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Advancing sustainable transport: Renewable energy integration in hydrogen refueling stations

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ABSTRACT

Decarbonizing the transport sector is imperative for achieving the global climate objectives outlined in the Paris Agreement. This review provides a systematic evaluation of renewable-powered hydrogen refueling stations within sustainable transportation frameworks. Drawing on forty-one high-impact studies published between 2019 and 2024, the analysis is structured around three principal themes: (1) integration of renewable energy with hydrogen production, (2) design, operational efficiency, economic viability, and safety considerations of hydrogen refueling stations, and (3) management and optimization of integrated energy systems. By synthesizing region-specific empirical data and computational modeling from these studies, this review consolidates critical operational, economic, and infrastructural opportunities and challenges associated with hydrogen refueling stations, addressing both the barriers and opportunities in the deployment of sustainable hydrogen infrastructure for transportation. Providing an in-depth snapshot of the current state of research in this rapidly evolving multidisciplinary domain, this review offers substantive policy recommendations for policymakers, industry stakeholders, and researchers.

1. Introduction

The intensifying impacts of climate change necessitate a comprehensive and systematic decarbonization of the transportation sector, which remains a major contributor global greenhouse gas emissions. Road transportation alone accounts for approximately 10 % of global greenhouse gas emissions, contributing to an estimated 59 $GtCO_2e$ from all anthropogenic sources, with the transportation sector emitting 7.98 Gt CO_2 in 2022 [1–3]. Achieving substantial reductions in these emissions demands transformative systemic changes, as emphasized by international agreements such as the Paris Agreement and the Conference of the Parties (COP) pledges, which collectively aim for net-zero carbon emissions by mid-century.

Battery electric vehicles (BEVs) and hydrogen fuel cell vehicles (HFCVs) have emerged as promising alternatives to internal combustion engines (ICEs), offering significant emission reductions through the use of renewable electricity and hydrogen as energy carriers [4–9]. Both vehicle types are critically dependent on the integration of renewable energy, underscoring the importance of concurrently decarbonizing energy systems to maximize their emission reduction potential [10,11].

Hydrogen refueling stations (HRSs) are essential to the clean energy transition, providing critical infrastructure for incorporating hydrogen into the transportation sector and facilitating the deployment of HFCVs for a sustainable future. As of 2022, approximately 1100 HRSs support over 70,000 HFCVs worldwide [12]. However, the expansion of HRS infrastructure presents considerable challenges, particularly due to the intermittency of renewable energy sources such as wind and solar photovoltaic (PV), as well as the high costs associated with producing low-emission hydrogen [13]. Nevertheless, the International Energy Agency's (IEA) Net Zero by 2050 report projects a hundred-fold increase in low-emission hydrogen production by 2030 [14], highlighting the need for cohesive, interdisciplinary efforts to address technical and economic barriers and to advance global decarbonization objectives.

With global renewable capacity projected to reach 7300 GW by 2028—a 70 % increase from 2022 levels [15]—the role of hydrogen in decarbonizing transportation is expected to expand significantly. This surge in renewable electricity creates a promising pathway for HRSs to scale green hydrogen production and reduce reliance on fossil fuels. Direct integration of solar PV and wind energy into HRSs enables low-carbon hydrogen production, while hybrid systems offer additional cost reductions, making renewable hydrogen increasingly competitive with conventional fuels [16–20].

The rapid deployment of renewable energy sources, however,

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Abbreviations

BEV	Battery electric vehicle
CCHP	Combined cooling, heating, and power
COP	Conference of the Parties
GHG	Greenhouse gas
HFCV	Hydrogen fuel cell vehicle
HRS	Hydrogen refueling station
IEA	International Energy Agency
IES	Integrated energy systems
LCOH	Levelized cost of hydrogen
PV	Photovoltaic

presents challenges for electrical grids, which often lack the flexibility and storage capacity needed to manage increased loads. Grid congestion in regions with renewable project backlogs, such as Spain, the United States, Japan, Brazil, and Italy, underscores the necessity of balancing grid demands with renewable growth [21]. This congestion limits grid availability for HRSs, adversely impacting electrolysis processes that depend on renewable electricity and hindering the economic optimization of renewable energy utilization for both grid consumption and resale. Conversely, converting curtailed renewable energy into hydrogen represents a promising solution, serving both as an energy storage medium and as a clean fuel source. Hydrogen can store excess energy and act as a dispatchable source to alleviate grid congestion, albeit requiring substantial initial investment.

