworks of 'Pak-German Energy Partnership' or the global 'PtX Hub' initiatives. Such alignment will facilitate knowledge exchange and development opportunity.

2. A collaboration between Pakistan–EU on hydrogen and PtX can be developed to support knowledge exchange, industrial development and technology transfer. Such an institutional mechanism would ensure coherence across hydrogen initiatives to meet the EU standards for import and other development considerations.

3. Engagement with Denmark under its Danish Energy Transition Initiative with Pakistan, capacity building and assistance on Power to X value chains.
4. Pakistan should seek access to EU climate and energy transition financing instruments, including the European Investment Bank (EIB) and blended finance under the Global Gateway program that is also now focusing on Asia. These can provide concessional finance and guarantees for RES hydrogen infrastructure, renewable integration, and export-oriented ammonia projects.

iii. Engagement with Japan

Given Japan's leadership in hydrogen technology, particularly fuel cells and its projected role as a major importer of low-carbon hydrogen in Asian market, Pakistan should strengthen and expand its bilateral collaboration with Japan across the full green hydrogen value chain. The partnership can cover key areas such as

1. The negotiation of long-term hydrogen (or ammonia) offtake agreements between Pakistani producers and Japanese industrial consumers.
2. Pakistan should pursue technology-transfer partnerships with Japan to gradually localize the manufacturing of critical hydrogen technologies and components. Japan has long-standing strengths in advanced manufacturing, fuel cell technologies, high-efficiency electrolyser components, hydrogen storage systems, and industrial engineering, and has built a strong ecosystem of firms across the hydrogen value chain. Leveraging Japanese expertise can help Pakistan move beyond being only a hydrogen producer and develop into a regional manufacturing and technology hub.

Alignment of Pakistan's hydrogen-certification and sustainability standards with Japanese import requirements. Mobilization of Japanese development-finance institutions alongside Pakistani public-private partnerships to de-risk large scale hydrogen export-oriented infrastructure.

In conclusion, Pakistan can leverage its strategic location and port infrastructure to position itself within emerging low-carbon energy trade corridors, but this will require targeted partnerships and a coordinated approach. Cooperation with China can fast-track technology transfer, investment, and infrastructure under CPEC/BRI, while engagement with the EU can support standards alignment, capacity building, and access to climate finance and offtake markets. Collaboration with Japan can further strengthen demand certainty through offtake arrangements and enable advanced technology transfer across the hydrogen value chain. Taken together, these engagements can underpin a credible RES hydrogen ecosystem that supports Pakistan's industrial transition, strengthens energy security, and advances progress toward NDC implementation and net-zero.

4.4.3 Certifications and standardization

Hydrogen certifications and standards are becoming essential tools for scaling global trade because they verify the origin, carbon intensity, and sustainability attributes of hydrogen and its derivatives (e.g., green ammonia, methanol, e-fuels). They provide a transparent way of verifying how hydrogen is produced, its life-cycle greenhouse gas (GHG) emissions, and whether it meets sustainability criteria (e.g. renewable electricity sourcing, traceability, and reporting).

In practice, certifications determine whether hydrogen qualifies as "renewable" or "low carbon," and whether it can access premium markets, is eligible for subsidies especially in Europe and Japan. It is important that while developing a hydrogen strategy for Pakistan, the standardization process is thought through and essentially it should correspond to the requirements and need of other import countries. Table 12 describes some certifications established across the globe to ensure the climate change mitigation potentials and the sustainability of hydrogen projects.

To delve into trade and access the export market, Pakistan also needs to consider rigorous hydrogen standards and certification to ensure environmental integrity, credibility, and market access for clean hydrogen. They provide certainty to investors and developers, enable alignment with international import requirements, and prevent greenwashing. Embedding these clearly in the hydrogen strategy will support NDC delivery and can position Pakistan competitively in emerging global hydrogen markets through compliance to international hydrogen market.

