

Article

Green Hydrogen in Jordan: Stakeholder Perspectives on Technological, Infrastructure, and Economic Barriers

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Abstract

Green hydrogen, produced via renewable-powered electrolysis, offers a promising path toward deep decarbonisation in energy systems. This study investigates the major technological, infrastructural, and economic challenges facing green hydrogen production in Jordan—a resource-constrained yet renewable-rich country. Key barriers were identified through a structured survey of 52 national stakeholders, including water scarcity, low electrolysis efficiency, limited grid compatibility, and underdeveloped transport infrastructure. Respondents emphasised that overcoming these challenges requires investment in smart grid technologies, seawater desalination, advanced electrolyzers, and policy instruments such as subsidies and public–private partnerships. These findings are consistent with global assessments, which recognise similar structural and financial obstacles in scaling up green hydrogen across emerging economies. Despite the constraints, over 50% of surveyed stakeholders expressed optimism about Jordan’s potential to develop a competitive green hydrogen sector, especially for industrial and power generation uses. This paper provides empirical, context-specific insights into the conditions required to scale green hydrogen in developing economies. It proposes an integrated roadmap focusing on infrastructure modernisation, targeted financial mechanisms, and enabling policy frameworks.



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1. Introduction

1.1. Background and Motivation

The global energy transition has positioned green hydrogen as a critical solution for deep decarbonisation, offering a clean alternative to fossil fuels through renewable-powered water electrolysis. Unlike conventional methods that emit significant CO₂, green hydrogen production achieves near-zero emissions, making it essential for meeting international climate targets [1,2]. This technology’s versatility enables applications across hard-to-abate sectors, from heavy industry to long-distance transport, though its widespread adoption faces substantial technical and economic barriers. These findings align with global assessments, including the IEA’s Global Hydrogen Review 2024, which highlights infrastructure, finance, low-emissions deployment challenges, and water-stress concerns [3]; the IEA’s Northwest European Hydrogen Monitor 2025, which examines regional infrastructure

retrofitting and large-scale deployment dynamics [4]; IRENA's Quality Infrastructure Roadmap 2024, emphasising standards, testing, and certification to support nascent hydrogen markets [5]; IRENA's Global Trade in Green Hydrogen Derivatives 2024 report, which outlines the regulatory and certification frameworks needed to develop international hydrogen trade [6]; and IRENA's Geopolitics of Hydrogen 2022 report, which anticipates that hydrogen will reshape global energy power dynamics and urges countries like Jordan to develop infrastructure, certification systems, and diplomatic strategies to participate in emerging hydrogen markets [7].

1.2. National Context: The Case of Jordan

Jordan's distinctive combination of high solar irradiance and strategic geographic location offers strong potential for green hydrogen development. With an energy import dependency of 94% and annual demand growth of approximately 3%, the country faces an urgent need for sustainable energy solutions [8]. While renewable energy sources currently account for 20% of electricity generation, green hydrogen presents an opportunity to further diversify the energy portfolio and enhance national energy security. Recent studies indicate that Jordan could produce cost-competitive green hydrogen by leveraging its solar resources, thereby supporting both domestic energy goals and export-oriented strategies [9]. Recognising this potential, green hydrogen has been formally integrated into the country's energy and economic development frameworks.

The Economic Modernisation Vision 2023–2033 identifies clean hydrogen as a priority for attracting foreign investment and supporting energy transition goals [10]. Similarly, the National Energy Strategy 2020–2030 outlines the need to develop a regulatory framework and strategy for hydrogen as part of broader targets to increase renewable energy penetration to 31% by 2030 [11].

To operationalise this vision, the Ministry of Energy and Mineral Resources released Jordan's draft National Green Hydrogen Strategy in 2023. The strategy sets clear targets for scaling green hydrogen, including the deployment of up to 8 GW of renewable energy for electrolysis by 2030, the production of 0.6 million tonnes of green hydrogen annually, and the export of 0.5 million tonnes per year by that date. By 2050, the strategy aims for up to 47 GW of electrolyser capacity and 3.4 million tonnes of hydrogen production, with most earmarked for export [12].

However, realising this potential requires overcoming systemic challenges across the hydrogen value chain. Jordan faces multifaceted technological hurdles, particularly in electrolyser efficiency and renewable energy integration [13]. Current infrastructure limitations compound these challenges, as Jordan lacks dedicated hydrogen storage and distribution networks [14]. Economic barriers loom large, with high production costs and immature markets requiring strategic policy interventions [15]. These constraints are exacerbated by Jordan's water scarcity, which complicates the water-intensive electrolysis process despite potential seawater solutions [16,17].

1.3. Objectives of This Study

This study systematically examines these interconnected challenges through empirical research with Jordanian energy stakeholders. By analysing technological readiness, infrastructure gaps, and economic viability, the research provides evidence-based recommendations for green hydrogen deployment. The findings aim to inform Jordan's ongoing energy transition while contributing practical insights to the broader literature on developing-country hydrogen economies.

Jordan's renewable energy targets—aiming for 1.8 GW capacity by 2025—demonstrate a strong commitment to sustainable development [8]. The government recognises green

hydrogen's potential to leverage these renewable investments while creating new industrial opportunities [9,18]. However, success depends on addressing critical infrastructure gaps in grid modernisation, storage systems, and transport networks. International partnerships and targeted policy support will be equally vital for attracting the necessary investments and technological capabilities to establish Jordan as a regional green hydrogen hub [19].

To guide this investigation, the study addresses three core research questions:

- RQ1: What are the primary technological limitations hindering green hydrogen production in Jordan, and how do they relate to renewable energy integration and electrolyser performance?
- RQ2: What infrastructure gaps currently exist in the country's electricity grid, water supply systems, and hydrogen transport networks, constraining sectoral development?
- RQ3: What economic and policy challenges—including costs, incentives, and investment risks—must be addressed to improve the feasibility and scalability of green hydrogen projects in Jordan?

2. Literature Review

Jordan's energy transition toward green hydrogen offers promising potential due to its abundant solar resources. However, it is also marked by critical constraints, particularly in water availability and infrastructure capacity [20–22]. In response to these challenges, Jordan has made notable strides through the signing of 13 international agreements and the adoption of a National Hydrogen Strategy, which aims to achieve 8 GW of renewable energy capacity by 2030 [23–25]. Nevertheless, successfully implementing this strategy depends on resolving persistent technological and economic barriers.

2.1. Technological Challenges

Several interrelated technological challenges impede the advancement of green hydrogen in Jordan. The most critical issues include integrating intermittent renewable energy sources, the operational efficiency of electrolysis technologies, and the country's severe water scarcity. These limitations must be systematically addressed to enable the large-scale deployment of hydrogen production systems.

2.1.1. Renewable Energy Integration

Jordan benefits from substantial solar energy potential, with average irradiance levels ranging from 5 to 7 kWh/m²/day, making it an ideal candidate for renewable-powered green hydrogen production via water electrolysis [26–28]. Despite this advantage, the intermittent nature of solar and wind energy introduces significant operational challenges. Power supply variability can reduce electrolyser efficiency and compromise system longevity, particularly under frequent start–stop cycles.

A range of advanced integration strategies is under active investigation to mitigate these effects. These include smart grid technologies, demand-side management systems, and hybrid renewable energy configurations that combine solar and wind with battery or thermal energy storage [22,29]. Among available electrolyser technologies, Proton Exchange Membrane (PEM) systems are considered especially suitable for such dynamic operating environments due to their fast transient response, compact form factor, and tolerance to variable power inputs [30,31].

Achieving stable grid–hydrogen coupling and maximising the utilisation of renewable energy sources will be critical to ensuring both the scalability and economic viability of green hydrogen production in Jordan.

2.1.2. Electrolysis Technology

Electrolyser technologies used in green hydrogen production exhibit distinct trade-offs regarding efficiency, cost, and compatibility with renewable energy sources. Alkaline Electrolysers (AELs) are commercially mature and widely available; however, they are less responsive to the variable output of renewables and generally require stable, continuous power input. In contrast, Proton Exchange Membrane (PEM) electrolyzers offer a faster dynamic response and better compatibility with intermittent energy supply but rely on costly noble-metal catalysts, significantly increasing capital expenditure (CAPEX) [30,32].