To address these barriers and opportunities, this review categorizes the literature into three primary areas: (1) the integration of renewable energy with hydrogen production, (2) the design, operational efficiency, economic viability, and safety considerations of HRSs, and (3) integrated energy systems management and optimization. This structured categorization provides a comprehensive snaphot of the current state of research, enabling the systematic identification of patterns, emerging trends, and key thematic insights across existing studies.

This review offers a novel, region- and context-specific perspective on integrating renewable energy into hydrogen production for transport, an angle largely absent in the existing literature. By synthesizing evidence across diverse geographies, and providing an in-depth snapshot of the current state of research in this rapidly evolving multidisciplinary domain; this review shows how local renewable resource availability, grid conditions, and policy environments shape techno-economic outcomes. The contribution is fourfold: (i) it establishes a comparative framework that normalizes outcomes across contexts, (ii) it develops a three-category synthesis—renewable integration, HRS design and operations, and IES optimization—that bridges technical, economic, and system-level perspectives, (iii) it identifies cross-cutting barriers and enablers such as water scarcity in arid zones, grid access as a decisive driver of levelized cost of hydrogen (LCOH), and scaling dynamics of centralized versus onsite production, and (iv) it situates HRSs within multi-vector integrated energy systems, highlighting their role in renewable absorption, microgrid resilience, and grid stabilization. This structured synthesis positions this review to offer well-founded recommendations for policymakers, industry stakeholders, and researchers with context-sensitive insights.

While this review centers on hydrogen production via electrolysis due to its compatibility with renewable electricity sources and prominence in the analyzed studies, it is important to recognize other emerging low-carbon pathways. Biomass gasification, methane pyrolysis, and photobiological processes have been investigated as alternative clean hydrogen production methods with varying degrees of technological maturity and scalability. For example, methane pyrolysis offers the potential for low-emission hydrogen with solid carbon byproducts, while biomass-based methods may be viable in regions with abundant agricultural waste. However, these alternatives often face limitations in terms of regional resource availability, infrastructure compatibility with HRSs, or integration challenges with intermittent renewable energy. Thus, while electrolysis remains the dominant technology discussed in this review, future research could benefit from broader techno-economic comparisons that incorporate these emerging methods.

2. Methodology, scope, and structure of the literature review

This systematic literature review provides a structured in-depth analysis of renewable energy integration into HRSs. Employing clearly delineated inclusion and exclusion criteria, the review synthesizes research pertaining to the economic, operational, and policy aspects of sustainable HRS development. The methodology, adapted from [22] and executed through fifteen well-defined stages, is designed to ensure both objectivity and reproducibility, summarized in Fig. 1.

2.1. Systematic review rationale and justification for timeframe (2019–2024)

This systematic review presents a synthesis of research on hydrogen and renewable energy from 2019 to 2024, a period characterized by significant technological advancements and evolving policy landscapes. The chosen timeframe encapsulates critical developments in policy frameworks, industrial momentum, and technological innovations that collectively shape the trajectory of hydrogen-based infrastructure.

During this period, significant policy initiatives, such as the IEA's Net Zero by 2050 roadmap and various COP agreements, catalyzed a heightened global emphasis on decarbonization and the transition to low-emission energy systems. Concurrently, the industry experienced a marked surge in momentum, driven by increased governmental and corporate commitments to hydrogen-based transportation solutions, underscoring a worldwide shift toward sustainable energy practices. Technological advancements in electrolysis, hydrogen storage, and the integration of renewable energy sources have enhanced the technical and economic viability of HRSs. Consequently, this timeframe is critical for investigating configurations that optimize the use of renewable energy in HRSs, within sustainable energy frameworks.