Table 10: Hydrogen certifications across the globe

Region	Mechanism	Description
European Union	Renewable Fuels of Non-biological Origins (RNFBOs)	The EU has formal rules for when hydrogen qualifies as RFNBO, including strict requirements on additionality, temporal matching, and geographic correlation between renewable power generation and electrolyser operation.
Europe	CertifHy: Guarantees of Origin (GO)	CertifHy is a widely recognized European certification initiative that issues GO, allowing hydrogen buyers to verify the origin and carbon category of hydrogen even when it is traded across borders. It supports registry-based issuance, transfer, and cancellation of certificates.
Global	ISO 14687	The hydrogen fuel quality standard is a major global technical standard defining minimum hydrogen quality requirements, including purity limits and impurity thresholds, for applications such as vehicles, stationary fuel cells, and industrial use.
Japan / Tokyo	Hydrogen Certification Scheme	Tokyo has introduced a certification system that recognizes and verifies the use of hydrogen produced from renewable electricity and is designed to stimulate market uptake and build credibility for green hydrogen claims.
Germany	TÜV SÜD Certification	It is a voluntary standard for renewable hydrogen. There are two active certification programs: GO at the hydrogen production point or certification at the point of use, utilizing a mass balancing approach.
France	AFHYPAC Certification	It is a voluntary GO scheme developed by the French Association for Hydrogen and Fuel Cells to certify hydrogen production pathways. It helps verify and document emission reductions, improving transparency and credibility for low-carbon and renewable hydrogen claims.

Sources: Author's compilation based on CERTIFHY (n.d); ISO (2025); Shulman advisory (2024); EUR-Lex (2023)

4.4.4 Hydrogen finance and derisking

Green hydrogen projects are typically capital-intensive, with large upfront costs for renewables, electrolysers, storage, and infrastructure, which means that the cost of capital (WACC) becomes a decisive driver of the LCOH. In EMDEs, high interest rates, currency volatility, political uncertainty and market immaturity often make projects difficult to finance. In this context, investors and lenders often require higher returns to compensate for perceived risks such as uncertain regulation, weak creditworthiness of domestic offtakers, and foreign exchange exposure. As a result, even technically strong projects can remain “unbankable” unless risk is reduced, and revenue streams are ensured through state-backed guarantees.

To address this, governments, Multilateral Development Banks (MDBs), and climate finance institutions are increasingly deploying a combination of instruments that can lower financing costs and improve investor confidence. These include concessional and blended finance, where cheaper public or climate-linked capital is layered with private investment to reduce overall project financing costs; guarantees and political risk insurance, which protect investors against sovereign, regulatory, and contract enforcement risks; and currency risk mitigation tools, such as local currency lending or hedging facilities, to reduce exposure to devaluation and capital controls (World Bank Group, 2025).

In parallel, mechanisms like long-term offtake agreements and auction-based procurement models help create predictable revenue streams and demand certainty, critical for bankability in early markets.Table-13 highlights some instruments that can substantially reduce risk premiums in case of developing economies particularly valuables for Pakistan and can enable them to move from scattered pilot projects toward a credible pipeline of scalable hydrogen investments.

Table 11: Financial and derisking instruments in case of Pakistan

Mechanism	Description and impact	Implementation
Blended Finance/ Concessional Debt	High interest rates and risk premiums significantly inflate LCOH. Concessional debt reduces the weighted average cost of capital (WACC) and improves project bankability.	Dedicated hydrogen window under national climate finance channels. Concessional loans for early hydrogen hubs and pilot electrolyser projects can help to reduce market uncertainty. Blended finance can also help to unlock private capital.
Political Risk Insurance (PRI) /Guarantee Facilities	Investors price in political instability, regulatory uncertainty, and contract enforcement risk. PRI and guarantees can immediately reduce country-risk premiums and unlock long-term financing for large scale export-oriented projects.	Cuts discount rate by improving lender confidence and reducing perceived sovereign risk. Partial credit guarantees (PCG) to improve debt rating. Debt-service guarantees for high CAPEX infrastructure (storage, pipelines, port assets.
Long-term Offtake Agreements (10–20 years)	Hydrogen markets are immature, and demand is uncertain. Long term offtake can provide stable contracts with industrial hydrogen consumers. Long-term offtake agreements can secure buyers for early-stage projects, particularly for the export of PtX products, providing stable and predictable revenue over time.	Export-focused green ammonia and methanol from port-linked zones. A bankable demand can be created that can lead to price certainty and reduced financial risk Offtake agreements can be structured through auctions to create demand certainty. In this model, a public entity procures hydrogen derivatives via competitive auctions and resells them to industry, helping bridge price gaps and reduce commercial risk; an approach exemplified by the H2Global mechanism.
Carbon Contracts for Difference (CCfDs)/ Price Support Mechanisms	RES hydrogen remains more expensive than fossil-based hydrogen in many cases. CCfDs can provide support to close the price gap and stabilize revenues.	-International buyer-led CCfDs (e.g., EU/industry programs paying for green premium) -It can be initiated in the form of Domestic CCfDs for local industrial hydrogen switching (fertiliser industry).