Empirical studies conducted in Aqaba indicate that photovoltaic-driven electrolysis using current technologies can yield a Levelised Cost of Hydrogen (LCOH) of approximately 3.13 USD/kg, underscoring the importance of integrating cost-effective renewable energy inputs into the production process [9].

Recent Anion Exchange Membrane (AEM) technology developments present a promising alternative. By eliminating the need for precious metals, AEM electrolyzers have the potential to reduce system costs by 30–40% while retaining the ability to operate under fluctuating input conditions [33]. These advancements suggest that strategic investment in next-generation electrolyser technologies could substantially enhance the economic feasibility of green hydrogen in Jordan.

2.1.3. Water Resource Management

Jordan's extreme water scarcity—estimated at just 100 m³ per capita per year—poses a critical constraint on the scalability of green hydrogen production [34]. The electrolysis process requires approximately 9 L of purified water to produce one kilogram of hydrogen, adding significant stress to already limited freshwater resources.

To address this challenge, researchers have explored alternative water sources, including seawater desalination, wastewater treatment, and the utilisation of brackish water [23,24,35]. Among these, coastal desalination appears promising given Jordan's access to the Red Sea through Aqaba.

Technological advancements in membrane filtration systems are also contributing to efficiency gains. Recent studies suggest that next-generation membranes can reduce the specific water consumption of electrolysis by 20–30% while enhancing overall system performance [30]. These innovations are critical for enabling hydrogen production in arid regions like Jordan and highlight the necessity of integrated water–energy planning in the national hydrogen strategy.

2.2. Infrastructure Challenges

The successful deployment of a green hydrogen economy in Jordan hinges on addressing critical infrastructure deficiencies. Three primary areas present substantial barriers: transportation networks, grid compatibility, and the availability of electrolyser facilities. These components are essential to supporting the full hydrogen value chain—from production to storage and distribution—at commercial scale.

2.2.1. Electrolyser Facilities

The expansion of electrolyser infrastructure in Jordan is constrained by high capital costs, ranging from USD 500 to USD 1400 per kilowatt, and heavy reliance on imported technologies [31,36,37]. These financial and supply chain dependencies pose a significant barrier to the timely scaling of domestic hydrogen production capacity.

As part of its National Hydrogen Strategy, Jordan has targeted deploying 1.5 GW of electrolyser capacity by 2030 [25]. Achieving this goal will require substantial investment in physical infrastructure and local technical capabilities, including workforce development,

research and development (R&D), and public–private partnerships [38]. Without these parallel efforts, deployment timelines may face delays and compromise cost-effectiveness.

2.2.2. Energy Grid Compatibility

Renewable energy sources currently contribute approximately 26% of Jordan's total energy mix. However, the grid infrastructure lacks the capacity and flexibility to accommodate large-scale electrolyser deployment [18]. The intermittent nature of solar and wind power exacerbates grid stability challenges, particularly when integrated with the high and variable electrical loads associated with hydrogen production.

To address these issues, one emerging solution is the establishment of “hydrogen valleys”—localised industrial clusters that integrate hydrogen production, storage, and end-use applications within a confined geographic area. These hubs can enhance grid efficiency by minimising transmission losses, smoothing renewable variability, and optimising local demand–supply dynamics [9,19]. Such an approach may be particularly well-suited to Jordan's infrastructure context, offering a scalable model for integrating hydrogen technologies with existing energy networks.

2.2.3. Transportation Networks

Hydrogen's inherently low volumetric energy density poses significant logistical challenges, necessitating energy-intensive processes such as compression, liquefaction, or chemical conversion into carriers like ammonia or methanol to facilitate efficient transport [22,39]. These processes add technical complexity and substantial costs to the hydrogen supply chain.

In response, Jordan is exploring the adaptation of existing infrastructure for hydrogen transmission. One transitional strategy under consideration involves repurposing natural gas pipelines for hydrogen blending in the range of 5–20% H₂, enabling early-stage transport without the immediate need for dedicated pipelines [40].

Additionally, the coastal city of Aqaba is positioned as a strategic export hub, capitalising on its maritime access to support international hydrogen trade [41]. Establishing a robust transportation infrastructure for domestic distribution and export will be essential for integrating Jordan into emerging regional and global hydrogen markets.

2.3. Economic Challenges

The economic viability of green hydrogen production in Jordan remains a critical barrier to large-scale deployment. Current estimates place the Levelised Cost of Hydrogen (LCOH) between USD 3.13 and USD 4.42 per kilogram, above global competitiveness benchmarks [9]. This cost challenge is further compounded by the country's water scarcity, necessitating additional purification processes that raise operational expenses (OPEX).

Moreover, the limited size of Jordan's domestic hydrogen market restricts the potential for economies of scale, further inflating production costs [26,29]. Financing green hydrogen infrastructure also presents structural challenges, with constrained access to capital and investor risk concerns.

To address these issues, stakeholders have proposed a range of innovative financial instruments, including green bonds, blended finance models, and risk-sharing mechanisms [20,23,27]. At the policy level, Jordan's Economic Modernisation Vision and recent amendments to the national Electricity Law aim to create a more favourable investment climate for hydrogen projects and stimulate domestic and foreign capital inflows [42].

2.3.1. Policy and Financing

Establishing a competitive green hydrogen economy in Jordan by 2030 will require an estimated investment of USD 5–7 billion [43,44]. This financing level necessitates

mobilising public and private capital, supported through public–private partnerships (PPPs) and sustained international cooperation.

To enhance feasibility planning, a preliminary cost distribution model is provided based on stakeholder expectations and recent techno-economic assessments. Approximately 40% of the investment is projected for electrolyser deployment and associated balance-of-plant (up to USD 2.8 billion), 25% for grid modernisation and energy storage (USD 1.75 billion), 20% for water infrastructure including desalination systems (USD 1.4 billion), and 15% for hydrogen transport, distribution, and export logistics (USD 1.05 billion). These proportions are indicative and depend on evolving project scope, technology costs, and financing structures, but they offer a grounded starting point for investment targeting [45,46].

Securing such investment is contingent upon clear policy signals and a stable regulatory environment that reduces investor risk and supports long-term infrastructure development. While Jordan has initiated several strategic roadmaps, key regulatory gaps persist, particularly in hydrogen safety standards, certification schemes, and cross-border trade protocols [40,47].

Accelerating the development of a comprehensive and harmonised governance framework that is aligned with the European Union (EU) and other best international practices will be vital. Such a framework will enhance investor confidence, attract green financing, enable technology transfer, and position Jordan as a credible hydrogen exporter within the MENA region.

In addition to these strategic gaps, stakeholders identified several operational policy bottlenecks. These include protracted permitting processes for renewable and hydrogen infrastructure, the absence of production-linked subsidies or tax incentives, and limited institutional coordination among energy, environment, and water authorities. A key issue is the lack of a dedicated regulatory body or inter-agency task force to streamline hydrogen governance. Furthermore, Jordan's regulatory frameworks for green finance, carbon trading, and transboundary hydrogen export remain underdeveloped, constraining access to climate-aligned investment and participation in regional markets. Addressing these challenges is essential to reducing administrative friction, improving project bankability, and accelerating hydrogen market readiness.

2.3.2. Economic and Policy Barriers

While recent reforms such as the Economic Modernisation Vision and amendments to the Electricity Law have improved the investment climate, several persistent barriers continue to hinder the realisation of green hydrogen projects in Jordan. These extend beyond direct financial challenges to political, administrative, and institutional dimensions.

- **Permitting and Administrative Delays:** Stakeholders have raised concerns about fragmented responsibilities across agencies, which result in prolonged permitting timelines for renewable and hydrogen-related infrastructure [40,47].
- **Regulatory Gaps and Institutional Capacity:** The absence of established hydrogen safety standards, certification schemes, and export procedures reduces investor confidence and complicates project structuring [40].
- **Insufficient Incentives and De-risking Tools:** Unlike fossil-based energy, green hydrogen lacks consistent support mechanisms. This misalignment discourages investment in early-stage projects, as highlighted by stakeholders and earlier reports [20].
- **Exposure to Cost Volatility and External Shocks:** As noted in techno-economic assessments, Jordan's dependence on imported electrolysis and renewable components exposes it to global price fluctuations, increasing project risk [9,26].