2.2. Database selection and search strategy

To establish a comprehensive and high-quality foundation for the literature review, three primary databases were utilized: Science Citation Index Expanded (Web of Science), Scopus, and ScienceDirect. Each of these databases provides distinct advantages, particularly in their coverage of interdisciplinary, high-impact research pertinent to energy, sustainability, and environmental sciences. The search strategy was systematically designed to incorporate specific keywords targeting key thematic areas: "hydrogen refueling station" (exact match) within abstracts, "renewable energy" (exact match) within titles, subject areas, and abstracts (all fields), and "hydrogen storage" (contains) within titles, subject areas, and abstracts (all fields). To ensure the rigor and quality of the selected literature, only full-text publications in English from peer-reviewed journals were considered. The initial search yielded one hundred eighteen papers which were subsequently subjected to a rigorous filtering process based on defined inclusion and exclusion criteria to refine the final selection.

"Hydrogen storage" is included in this review as a complementary aspect to hydrogen refueling and renewable energy integration rather than as a primary focus. The analysis centers on integrating renewable energy into HRS to advance sustainable transportation. Hydrogen storage is considered specifically in cases where it directly supports HRS operations, including scenarios where battery energy storage systems are involved together with hydrogen energy storage systems. This narrowed scope allows the review to maintain a concentrated emphasis on renewable-integrated HRSs, effectively avoiding an expanded focus on

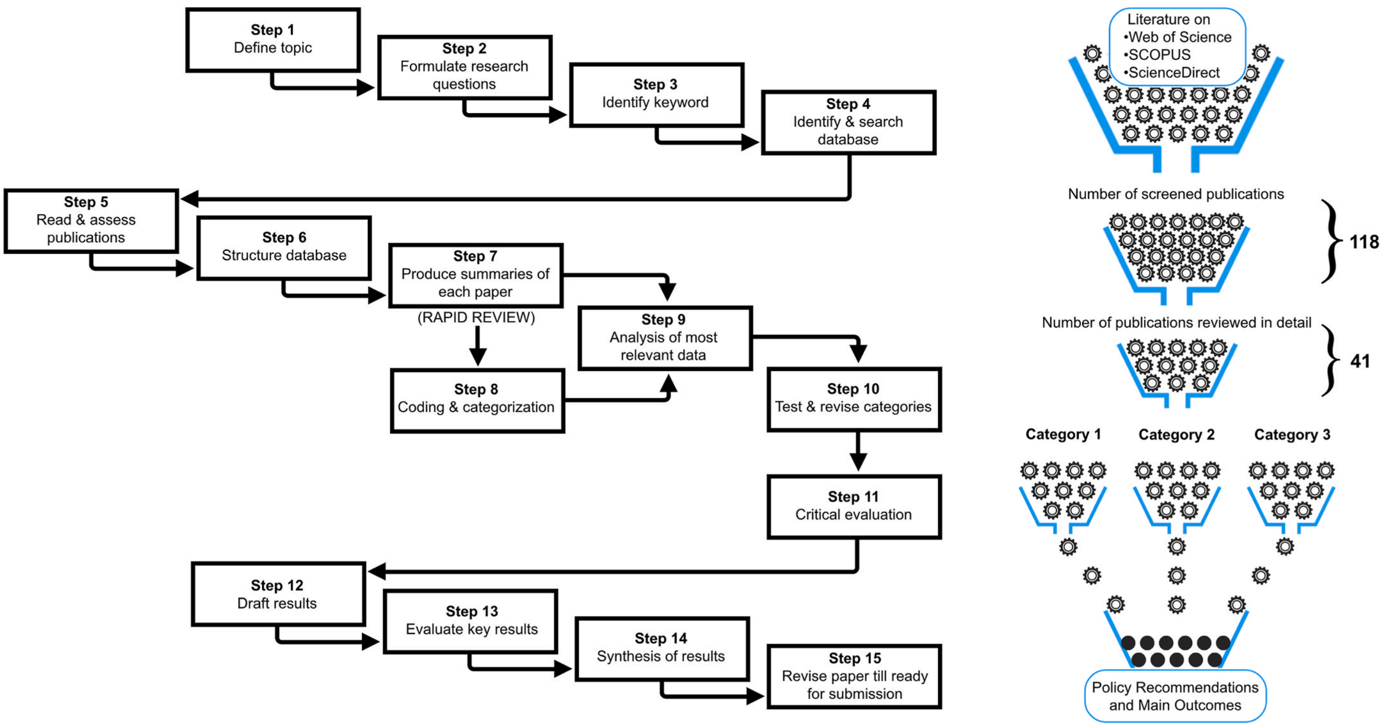

Fig. 1. Procedure of systematic literature review in 15 steps. Modified version from Ref. [22].

general energy storage technologies.