Source: Author’s compilation based on H2Global Foundation (2026)

4.5 Addressing the risks of “quixotic” policies and misalignment

Pakistan can avoid policy misalignment and “quixotic” hydrogen pathways by pursuing a demand-led, sequenced approach that prioritizes credible early end-use markets (fertilizers), integrates hydrogen deployment with renewable electricity and grid planning, phased infrastructure development and embeds sustainability safeguards and certification governance for export orientation. If these conditions are met, RES hydrogen projects can become a bankable investment, enabling industrial decarbonization, improved energy security and long-term competitiveness.

In the past, energy policies lacked practical planning, making it difficult to build an attractive business environment for large-scale renewable energy markets. This section addresses the potential future misalignments within energy policy landscape, highlighting where gaps or inconsistencies exist. It considers how these misalignments may evolve over time and affect overall outcomes. Based on this analysis, the section then derives key insights and discusses their implications for policy design and implementation.

Misalignment-1: Hydrogen supply targets exceed renewable electricity realities

Hydrogen production requires large amounts of electricity, making it highly dependent on the availability of sufficient renewable energy. Misalignment can arise if hydrogen target is pursued more rapidly than the supporting infrastructure is developed. If renewable generation capacity, grid expansion and interconnections, and necessary power market reforms do not keep pace, this can lead to inefficiencies, higher costs, and increased pressure on the electricity system.

Policy intervention: Hydrogen targets should be linked to additional renewable capacity and grid readiness milestones, consistent with ARE 2019 policy directions.

Mislalignement-2: Consistent end-use consumer relief on fossil fuels

Pakistan’s most credible near-term domestic anchor demand is fertilizer, since a significant portion of gas demand is used in the fertilizer production and ammonia remains a strategic commodity. Multiple Pakistan-focused assessments identify green ammonia for fertilizer as the most realistic early end-use case. If hydrogen policies prioritize electrolyser deployment without parallel support for offtake agreements and pre-FID feasibility work, project development risks stalling.

Policy intervention: Pakistan should prioritize end-use market making mechanisms for domestic market just as the concept of ‘lead markets’ in EU is being encouraged to stimulate consumer side. Production incentivization at the supply end will not be enough to address the implementation gap.

Misaligment-3: No consideration of sustainability governance (water, land)

Hydrogen has social risks particularly in case of water use in arid regions, land competition for renewables, uneven distribution of benefits and community engagement. At present, most of Pakistan's policies do not adequately address sustainability considerations, even though these are essential for contributing to SDGs.

Policy intervention: Sustainability safeguards and transparent lifecycle emissions accounting must be embedded early in the strategy formulation.

Misalignment-4: Lack of compliance with international hydrogen standards and certifications

Export-oriented hydrogen and PtX must meet evolving requirements in potential destination markets e.g. emission limits and verifiable carbon accounting methodologies. Without alignment to major certification regimes, Pakistan's export competitiveness could be undermined.

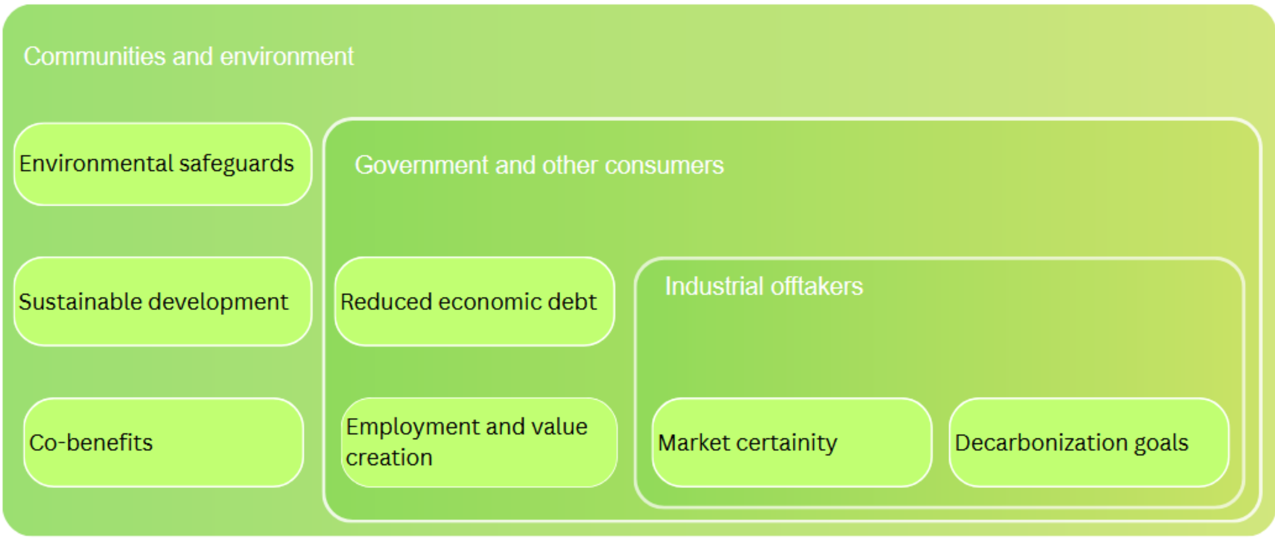
Policy intervention: Pakistan needs a credible national certification approach compatible with international frameworks and credible reporting and verification systems.