- **Integration with Renewable Energy Systems:** Barriers to land acquisition, grid readiness, and infrastructure siting for RES have cascading effects on hydrogen deployment, as green hydrogen is critically dependent on large-scale renewables [29,42].

Overcoming these intertwined economic and policy challenges will require regulatory streamlining, inter-agency coordination, and well-designed incentive frameworks. These steps are essential to transitioning from strategy development to actionable, bankable green hydrogen projects.

3. Materials and Methods

This study employs a quantitative research design to assess the perceived challenges and potential solutions for green hydrogen deployment in Jordan. The research utilises a structured stakeholder survey to gather empirical data from professionals across the national energy landscape. The approach generates context-specific insights on three core domains: technological readiness, infrastructure capacity, and economic viability.

3.1. Target Population and Sampling

The target population included professionals and domain experts actively engaged in Jordan's energy sector. This sample encompassed individuals working in public institutions, private energy companies, academic and research organisations, regulatory bodies, and non-governmental organisations. Disciplines include policy and regulation, engineering and technology, finance and investment, environmental science, and technical education.

A purposive sampling method was employed to ensure the selection of informed participants with direct experience in green hydrogen or broader energy-related initiatives. This non-probability technique is well-suited for exploratory studies where expert judgment is essential. It enabled the researchers to engage respondents with nuanced perspectives on sector-specific challenges and opportunities.

3.2. Sample Size and Participant Distribution

The final sample was determined based on professional accessibility and sectoral diversity. Fifty-two respondents participated in the study, ensuring adequate representation across stakeholder categories. The sample was stratified to reflect proportional input from the government, private sector, academia, and civil society, thereby enhancing the generalizability of the findings within the Jordanian energy context.

While the sample ensures strong representation from domestic government, private industry, academia, and civil society stakeholders, it does not include international investors or national utility companies. This limitation was primarily due to accessibility constraints during the data collection period. Nonetheless, the selected participants reflect a wide spectrum of professional expertise and institutional roles directly engaged in Jordan's green hydrogen and energy transition efforts.

3.3. Survey Instrument Design

Data were collected using a structured questionnaire titled "Green Hydrogen Production Challenges in Jordan". The instrument was designed to capture both quantitative ratings and qualitative insights and was divided into seven sections:

- **Demographic Information:** This captured organisational affiliation, professional role, sector, years of experience, and field of expertise.
- **Knowledge of Green Hydrogen:** This assessed familiarity with green hydrogen concepts, applications, and relevance to Jordan's energy future.
- **Technological Challenges:** These investigated perceptions of technical barriers such as renewable integration, electrolyser efficiency, and water resource limitations.

- **Infrastructure Challenges:** These evaluated views on grid readiness, transport logistics, and facility availability.
- **Economic Challenges:** These explored issues related to cost competitiveness, market maturity, and financing mechanisms.
- **Solutions and Recommendations:** These collected expert judgments on strategic enablers and policy interventions.
- **Additional Comments:** These provided an open-ended section for supplementary observations and insights.

Most closed-ended questions used a 5-point Likert scale (1 = Strongly Disagree, 5 = Strongly Agree). In addition, multiple-choice items with “select all that apply” options were used to capture nuanced stakeholder inputs. Each thematic section included 5–8 items on average, accompanied by one open-ended question to elicit qualitative elaboration.

The survey was administered electronically and underwent a two-stage validation process. First, a pilot test was conducted with five experts to ensure clarity and relevance. Second, feedback was incorporated to refine question wording and improve thematic alignment.

Participation was voluntary, and all respondents provided informed consent before completing the survey.

3.4. Data Analysis

Responses were analysed using R statistical software (version 4.3.1). Descriptive statistics were used to quantify trends and distributions across survey sections. Inferential methods, including chi-square tests and ANOVA, were applied to examine associations between respondent characteristics and perceived barriers.

In addition, correlation matrices were developed to identify interdependencies among technological, infrastructural, and economic variables. These analyses revealed co-occurrence patterns and potential causal linkages, particularly between renewable integration challenges and cost-related constraints.

The analytical process was structured to support evidence-based recommendations and inform future policy formulation. The triangulation of quantitative ratings and qualitative insights ensured a comprehensive understanding of stakeholder perspectives on green hydrogen deployment in Jordan.

4. Results

4.1. Stakeholder Demographics

A total of 52 professionals participated in the survey, providing a broad cross-section of Jordan’s energy community. Most respondents (74%) reported more than five years of sector experience, with the largest cohort (55%) exceeding ten years. Sector representation was well distributed: private industry (36%), government agencies (32%), academia (18%), non-governmental organisations (12%), and consulting firms (2%).

Participants occupied six primary professional roles: engineers (16), managers (13), industry professionals (10), academics (8), consultants (3), and researchers (2). Figure 1 illustrates how years of experience are distributed within each role, underscoring the seniority of the sample, particularly among engineers and managers, who together account for 29 of the 52 respondents.

4.2. Knowledge of Green Hydrogen

Respondents exhibited a broad spectrum of familiarity with green hydrogen concepts. The largest share was neutral in their self-assessment (34.6%), followed by those who described themselves as very familiar (26.9%). Participants reporting slight familiarity or no familiarity together constituted 23.1%, while expert-level familiarity accounted for 15.4%.

This distribution confirms that the survey captured viewpoints ranging from introductory awareness to deep technical expertise.

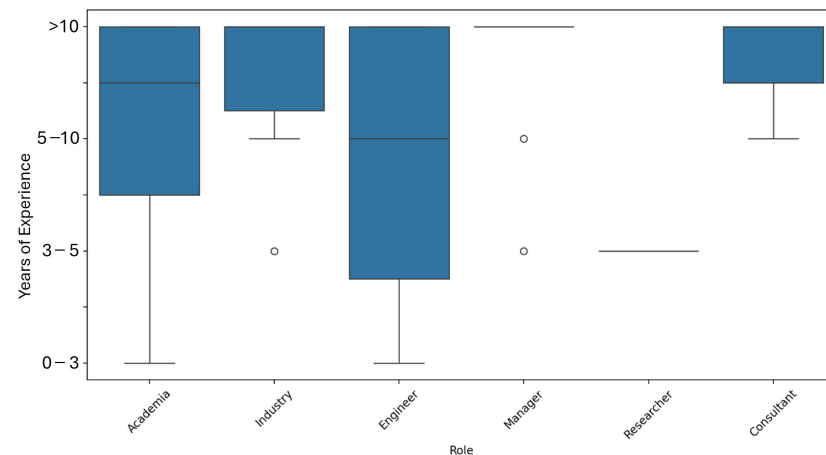


Figure 1. Experience profile of survey respondents by professional role. Bars indicate number of individuals in each role, segmented by years of experience. White circles represent statistical outliers within each experience category.

A one-way ANOVA indicates that years of energy-sector experience significantly influence green hydrogen knowledge ($F = 4.131$, $p = 0.013$). Figure 2 visualises this relationship: professionals with more than ten years in the field are disproportionately represented in the very familiar and expert categories, whereas early-career respondents cluster around the neutral midpoint.