2.3. Inclusion and exclusion criteria

To refine the dataset and ensure alignment with the review's objectives, a thorough inclusion and exclusion process was employed.

- Inclusion criteria: Studies were selected if they (1) provided empirical, experimental, or modeling-based insights into the integration of renewable energy with HRSs, (2) investigated economic, technical, or policy aspects critical to HRS development, and (3) were published in full-text, peer-reviewed English-language journals.
- Exclusion criteria: Conference proceedings, book chapters, and review articles were excluded to maintain a focus on primary research contributions. Furthermore, studies with only superficial references to HRSs or renewable energy, as well as those centered on non-renewable hydrogen production, were excluded to ensure a consistent emphasis on sustainable energy systems.

Following the application of these criteria, forty-one studies were identified for in-depth examination. This process distilled the dataset to encompass studies that most effectively represent contemporary research trends and challenges in renewable energy integration with HRSs facilitating a thorough analysis of key findings. The screening process proceeded in three stages: initial filtering of one hundred eighteen records by title and abstract, and full-text review to apply inclusion/exclusion criteria (Step 1 – Step 5 in Fig. 1.). This ensured that the final forty-one studies were not only topically relevant but also methodologically robust and transparently reported.

2.4. Analysis and synthesis process

The selected studies were analyzed through a multi-step process to provide a coherent synthesis.

- Database structuring, coding and categorization: For each study, a broad set of variables was extracted, including contributions, keywords, highlights, objectives, methods, results, conclusions, findings, proposed future work, participants (where applicable), and citations. These fields were systematically recorded to enable comparative synthesis. The extracted data were coded and classified into three distinct thematic categories, as delineated in the introduction. This categorization enabled a focused examination of the relevant topics. (Step 6 – Step 10 in Fig. 1.).
- Critical evaluation and drafting results (Step 11): Quality assessment focused on methodological rigor and transparency. Modeling studies were assessed for validation methods, sensitivity analyses, and clarity of assumptions, while empirical studies were evaluated based on data transparency, reproducibility, and robustness of findings. Studies failing to meet these standards were excluded from synthesis.
- Synthesis (Step 12–15): Thematic findings were systematically synthesized to develop an integrated understanding of the current knowledge landscape, elucidate practical implications, and inform evidence-based policy recommendations.

These steps were conducted in line with the 15-stage workflow adapted from [22], ensuring consistency between the screening, coding, evaluation, and synthesis phases.

2.5. Limitations and sources of potential error

This systematic review is subject to several limitations that shape the scope and applicability of its findings. First, the review exclusively examines studies published between 2019 and 2024, with the intent of capturing advancements in HRSs and renewable energy integration. While this temporal focus ensures the relevance of the review to contemporary developments, it inevitably excludes earlier foundational research that may offer critical contextual insights or alternative methodologies, thus potentially narrowing the analytical scope.

A further limitation arises from the exclusive reliance on peer-reviewed journal articles as the primary data source. Although peer-reviewed literature provides a high level of methodological rigor and reliability, this focus may inadvertently omit valuable practical insights found in industry reports, government publications, and other non-peer-reviewed sources. As a result, the review's applicability to operational decision-making and policy formulation may be constrained by the lack of diverse perspectives.

The synthesis of modeling-based and empirical studies is intended to provide a comprehensive understanding of HRS performance. However, the inherent limitations of modeling studies must be acknowledged, as they frequently depend on controlled assumptions that do not always capture the complexity and variability of real-world conditions. This can lead to discrepancies in economic, efficiency, and scalability projections. Additionally, substantial regional heterogeneity exists in the studies reviewed, encompassing differences in renewable energy resources, infrastructure maturity, and economic contexts, all of which limit the generalizability of the findings.

3. Review of category one: integration of renewable energy with hydrogen production

The reviewed category one studies demonstrate adaptable, region-specific strategies for integrating renewable energy into hydrogen production. Table 1 summarizes the key configurations, contexts, and findings of the reviewed studies.

Table 1
Overview of key aspects in category one studies.