4.6 Building a "win-win" hydrogen ecosystem

A "win–win" hydrogen business ecosystem could be one in which the benefits are shared across all stakeholders and the transition is both economically viable and socially inclusive. Industry can benefit from predictable regulatory frameworks, bankable long-term offtake arrangements, and access to competitively priced clean energy. At the same time, government and consumers benefit through affordable electricity, and reduced dependence on imported fuels, which strengthens energy security and economic stability. Pakistan as a latecomer in developing hydrogen value chains, must adopt targeted industrial policy mixes to attract foreign direct investment and measures to build domestic absorptive capacity and facilitate knowledge transfer (Altenburg & Strohmaier, 2025)

Figure 37 highlights the stakeholder and balanced ecosystem dimensions that ensures local economies win through the creation of quality jobs, skills development, and increased domestic value addition via local supply chains and manufacturing. Finally, communities and the environment benefit when strong safeguards are in place to manage impacts on water and land resources ensuring equitable energy transition. Few interventions are gathered from the literature that can help to make viable hydrogen ecosystems (World Bank Group, 2025; Cotton, Cooper, Milner, & Towers, 2025; Öko-Institut e.V, 2024; Altenburg & Strohmaier, 2025; Lentschig, Patonia, & Quitzow, 2025; UNIDO, 2023) (Ali, Afaf, 2024).

Figure 37: Hydrogen business ecosystem stakeholders and dimensions



Source: Author's compilation

1. Make hydrogen bankable for priority sectors such as fertilizers

Pakistan's most feasible near-term end-use opportunity lies in producing ammonia for the fertilizer sector, as it builds on established hydrogen–ammonia supply chains, reinforces food security objectives, lowers vulnerability to fluctuating gas import prices, and provides the reliable offtake required to underpin early-stage projects. Industry acquires predictability and reduced import exposure in the food sector.

Policy measures	Ammonia offtake programme can be government-backed, tendered offtake volumes for fertilizer producers, with clear mandates on carbon emissions.
	A national roadmap for industrial decarbonization cross linked with Net-Zero strategy is an equally important element for local demand creation.
	Develop a phased roadmap for introducing substitution , starting with limited targets and scaling up over time.
	Industrial conversion support through provision of capital or concessional loans for retrofits i.e ammonia plants, Haber-Bosch reformer replacement and integration upgrades.

2. Use “market-making” instruments to close the price gap

Hydrogen cost gaps will remain high in the early years; the ecosystem needs mechanisms that make clean hydrogen competitive without rolling subsidies. Hydrogen is only a climate and economic opportunity if it is based on additional renewable power and does not worsen Pakistan’s power sector’s affordability challenges.

Policy measures	Operationalization of carbon markets and incentives for priority industrial switching to low carbon options.
	Tax rebates in developing the hydrogen projects, i.e custom, VAT and sales tax exemptions that have already proven beneficial in early renewable energy deployment in Pakistan.
	Building strategic international hydrogen partnerships for technology and finance mobilization for economic growth opportunities. Competitive auctions for RES hydrogen and derivatives for international and national players equally.
	Pakistan Hydrogen Blended Finance Facility: combines concessional loans, partial guarantees, and project prep grants for: early hubs, industrial retrofits, and port logistics.
	Guarantees for offtake (limited and conditional) to improve bankability while avoiding long-term fiscal lock-in.