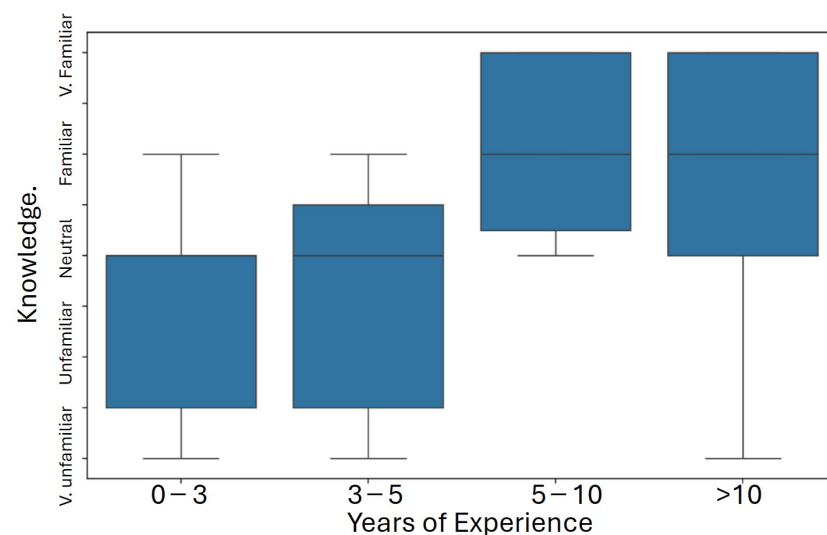


Figure 2. Effect of professional experience on self-reported green hydrogen knowledge. Columns show the percentage of respondents in each knowledge tier, ranging from *Very Unfamiliar* to *Very Familiar*.

These findings suggest that practical exposure over time is a primary driver of subject-matter confidence. They also highlight a training opportunity: practitioners with fewer than five years of experience form the largest share of the slight and no familiarity groups, indicating where capacity-building programs could be most impactful.

4.3. Applications of Green Hydrogen

A clear consensus emerged on the strategic value of green hydrogen for Jordan's energy transition. More than two-thirds of respondents (69.2%) rated green hydrogen deployment as either Important or Very Important; only 3.8% viewed it as Not Important.

Multiple end-use segments were highlighted, often in combination:

- Industrial processes—71.2%;
- Power generation—63.2%;
- Energy storage—59.6%;
- Transportation—57.7%.

The perceived benefits map closely onto these applications. Carbon-emission reduction was most frequently cited (71.2%), followed by enhanced energy security (69.2%), diversification of energy sources (67.3%), and new economic opportunities (61.5%).

Together, these results indicate strong stakeholder alignment around the multifaceted utility of green hydrogen, particularly in industry and power generation, and reinforce the technology's role as both an environmental and economic lever for Jordan.

4.4. Technological Challenges

Survey respondents identified three principal technical barriers to large-scale green hydrogen deployment in Jordan: (i) renewable energy integration; (ii) electrolyser efficiency; (iii) water resource management. The following subsections present the quantitative findings that underpin each theme.

4.4.1. Renewable Energy Integration

Overall sentiment toward the current effectiveness of renewable–hydrogen coupling was mixed: a total of 36.5% of participants selected Neutral, while 28.8% rated it Effective. Three barriers dominated stakeholder concern:

- High costs—69.2%;
- Technology gaps—50.0%;
- Intermittent supply—46.2%.

Figure 3 shows how perceptions vary by professional role. Intermittency was strongly role-dependent ($\chi^2 = 12.4$, $p = 0.03$), whereas cost and technology concerns were broadly shared ($\chi^2 = 4.8$, $p = 0.4$).

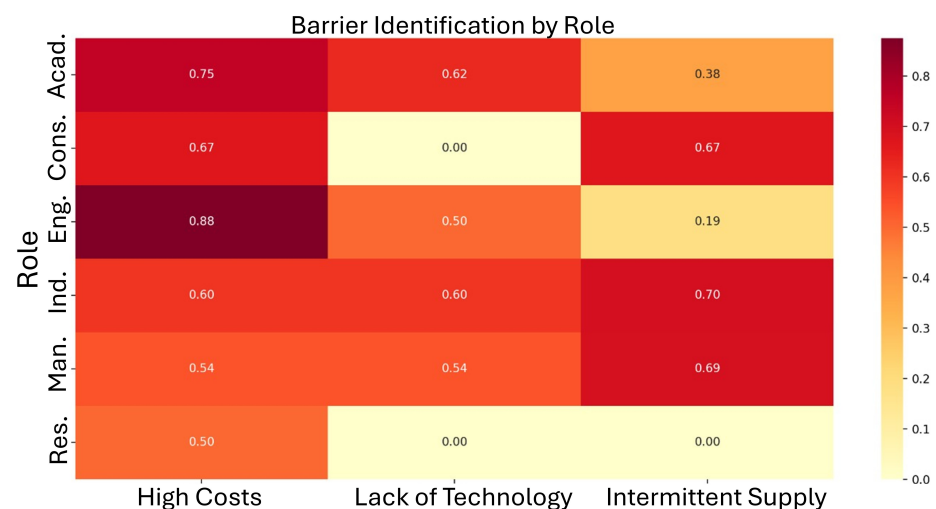


Figure 3. Barrier identification by role.

Experience and knowledge further shape these views (Figures 4 and 5). Respondents with > 10 years in the sector showed $\geq 80\%$ agreement on the three fundamental barriers, while higher technical-knowledge scores significantly increased the likelihood of selecting Technology Gaps ($\chi^2 = 10.5$, $p = 0.03$).

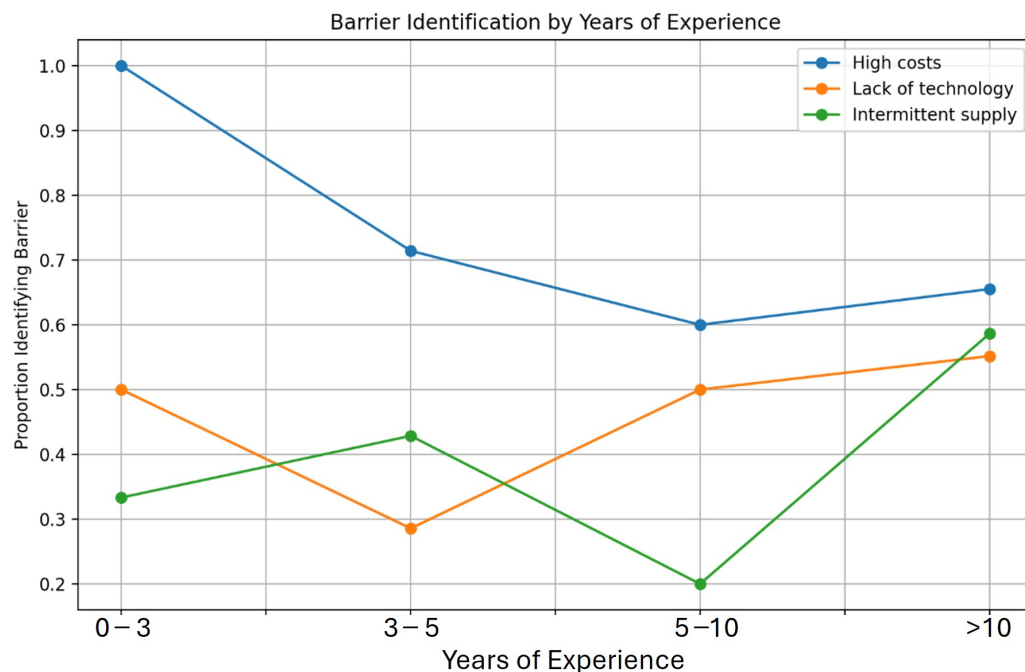


Figure 4. Barrier identification as a function of years of experience.