Authors	Focus	Region/ Context	Key Findings
[23]	Optimal sizing of wind-hydrogen systems	China	Producing hydrogen with wind and grid power is advantageous under low wind conditions, with fuel cells proving cost-ineffective
[24]	Sizing, optimization, and financial analysis of HRS	Greece; isolated, grid-limited regions	Cost-effective strategies for remote areas focus on sizing and storage, but low HFCV penetration limits economic viability
[25]	Techno-economic analysis of off-grid PV-HRS	Tunisia	Feasible under high solar irradiance; off-grid configurations offset regulatory limitations.
[26]	PV-wind hybrid system optimization	Saudi Arabia; high solar and wind areas	Hybrid PV-wind configurations reduce LCOH, enhancing economic feasibility through seasonal optimization
[27]	On-grid vs. off-grid hydrogen costs	Sweden	Grid integration significantly reduces costs; wind speed is crucial, while solar radiation is less impactful
[28]	Optimal design and site selection for wind-powered HRS	South Africa; wind-rich coastal regions	Coastal regions in South Africa are promising for wind-powered hydrogen production
[29]	Operational strategy and modeling of on-site HRSs; dual-mode electrolysis	Spain	Dual-mode electrolysis (renewable/grid) lowers costs and increases flexibility
[30]	Grid-connected wind-based HRS optimization	Oman (Salalah); high-wind region	Grid-supported HRS achieves optimal hydrogen costs in high-wind areas, emphasizing the grid's role in cost control.
[31]	Standalone PV-wind-battery system configurations	France; urban settings in twenty cities	PV-only configurations yield the lowest hydrogen costs in high solar exposure areas

3.1. *Global efforts in renewable hydrogen production and context-driven hydrogen refueling station deployment strategies*

Renewable hydrogen production is increasingly recognized as a cornerstone of energy sustainability and global decarbonization. The case studies reviewed in this section underscore how techno-economic feasibility depends on local resource profiles, infrastructure, and regulatory frameworks, rather than technology choice alone. Across regions, lower LCOH is consistently associated with the strategic deployment of regionally optimized renewable resources and tailored system architectures.

[26] examines hybrid solar PV and wind systems in Riyadh, Saudi Arabia, demonstrating how seasonal complementarities between solar and wind resources can be exploited to minimize costs, achieving an LCOH of $4.23/kg. In a similar climatic region yet constrained by the absence of regulatory and infrastructural frameworks for hydrogen mobility, [25] presents an off-grid PV-based HRS in Tunisia. The system achieves an LCOH of 3.32 EUR/kg while supplying 150 kg/day of hydrogen, confirming its technical feasibility under high solar irradiance conditions. However, the study also identifies water consumption—estimated at approximately 9 L per kilogram of hydrogen—as a limiting factor, particularly for arid environments [25]. These two cases highlight how similar resource profiles can yield divergent outcomes depending on infrastructure readiness and environmental constraints.

Nevertheless, the mere presence of abundant renewable resources does not inherently guarantee economic viability. Seasonal variability and resource intermittency can significantly affect system performance. Ref. [27] demonstrates this in the Swedish context, where grid-connected wind-based hydrogen production remains economically favorable in Gothenburg and Stockholm due to relatively stable wind conditions. Conversely, in Mariestad and Halmstad, where wind variability is more pronounced, LCOH increases markedly, reinforcing the necessity of grid support mechanisms in temperate zones with fluctuating renewable inputs. Similarly, in China, hybrid wind–grid systems stabilize production under low wind availability, but low fuel cell utilization (~3.1 %) undermines economics [23]. Oman provides further evidence that grid-connected designs are more cost-effective (6.24 €/kg) than off-grid alternatives relying on batteries or fuel cells [30].

Spatial mapping of renewable resources emerges as another critical determinant. In South Africa, coastal wind-powered HRSs achieve much lower costs (~6.34 $/kg) compared to inland stations (~8.97 $/kg), reinforcing the importance of siting strategies [28]. A comparable lesson arises in Greece, where an isolated off-grid system utilizing surplus wind from a 10 MW farm demonstrates technical feasibility but faces economic hurdles due to limited HFCV penetration and policy gaps [24].