3. Address RE additionality for hydrogen production

RES hydrogen project approvals can be tied to verified RE capacity additions and demonstrable grid readiness so that new hydrogen demand does not displace existing electricity users or force greater reliance on fossil generation. This linkage protects the credibility of "green" hydrogen claims and avoids or future compliance risks in export markets. It also reduces stress on the power system by ensuring sufficient generation, transmission capacity and strengthening investor and lender confidence in long-term operational reliability and project bankability.

Policy measures	
	Additionality requirements to be addressed because grid mix is dominated by fossil fuels and electrolyzer must have new renewable capacity (dedicated PPAs or new grid connected RE with traceability).
	Addressing the infrastructure bottlenecks for transmission and distribution in case of RE supply through grid.
	Tie hydrogen project approvals to verified renewable capacity additions and demonstrable grid readiness to prevent reputational and emissions risks, reduce pressure on the power system, and strengthen investor confidence in reliable long-term supply.

4. Make RES hydrogen a decarbonization opportunity through industrial cluster formation

Hydrogen ecosystems become cost-effective when shared infrastructure and services are anchored by multiple users. Shared assets increased utilization rates and distributed fixed costs, reducing unit costs and improving competitiveness. They also mitigate the risk of stranded infrastructure by ensuring stable demand over time. This clustering effect builds clearer, predictable investment pipelines, enabling developers and financiers to scale projects in a coordinated and bankable way.

Policy measures	
	Developing hydrogen cluster / hub programme that provide competitive locations where renewables and electrolysis are co-located with storage, and integrated transport/logistics infrastructure. The Gharo wind corridor can also acts as a strategic hydrogen hub due to its proximity to industrial hubs and transport viability
	Expand pipelines, terminals, and related assets only once minimum contracted volumes are secured, ensuring infrastructure roll-out follows proven demand and reducing the risk of overbuilding or stranded capacity.

5. Develop domestic supply chains and skills

Prioritise local industry development in hydrogen components and services through targets tied to market competitiveness. Initially service-related industries could be enabled in construction, electrical works, logistics, O&M, balance-of-plant and later it can be expanded towards higher-value manufacturing i.e. electrolyzer components, compression equipment, storage vessels, conversion equipment that will support long term employment opportunities and skills.

Policy measures	
	Emphasis on training and skill development on hydrogen technologies overarching the certification programmes for safety, operations, and maintenance focused on electrolysers, ammonia handling, and port operations.
	Hydrogen-related services should be focused (O&M, civil works, electrical works, logistics) and progressively expand to local manufacturing of components where domestic capacity and cost competitiveness are viable.
	Gender mainstreaming and equal opportunities to enhance gender equity in the developing hydrogen sector.
	Community engagement in the rural spaces and ensuring the local needs are addressed and benefit from developing hydrogen projects in their areas.

6. 'One window service' for hydrogen developments

In early hydrogen projects, economics are extremely sensitive to timing and small delays can quickly erode viability because capital costs can increase due to inflation, contracts have deadlines, and off-takers expect delivery on fixed schedules. Streamlined, predictable permitting and execution reduces schedule risk, improves investor and lender confidence, and strengthens governance credibility through transparent decision-making.

Policy measures	Single window permitting services overarching the financing institutions, grid requirements, environmental and land paperwork.
	Develop standardised template contracts for hydrogen offtake agreements, and port/terminal handling services to reduce negotiation time and improve bankability for early projects.
	Gender mainstreaming and equal opportunities to enhance gender equity in the developing hydrogen sector.
	Community engagement in the rural spaces and ensuring the local needs are addressed and benefit from developing hydrogen projects in their areas.
	Support developers with pre-feasibility studies and structured local governance coordination particularly for international firms to reduce uncertainty around permitting land/water access, grid connection, and stakeholder engagement.
	Fast-track approvals for projects in designated hydrogen zones and streamlined regulatory compliance

7. Standards, certification, and trade readiness

Access to export markets and project finance depends on proof of origin and emissions performance and verifiable certification and traceability frameworks that reduces the risk of greenwashing and ensures compliance with emerging trade requirements and buyer standards. This is critical to strengthens Pakistan's ability to participate in international hydrogen trade, attract lower-cost capital, and access climate finance and high-value markets that reward verified low-carbon production.