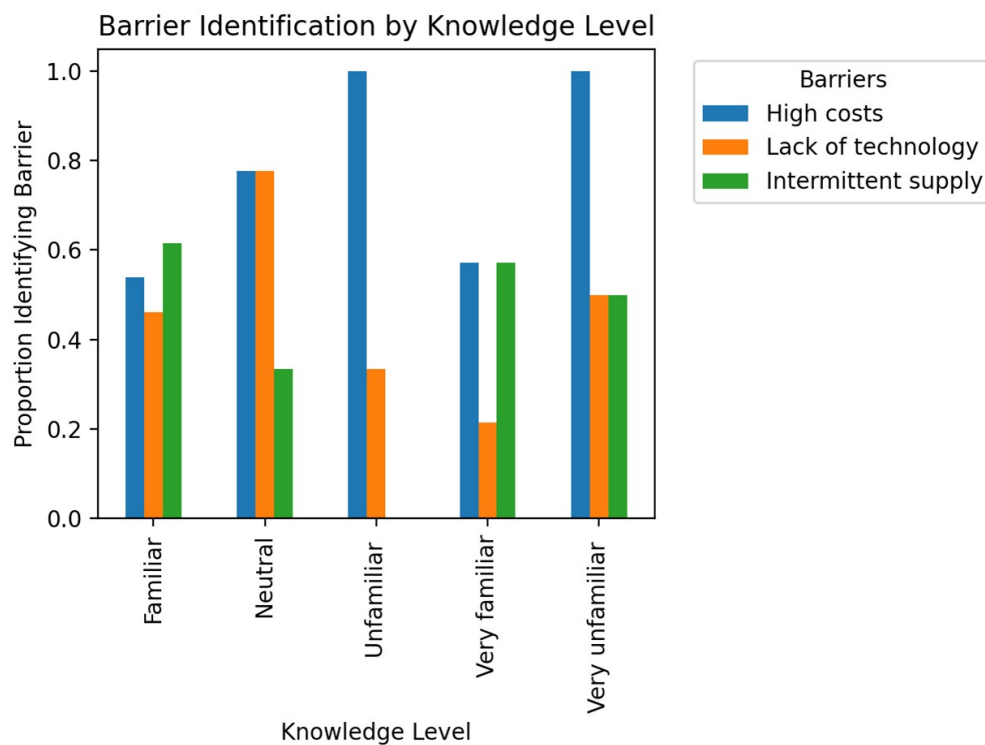


Figure 5. Barrier identification by self-reported knowledge level.

Proposed technical remedies cluster around four options: advanced energy-management systems (31.5%), hybrid renewable portfolios (17.5%), battery storage (16.9%), and smart-grid

upgrades (15.7%). Niche solutions—e.g., concentrated solar power and solar gasification—each attracted 0.6% support.

4.4.2. Electrolysis Technology

Figure 6 summarises stakeholder preferences for electrolyser types and associated hurdles. Proton Exchange Membrane (PEM) units were deemed most suitable (30%), marginally ahead of Alkaline Electrolysis (AEL) (26%). Nearly half of the respondents (44%) expressed no clear preference, signalling a need for greater technical outreach.

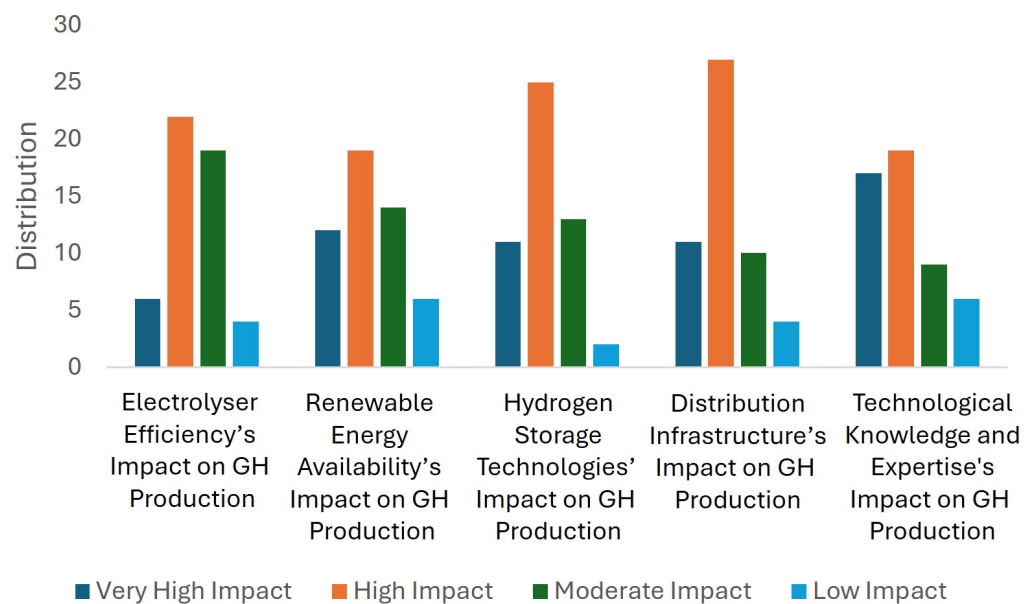


Figure 6. Perceived impact of specific technological barriers.

Key findings include

- Distribution infrastructure was identified as the highest-impact barrier (51.9%);
- Hydrogen storage followed closely as the next most significant barrier (48.1%);
- Renewable energy availability was rated as Very High by 23.1% of respondents, while electrolyser efficiency received a Very High rating from 11.5%.

Operational pain-points echo these themes: high operating costs (33%), energy consumption (30.6%), and efficiency limitations (20%). Uncertainty about true barriers remains for 10.6% of respondents—evidence of lingering knowledge gaps.

Suggested remedies prioritise R&D investment (36.6%) and broader technology advancement (34.7%), followed by increased capital investment (CAPEX) (24.8%).

4.4.3. Water Resource Management

Water scarcity is nearly unanimous as a critical concern: a total of 86% of respondents rated it Significant or Very Significant. Alternative water sources favoured are

- Seawater desalination—76.9%;
- Wastewater reuse—46.2%;
- Brackish water—32.7%.

Technological solutions mirror these preferences. Desalination technologies led with 78.8% support, while improved water-use efficiency 21%, alternative sources (22%), and integrated water–energy strategies (16%) formed the secondary tier.

The data suggest that an integrated pathway—combining robust renewable supply, next-generation electrolysis, and coastal desalination—is considered the most viable route for Jordan’s hydrogen ambitions.

4.5. Infrastructure Challenges

Survey responses highlight substantial infrastructure gaps that must be bridged before Jordan can scale green hydrogen deployment. Two domains emerged as the most pressing: grid compatibility and transport logistics.

4.5.1. Grid Compatibility

Respondents expressed limited confidence in the existing electrical grid’s readiness for large-scale electrolyser integration. Fewer than one in ten (9.6%) deemed the grid compatible, and only 3.8% rated it highly compatible. The remainder described the grid as either slightly compatible (38.5%) or not compatible (23.1%). A chi-square test confirms that perceived compatibility is significantly associated with suggested remedies ($p < 0.05$).

Key obstacles:

- Insufficient investment—40%;
- Needed grid upgrades—36%;
- Technology limitations—22%.

Priority solutions:

- Smart-grid deployment—41%;
- Physical grid modernisation—28%;
- Enhanced regulatory support—28%.

A minority of respondents advocated for decentralised approaches (e.g., micro-grids, export-first strategies) to mitigate central-grid stress.

4.5.2. Transport-Network Development

Figure 7 summarises stakeholder assessments of hydrogen transport readiness. Over half (51.9%) reported no network development, while only 3.8% judged the current infrastructure well-developed.

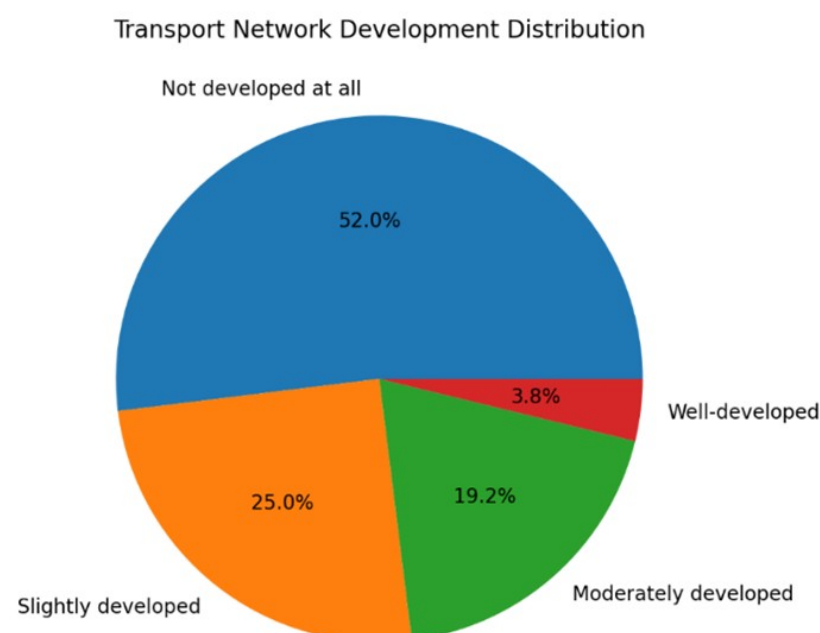


Figure 7. Perceived maturity of Jordan’s hydrogen transport infrastructure.