Urban contexts present additional complexities. In France, a comparative analysis across twenty cities finds PV-only systems outperforming wind-inclusive hybrids, with LCOH ranging from 13.5 to 16.5 $/kg [31]. These results implicitly reflect siting constraints and infrastructure limitations despite strong solar resources. To enhance system flexibility, [29] proposes dual-mode electrolyzers capable of switching between renewable and grid electricity in Spain. This configuration improves operational resilience and cost-efficiency in environments with intermittent renewable availability. However, its practical applicability remains constrained by the assumption of robust grid infrastructure—an assumption not always valid in remote or underdeveloped areas. Standalone systems are most suitable for resource-rich but grid-limited areas such as Tunisia, coastal South Africa, and remote Greek regions, while grid-connected or dual-mode systems perform better in regions with renewable variability but reliable grid access, such as Sweden, Oman, and Spain.

On a normalized basis, Tunisia's PV-only HRS achieves among the lowest costs (~3.3 €/kg), Saudi Arabia leverages hybrid complementarities under Vision 2030 achieving an LCOH of $4.23/kg, and South Africa shows a stark coastal–inland cost divide (~6.34 vs. 8.97 $/kg). In

Sweden, costs range from ~3.5 to 7.2 €/kg depending on wind resources, while Oman reports 6.24 €/kg. In France, HOMER-optimized standalone PV–wind–battery systems across twenty urban locations yield LCOH values of 13.5–16.5 $/kg, with PV-dominant designs (e.g., Marseille) outperforming wind-inclusive configurations. China, integrating wind with grid electricity stabilized production under low-wind conditions and reduced costs relative to wind-only systems, though fuel cells were deemed uneconomical due to low utilization.

Three recurring factors explain techno-economic outcomes across contexts: (1) renewable resource availability and seasonal complementarity, as seen in Saudi Arabia and Tunisia, (2) Grid access and connection capacity, highlighted in Sweden, Oman, and Spain, and (3) market demand, particularly linked to the penetration of HFCVs as demonstrated by Greece where the economic outlook remains constrained due to limited vehicle deployment and extended payback periods, indicating the importance of market readiness and policy support.

Collectively, these findings demonstrate that renewable resource complementarity (PV–wind seasonality), grid availability, water use constraints, and spatial siting conditions—not technology type alone—determine techno-economic outcomes. This region-specific synthesis moves beyond technology-centered surveys by clarifying why results converge or diverge across contexts and by offering a comparative framework that supports evidence-based planning.

4. Review of category two: design, operational efficiency, economic viability, and safety considerations of hydrogen refueling stations

This section synthesizes findings focusing on design, operational strategies, economic viability, and safety protocols. It highlights critical advancements in HRS infrastructure despite regional differences in implementation. The synthesis emphasizes that regional tailoring of HRS designs can drive substantial gains for hydrogen refueling solutions in diverse geographic contexts. Across cases, geography (urban hubs vs. corridors; grid reliability), electricity tariffs (level and volatility), delivered distance/logistics (trailer utilization, route length), and storage strategy (onsite buffer vs. underground/corridor storage) are the proximate determinants of LCOH alongside fleet scale. Table 2 provides focus and insights into strategic adaptations suited to the challenges and resources of its respective region.

4.1. Innovative design approaches, and Italian case studies

[32] proposes repurposing conventional gasoline stations into electric–hydrogen hybrid refueling facilities using a DC microgrid architecture. Their model integrates hydrogen production, battery storage, and renewables in an islanded configuration, with fuzzy-logic control optimizing real-time energy flows based on demand and storage status. Although not situated in Italy, by minimizing AC–DC conversion losses and maintaining operation during grid outages, this design offers practical lessons for regions with unreliable grids or islanded systems seeking autonomous refueling infrastructure.

In Sardinia, Italy, [35] assesses a hydrogen valley concept that links renewable electricity from wind and solar sources with multiple end uses—HRSs, natural gas grid injection, and biomethanation. By converting excess hydrogen into synthetic methane, the system achieves a competitive LCOH of ~5 €/kg while reducing renewable curtailment and diversifying its revenue streams. This highlights how multipurpose integration can stabilize utilization rates and improve financial viability in regional hydrogen valleys. Ref. [36] examines the i-NEXT project in Capo d'Orlando, Sicily, where PV-based electrolysis combined with battery storage reduces procurement costs and cuts hydrogen production expenses by up to 64 % annually compared to grid-reliant alternatives. By shifting electrolysis into solar hours and using stored power at night, the system directly exploits Southern Italy's high solar availability while avoiding elevated grid tariffs, demonstrating how local resource profiles can be leveraged for small-to-medium HRS deployment. In Naples, [37] presents an on-site HRS model that utilizes a grid-connected solar plant, incentivized by CO_2 credits linked to emissions reductions. The system only reaches cost competitiveness when carbon credit values surpass a defined threshold, underscoring the

Table 2
Overview of key aspects in category two studies.