Policy measures	Developing a hydrogen "emission benchmark" and standardized methodology for carbon accounting.
	National hydrogen certification scheme aligned with international standards (lifecycle emissions, renewable energy sourcing, traceability).It is very important in case of tapping into international hydrogen market, where emission regulations are stringent for the quality of PtX molecules.
	Provision of audit facilities and third-party verification requirements.
	A "passport" approach for hydrogen and PtX products, i.e. ammonia and methanol to facilitate trade in international markets.

A successful hydrogen strategy will depend on phases as mentioned above. These start with a small number of competitively selected hubs where renewables, electrolysis, conversion, storage, and logistics are co-located and shared across multiple users. Aligning hydrogen approvals with renewable additions and grid readiness reduces emissions and reputational risks while protecting system reliability.

In parallel, a phased local-industry pathway can build jobs and domestic capability in hydrogen technologies without undermining early project viability. Standardized model contracts and targeted pre-feasibility/governance support specially for international developers can reduce delays, strengthen transparency, and improve bankability. Finally, standardization will secure market access, investor confidence, and eligibility for climate finance and premium export markets.

5 Conclusion and the outlook

Pakistan’s hydrogen strategy development sits at a critical intersection of energy security, industrial transformation, and climate resilience. While global momentum towards RES hydrogen has progressed more slowly than anticipated, with financing and final investment decisions lagging early projections. However, the long-term trajectory remains intact, underpinned by declining renewable energy costs. Without stringent climate policy and carbon pricing, the business case for RES hydrogen weakens considerably, as fossil-based alternatives remain cost-competitive in the absence of meaningful carbon constraints. Pakistan should therefore use this window to build the necessary regulatory, financial, and infrastructure foundations, positioning itself as a regional green ammonia supplier in anticipation of the policy-driven market transition.

Pakistan is well placed to pursue RES hydrogen opportunities because it has strong renewable energy potentials and a growing need to address its climate commitments. Hydrogen developments can bring multiple benefits for Pakistan, including reduced dependence on imported fossil fuels, new export opportunities through PtX products, greater industrial diversification, and job creation. However, hydrogen is not a straightforward solution, it requires coordinated action across policy, infrastructure, energy market, and sustainability governance. Without this coordination, Pakistan risks pursuing pathways that are too ambitious or poorly aligned with market realities, resulting in high costs, stranded assets, and missed development opportunity.

The way forward must be demand-led and grounded in engagement with local actors in priority sectors. In the near term, Pakistan’s most credible entry point is the development of green ammonia for fertilizer industry, as it builds on existing hydrogen-ammonia value chains, supports food security priorities, and can provide stable offtake to unlock early investment. This can serve as the foundation for piloting hydrogen hubs and scaling supporting infrastructure. At the same time, hydrogen policy must be carefully aligned with Pakistan’s broader electricity transition. Electrolyzer deployment should be tied to additional renewable generation, grid readiness, and integrated planning to avoid unintended impacts such as increased fossil dispatch, grid bottlenecks or higher system costs.

The development of a strong business ecosystem is equally important that creates a ‘win–win’ outcome for investors, government, and consumers. This requires policy instruments that improve the bankability of hydrogen projects through state-backed blended finance opportunities, carbon markets and public procurement, alongside phased infrastructure development. It is also crucial to develop strategic hydrogen partnerships with countries that have started developing a hydrogen market and can support with the trade and technology transfer. It will also help to establish standards and certification frameworks that are essential to ensure credibility to enable future exports and attract climate finance. A particular focus on use of water, land impacts, and community benefit-sharing should be given to secure long-term sustainable development by addressing the SDGs.

Ultimately, Pakistan’s renewable hydrogen strategy should be defined not by aspirational targets alone, but by its ability to create a coherent transition pathway, one that delivers near-term demonstrable value, mobilize climate finance and builds institutional capacity for scaling up. RES hydrogen could become a strategic pillar of Pakistan's energy transition and economic development, supporting domestic decarbonization while opening access to emerging global hydrogen trade opportunities. However, realizing this potential will require tangible progress in reducing the country's political and economic risk profile, which currently represents one of the most significant barriers to attracting the investment needed to scale RES hydrogen production. However, a carefully crafted hydrogen strategy could contribute to Pakistan’s energy transition goals.

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AI declaration: The authors acknowledge the use of AI tools in the preparation of this work, including Google Gemini (Flash 3.5) for image generation, and ChatGPT 5 and Claude (Sonnet 4.6) for writing assistance, refinement and grammatical correction.