Principal barriers:

- High costs—82.7%;
- Infrastructure deficits—71.2%;
- Safety concerns—61.5%.

Proposed remedies:

- Broad infrastructure investment—84.6%;
- Storage facility build-out—71.2%;
- Advances in storage technology—57.7%.

Several respondents underscored Aqaba's potential as an export node, suggesting an export-driven, phased approach: prioritising port and pipeline upgrades to attract early investment and extending domestic distribution once volumes justify dedicated hydrogen lines.

The grid and transport findings depict an infrastructure ecosystem in its infancy. Stakeholders converge on large-scale investment and smart-technology deployment as necessary precursors to Jordan's hydrogen rollout.

4.6. Economic Challenges

Stakeholders identified a multifaceted economic landscape in which high production costs, uncertain market demand, and limited access to finance constitute the primary hurdles to green hydrogen deployment.

4.6.1. Production Costs

Cost perceptions followed a trimodal distribution (Low, Moderate, High). A cautiously optimistic minority (1.9%) classified levelised production costs as Low. The modal response was High (40.4%), followed by Moderate (25.0%) and Very High (32.7%).

Three cost drivers dominated:

- Expensive technology;
- High energy costs;
- Scarcity of resources (primarily water).

Suggested cost-reduction levers formed a balanced set: policy incentives, technological advancements, increased investment, and economies of scale.

4.6.2. Market Demand

Demand expectations were moderately positive. While 26.9% of respondents rated market pull as Very High and 32.7% as High, the modal response was Moderate (34.6%). Only a small minority considered demand to be Low (3.8%) or absent (1.9%).

Priority uptake sectors are:

- Industry;
- Power generation;
- Transportation.

Subsidies (30%), regulatory support (28%), and tax incentives (26%) are preferred demand-stimulation tools; public awareness campaigns were less favoured (15%).

4.6.3. Investment Climate and Financing

Only 11.5% of stakeholders deemed Jordan's investment climate Very Attractive, 32.7% found it Moderately Attractive, and 26.9% Slightly Attractive. Key deterrents are

- Regulatory uncertainty—69.2%;
- Financing accessibility—63.4%;

- Perceived risk—59.6%.
Favoured financing instruments are tax breaks (71.2%), grants or subsidies (63.4%), and public–private partnerships (59.6%); streamlined regulation ranked fourth (46.2%).
Cross-tabulation reveals that respondents prioritising infrastructure investment (38%) are 22 percentage-points more likely to endorse PPPs, while those emphasising R&D (37%) show elevated preference for grant funding (31% versus the 26% baseline).
Qualitative feedback underscores an export-led vision: a total of 18% of open-ended comments cite Jordan’s geographic advantage for serving European and Asian markets, whereas 12% remain sceptical of near-term international demand.
Overall, respondents converge on three financial imperatives:
 1. Cost-reduction measures (cited by 35%) paired with targeted incentives (34%);
 2. Regulatory alignment and risk mitigation (37%);
 3. Coordinated infrastructure and financing strategies, frequently anchored in PPP models.

4.7. Summary of Key Findings

The quantitative evidence reveals (i) a mature, experienced stakeholder base, (ii) strong consensus on green hydrogen importance across multiple end-use sectors, (iii) three dominant technical barriers—renewable integration, electrolyser performance, and water scarcity—and (iv) infrastructure and financial hurdles that remain unresolved. These results provide the empirical foundation for the subsequent discussion, where policy, investment, and technology implications are examined in detail. Table 1 summarises these findings.

Table 1. Summary of key barriers and insights.

Barrier Category	Specific Barriers	Key Insights
Technological	Electrolysis efficiency limitations	Current electrolyser technologies exhibit suboptimal efficiency, increasing overall production costs.
	Limited availability of advanced renewable energy	Renewable capacity is insufficient to sustain large-scale hydrogen production.
	Compatibility issues with existing energy grids	Grid infrastructure requires upgrades to effectively integrate hydrogen systems.
	Water resource security	Water-intensive processes pose a major constraint in water-scarce countries like Jordan.
Infrastructure	Lack of smart grid and hydrogen transport networks	Absence of hydrogen-ready infrastructure limits distribution and commercial deployment.
	Insufficient water desalination and treatment systems	Desalination is essential but adds energy costs, reducing overall system efficiency.
Economic	High production costs (LCOH)	Green hydrogen remains more expensive than fossil-based alternatives without subsidies.
	Limited investment and financing mechanisms	Lack of de-risking tools and financial incentives constrains private sector involvement.
Policy and Regulatory	Absence of a clear regulatory framework	Undefined hydrogen laws and standards delay project implementation.
	Insufficient policy incentives and subsidies	Targeted financial support and national programs are needed to catalyze market growth.

5. Discussion

The stakeholder survey reveals a complex interplay of technological, infrastructural, and economic challenges shaping the development of green hydrogen in Jordan. This discussion integrates those empirical insights with the relevant literature to reflect on the country’s opportunities and constraints.

To structure the analysis, Table 2 summarises the main challenges and insights identified by stakeholders, grouped into three core dimensions. This table also highlights potential mitigation strategies further elaborated on in the following thematic subsections.

Table 2. Summary of key barriers and stakeholder insights on green hydrogen in Jordan.

Category	Key Barriers	Stakeholder Insights/Suggested Interventions
Technological	Low electrolyser deployment; limited R&D; compatibility with intermittent renewables	Favour PEM for solar-rich grid; call for public R&D support and international tech transfer
Infrastructure	Weak grid integration; no H ₂ storage or pipelines; transport bottlenecks	Prioritise smart grid upgrades; coordinate hydrogen hubs with desalination and logistics
Economic	High LCOH; limited subsidies; lack of carbon pricing	Support PPPs; design incentive mechanisms; integrate hydrogen into national energy strategy

While many of the identified challenges—such as water scarcity, electrolyser limitations, and grid constraints—are well-documented in the literature, this study adds novel empirical depth by capturing how stakeholders perceive and prioritise these issues in the Jordanian context. Notably, contrary to some techno-economic projections that minimise the impact of water supply, stakeholders view water availability as a core limiting factor, even in the early stages of hydrogen planning. Moreover, despite these structural challenges, over half of the respondents expressed moderate-to-high optimism about Jordan’s green hydrogen potential, reflecting confidence in long-term opportunities if infrastructure and policy frameworks are aligned. This optimistic outlook, grounded in direct practitioner input, is an important deviation from model-based assessments that often emphasise cost barriers alone.

5.1. Technology and Infrastructure Alignment

Stakeholders favoured Proton Exchange Membrane (PEM) electrolyzers over alkaline systems due to their compatibility with intermittent renewable energy, an important factor in a solar-dominant context like Jordan. This preference contrasts with certain techno-economic models prioritising alkaline systems for lower capital costs, suggesting practitioners emphasise system responsiveness over initial expenditure.

Water scarcity emerged as a universal concern, frequently identified as a core barrier to hydrogen production. This concern differs from many theoretical assessments where water availability is considered a secondary issue. Respondents commonly supported seawater desalination as a mitigation strategy, reflecting Jordan’s geographic proximity to the Red Sea, though this approach introduces additional infrastructure and energy demands.

Seawater desalination is a promising solution to address water scarcity in green hydrogen production, especially in arid regions. However, the energy required for desalination processes can contribute marginally to the overall economics and environmental footprint of hydrogen production. The energy demand for producing one cubic meter of freshwater through desalination varies depending on the technology, typically ranging from 3 to 10 kWh/m³ [48].

Optimising the coupling between desalination units and electrolyzers, such as advanced membrane distillation techniques, can improve overall system efficiency.

While desalination-related energy reductions are unlikely to lower the Levelised Cost of Hydrogen significantly, system-level integration still supports sustainability and reliability objectives. This analysis highlights the critical importance of considering water supply technologies within the green hydrogen production chain, as neglecting desalination’s energy and cost implications can lead to underestimating overall production challenges. Integrating these factors strengthens the assessment of green hydrogen feasi-

bility in water-scarce regions and guides more informed decision-making for sustainable project development [49].

Confidence in the country's grid infrastructure was limited, with most stakeholders viewing it as inadequate for supporting large-scale electrolyser integration. Transport networks were also considered underdeveloped. Commonly cited barriers included insufficient investment, physical infrastructure gaps, and unresolved safety considerations.

A core barrier identified by stakeholders is the suitability and economic feasibility of electrolyser technologies under Jordan's renewable energy conditions. While PEM electrolysers are favoured for their rapid response to variable solar input, their capital and operational expenditures remain higher than alternatives. To enhance the discussion, Table 3 provides a comparative overview of three key technologies—alkaline (AEL), Proton Exchange Membrane (PEM), and Anion Exchange Membrane (AEM)—across key performance indicators, including CAPEX, OPEX, efficiency, and scalability [45].

Table 3. Comparison of key electrolyser technologies relevant to renewable hydrogen deployment.

Technology	CAPEX	OPEX	Efficiency (HHV)	Scalability and Notes
Alkaline (AEL)	500–900 USD/kW	Low (mature tech)	60–70%	Widely deployed; slow ramp-up; best for steady loads
PEM	1000–1800 USD/kW	Medium to High	65–75%	Fast response; suited for intermittent renewables; higher cost
AEM (emerging)	700–1200 USD/kW (estimated)	Medium	65–70% (lab-scale)	Promising hybrid; limited commercial data; under development

As shown in Table 3, AEL remains the most cost-effective option for large-scale base load operation. Despite higher costs, PEM is better suited for Jordan's solar-dominated grid due to its flexibility and fast ramping characteristics. Although still emerging, AEM technology may offer a future middle ground once it achieves commercial maturity.

5.2. Economic and Policy Perspectives

Stakeholders expressed mixed views on the economic feasibility of green hydrogen. Key cost drivers were identified as capital expenses (CAPEX) related to electrolyser technologies, the cost of renewable energy inputs, and challenges related to water access. Respondents called for comprehensive solutions, including financial incentives, investment mobilisation, technological innovation, system scale, and efficiency improvements.

The industrial and power-generation sectors were seen as the most viable entry points for green hydrogen adoption, with less emphasis on transportation. Although there is cautious optimism about the investment climate, stakeholders noted the need for greater regulatory clarity, improved access to finance, and mechanisms to manage investment risk. Preferred financial instruments included tax breaks, direct subsidies, and public–private partnerships.

To move from strategic ambition to implementation, Jordan should adopt several concrete policy measures. First, a dedicated Hydrogen Regulatory Taskforce could be established to streamline permitting, coordinate ministries, and oversee certification and safety standards. Second, a “Green Hydrogen Investment Platform” could be developed to consolidate incentives such as concessional loans, guarantees, and green bonds. Third, fast-track permitting zones could be replicated in Aqaba or Ma'an to accelerate project development. Finally, Jordan should explore Contracts-for-Difference mechanisms to reduce investor risk, taking cues from Germany's H2Global and the EU Hydrogen Bank. These targeted policy instruments would address the critical gaps in governance, bankability, and infrastructure development identified by stakeholders in this study.

5.3. Integrated Strategy and Outlook

The findings support an integrated, three-pillar framework for green hydrogen deployment in Jordan:

- **Technology–Infrastructure Nexus:** Prioritizing investment in renewable energy integration, electrolyser deployment, grid modernization, and seawater desalination.
- **Economic–Policy Ecosystem:** Implementing targeted financial instruments and regulatory reforms to enhance bankability and reduce perceived investment risks.
- **Knowledge–Capacity Foundation:** Strengthening technical expertise, institutional preparedness, and inclusive stakeholder participation.

This coordinated approach acknowledges technical, economic, and policy progress interdependence. Advancing one dimension in isolation is unlikely to deliver transformative outcomes.

The survey findings also reveal that while stakeholders remain cautious about short-term deployment hurdles, their medium- to long-term outlook on hydrogen in Jordan is largely optimistic. As shown in Figure 8, most respondents expressed positive expectations about the country’s capacity to develop a competitive green hydrogen sector, reinforcing the need for coordinated national planning and investment.

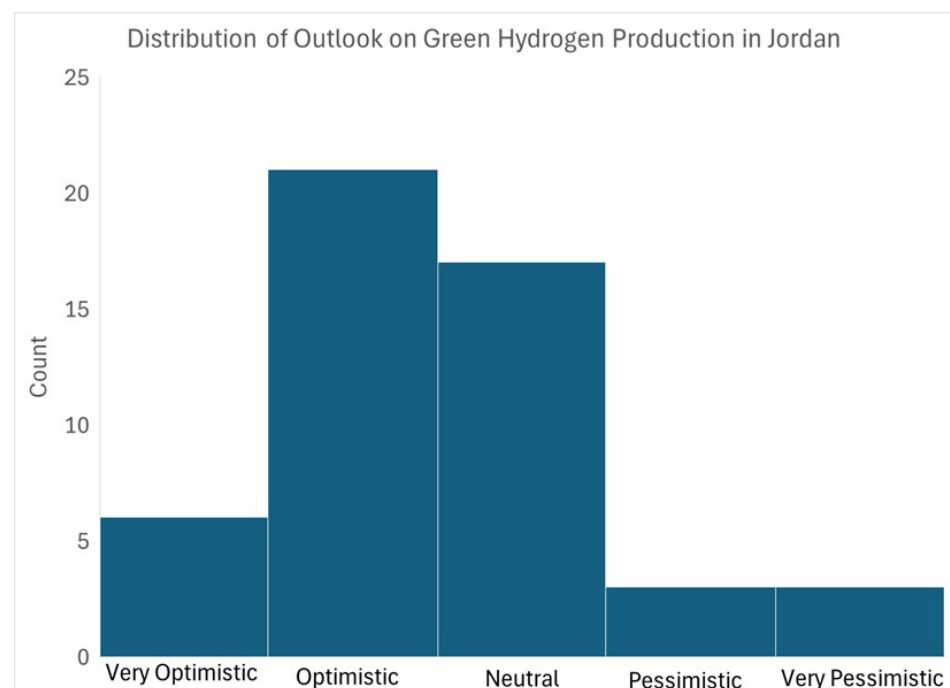


Figure 8. Stakeholder outlook on future of green hydrogen production in Jordan.

The findings reflect cautious optimism among stakeholders. Jordan’s abundant renewable resources and strategic location offer a foundation for regional leadership in hydrogen. Still, success will depend on sustained infrastructure investment, effective governance, and capacity building across the public and private sectors.

5.4. Comparative Analysis with Existing Studies

The results of our stakeholder-driven study align with and expand upon several existing assessments of green hydrogen development in Jordan. Across the literature, common challenges, such as renewable energy integration, electrolyser efficiency, and water scarcity, are frequently cited. Our findings confirm these issues but further reveal how practitioners perceive them regarding urgency, interdependency, and practical feasibility.

Our study adds depth by directly capturing the views of energy-sector professionals, who consistently emphasise operational concerns like grid compatibility, infrastructure readiness, and gaps in regulatory and investment frameworks. These perspectives complement model-based studies, such as those by Gado et al. [50], which rely on techno-economic projections without incorporating on-the-ground stakeholder input. For instance, while prior analyses suggest that water scarcity has a limited impact on hydrogen production costs, our respondents view it as a critical barrier, indicating a disconnect between modelled assumptions and stakeholder risk perceptions.

Similarly, the national-level analysis by Shboul et al. [18] highlights the importance of a national strategy, international collaboration, and social acceptance—points that our respondents support. Still, it does not fully address operational barriers such as permitting delays, financial instrument preferences, or real-time grid limitations that emerged in our study.

The techno-economic modelling by Jaradat et al. [9] provides valuable cost comparisons of ALK and PEM electrolyzers in Aqaba, identifying photovoltaic energy as the most economical source. Our findings support this conclusion while adding insight into perceived technical gaps, stakeholder knowledge levels, and investment bottlenecks not visible in simulation-based studies.

Unlike earlier studies focusing on long-term macroeconomic benefits, our results emphasise short-term priorities and practical enablers grounded in stakeholder-validated implementation needs, such as subsidies, PPPs, and regulatory clarity. This micro-level perspective extends the existing literature by connecting strategic objectives to local operational realities, offering actionable insights for decision-makers.

5.5. Comparative Analysis with MENA Peers

To situate Jordan's green hydrogen challenges within a broader regional context, we conducted a comparative analysis with other MENA countries actively pursuing hydrogen strategies—namely Morocco, Egypt, Oman, and Saudi Arabia. Each country shares renewable energy potential and export ambitions yet faces distinct technological, infrastructural, and economic barriers.

Jordan's reported LCOH range of 3.13–4.42 USD/kg [9] is broadly consistent with estimates for Morocco (2.54–3.49 USD/kg) [51], Egypt (1.02–3.94 USD/kg) [52], and Oman (2.74–4.65 USD/kg) [53], but remains notably lower than the figures reported for Saudi Arabia under hybrid diesel–renewable configurations (5–7 USD/kg) [54].

Regarding technology readiness, Morocco and Egypt are deploying hybrid PV–wind systems with spatial optimisation, while Oman benefits from existing experience in ammonia and synthetic fuel exports. Saudi Arabia's hydrogen program is closely tied to large-scale solar and wind developments integrated with industrial megaprojects like NEOM. Jordan, in contrast, has not yet implemented full-scale hydrogen pilots or established a local supply chain for electrolyser components.

Infrastructure readiness also varies significantly. Morocco is advancing port retrofits and hydrogen-ready pipelines; Egypt is expanding desalination capacity and internal transport links to hydrogen zones like the Suez Canal Economic Zone. Oman is leveraging its deep-water ports and gas infrastructure, while Saudi Arabia's infrastructure is state-led and part of broader Vision 2030 industrial investments. Jordan's 400 kV grid is modestly developed but lacks hydrogen-compatible storage and distribution assets.

From an economic perspective, Morocco and Egypt benefit from early foreign direct investment, clear institutional arrangements, and alignment with EU energy markets. Oman has positioned itself as a low-cost exporter through large consortia such as the Duqm hydrogen cluster, targeting primarily Asian markets. Saudi Arabia's unmatched scale

and strong government backing are accompanied by high capital intensity and exposure to global pricing risks. Jordan's policy framework remains under development, with stakeholders emphasizing the need for public–private partnerships (PPPs), subsidies, and clearer investment incentives.

This comparative synthesis is supported by the recent literature, including Ersoy et al. [51], Rezk [55], Marzouk [56], and Muhieithen et al. [54], and underscores both the alignment and divergence of regional trajectories. Table 4 consolidates these findings.

Table 4. Green hydrogen barriers and solutions in selected MENA countries.

Country	Technological Challenges	Infrastructure Challenges	Economic Challenges	Proposed Solutions
Jordan	Limited electrolyser deployment; low R&D capacity	Grid not hydrogen-ready; no pipelines or storage	LCOH 3.13–4.42 USD/kg; weak incentives	Boost R&D; grid upgrades; clear PPP rules
Morocco	Limited local tech expertise; desalination constraints	Ports/pipelines under retrofit	Export competition; financing gaps	EU export ties; capacity building; long-term deals
Egypt	Tech localisation; foreign equipment dependence	Grid/logistics upgrades in hydrogen zones	High CAPEX; evolving policy	FDI; regulatory streamlining; PPPs
Oman	Imported tech adaptation; water–energy integration	Ports/gas infra adapted gradually	Price uncertainty; demand volatility	Duqm hub; bilateral deals; Asian markets
Saudi Arabia	Scaling systems to industrial level; water access	NEOM ports/pipelines developing	High investment needs; global exposure	Megaproject backing; policy support; global capital

Jordan's positioning of Aqaba as a green hydrogen export hub gains strategic relevance when viewed against global demand and regional competition. European and Asian markets will dominate green hydrogen imports by 2030 and beyond. The European Union aims to import approximately 10 million tonnes per year of renewable hydrogen by 2030, with further increases through 2040 [7]. Japan and South Korea have announced similar ambitions, with combined import needs projected to exceed 6 million tonnes annually by 2030 [46]. These targets are driving a surge in supply-side activity from countries like Australia, Oman, Saudi Arabia, and Namibia, each offering large-scale, low-cost production potential and increasingly sophisticated port and ammonia infrastructure [50,57].

Jordan's strategic use of Aqaba within this competitive landscape offers distinct logistical advantages. As Jordan's only maritime outlet on the Red Sea, Aqaba allows access to European markets via the Suez Canal and Asian destinations without territorial transit dependencies. The Aqaba Special Economic Zone already hosts petrochemical and logistics infrastructure and has been identified in Jordan's draft hydrogen strategy as a core enabler for hydrogen exports [12]. Planned projects include integrated solar–wind–electrolyser systems coupled with desalination and dedicated port terminals. These co-located developments are expected to reduce the Levelised Cost of Hydrogen (LCOH) while accelerating infrastructure readiness. By aligning project commissioning timelines with anticipated demand surges in Europe and Asia, Jordan aims to secure early-mover status in the green hydrogen trade and differentiate itself through proximity, cost-efficiency, and cross-border alignment with key energy partners.

6. Conclusions

6.1. Synthesis of Findings

This study comprehensively assesses Jordan's green hydrogen landscape by synthesising insights from national stakeholders across the energy, policy, industry, and academic

domains. The findings reflect cautious optimism rooted in the country's solar abundance and geographic advantage, yet they are tempered by significant technological, infrastructural, and economic barriers.

Technological challenges—namely intermittent renewables, electrolyser efficiency limitations, and water scarcity—are among the most pressing barriers. Infrastructural gaps in smart grids, hydrogen storage, and transport networks compound these.

From an economic standpoint, high production costs and limited access to financing remain major obstacles. Nevertheless, stakeholders identified key enablers—such as financial incentives, PPPs, and export-oriented investment strategies—that can support green hydrogen development if aligned with infrastructure and policy improvements.

Based on these findings, three strategic priorities emerge: (1) infrastructure development, particularly in grid integration, desalination, and storage systems; (2) policy reform that includes incentive mechanisms, investment guarantees, and safety standards; and (3) international partnerships for technology transfer, certification harmonisation, and market access.

Jordan's combination of high solar irradiance, regional access via the Port of Aqaba, and political stability makes it a credible candidate for regional leadership in green hydrogen. However, unlocking this potential depends on cross-sectoral coordination, pilot-scale validation, and evidence-based planning.

6.2. Future Research Directions and Pilot Integration

To support practical implementation, future research should prioritise the following areas:

- **Desalination–Electrolysis Integration:** Assess co-located seawater desalination and hydrogen production in Aqaba, focusing on system efficiency, LCOH, and brine management.
- **Floating PV Electrolysis:** Test small-scale floating PV–electrolyser systems to evaluate water savings, PV cooling effects, and suitability in arid regions.
- **Localised End-Use Pilots:** Conduct feasibility studies for small-scale H₂ end-uses such as fuel-cell bus fleets or port logistics operations.
- **Monitoring of Flagship Projects:** Evaluate real-world outcomes from pilot initiatives like the Jordan Green Ammonia project and track lessons learned on integration, permitting, and infrastructure.
- **Infrastructure and Regulatory Models:** Explore centralised infrastructure concepts and regulatory enablers (e.g., shared pipelines, electricity pricing) to guide scalable hydrogen clusters.

These directions align with Jordan's strategic goals and help operationalise the country's hydrogen roadmap through actionable pilot studies and implementation-focused research.

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Abbreviations

The following abbreviations are used in this manuscript:

PEM	Proton Exchange Membrane
AEL	Alkaline Electrolyser
AEM	Anion Exchange Membrane
LCOH	Levelised Cost of Hydrogen
PPP	public–private partnership
R&D	research and development
GW	Gigawatt
kWh	Kilowatt-hour
H ₂	hydrogen
ANOVA	Analysis of Variance
CAPEX	capital expenditure
OPEX	operational expenditure
EU	European Union

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