Authors	Focus	Region/ Context	Key Findings
[32]	Conversion of gasoline stations to electric-hydrogen hybrid HRS stations using DC microgrid	China	Stabilizes hydrogen and battery storage; high initial investment
[33]	Optimizing electrolyzer operations for cost efficiency and wind energy utilization	Germany	Reduced hydrogen costs by optimizing electrolyzer with wind power
[34]	Two-layer optimization model for HRS using water electrolysis and methanol-based production	China	Flexible production adapts to fluctuating energy prices, improving cost efficiency
[35]	Economic optimization of green hydrogen valley using wind/solar energy	Italy	Cost-effective green hydrogen production for multiple end-users
[36]	Economic analysis of solar-powered HRS	Italy	PV-based HRS lowers hydrogen production costs
[37]	On-site solar-powered HRS with CO2 avoidance incentives	Italy	Incentives based on CO2 avoidance promote sustainable solar HRS operations
[38]	Cost minimization strategy based on electricity demand fluctuations	China	Off-peak electricity usage reduces costs and optimizes hydrogen production
[39]	Transitioning taxis to HFCVs with PV energy	Brazil	PV reduces HRS costs, supporting cost-effective taxi fleet HFCVs
[40]	Economic evaluation of fuel cell bus fleets and storage strategies	Europe	Strategic storage configuration impacts costs and fuel availability
[41]	Scaling up HRS with centralized/decentralized production, supply to a fuel cell bus fleet	Europe	Centralized HRS saves 35 % in costs; decentralized depends on transport costs
[42]	Renewable hydrogen supply chain for urban bus networks	Ireland	Wind and solar use reduce operational costs for decarbonized bus networks
[43]	Grid-free hydrogen supply chain for heavy goods vehicles with storage optimization	United Kingdom (UK)	Storage optimization enhances cost-effectiveness for heavy goods vehicles hydrogen transport
[44]	Grid-connected HRS design for heavy-duty transport along Highway 401	Canada	Grid-tied HRS with solar/wind cuts emissions in transportation
[45]	Simulating hydrogen leakage/explosion risk with safety recommendations	China	High-pressure safety protocols essential to mitigate explosion risks
[46]	Hydrogen leakage/diffusion safety analysis	China	Wind flow and tank placement critical for safety in hydrogen diffusion
[47]	Leakage and dispersion risk assessment for mobile HRS safety	General	Identifies high-risk areas, enhancing mobile HRS safety design
[48]	Protective barriers around HRS for explosion risk mitigation	Korea	Protective barriers around HRS reduce explosion risks by 30 %
[49]	Integrated safety-economic model post-Norway explosion	Norway	Proactive design integrates safety and economic efficiency

volatility of carbon pricing and its central role in the feasibility of urban hydrogen production where space constraints and high electricity costs amplify dependence on stable incentives.

These case studies, while contextually diverse, converge on several critical insights. First, modularity and flexibility in system design—whether through DC microgrids, battery-supported solar electrolysis, or multi-vector hydrogen valleys—emerge as instrumental in enabling adaptation to local energy availability and regulatory environments. Second, integrating hydrogen with other end-uses (e.g., bio-methanation, natural gas blending) helps mitigate variability in demand and supports economic viability. Third, the role of financial mechanisms, especially carbon credit systems, is central but region-dependent, underlining the importance of aligning technical planning with evolving policy frameworks. Overall, these findings show that techno-economic viability depends not on generic technical templates but on solutions anchored in renewable profiles, grid economics, and policy frameworks.

4.2. Strategic applications of hydrogen refueling stations for diverse vehicle fleets in global contexts: heavy-duty vehicles, fuel cell buses, taxis

This section examines the deployment of HRSs across diverse vehicle categories—specifically heavy-duty trucks, public transit buses, and taxis. The focus lies on techno-economic performance, spatial deployment strategies, and renewable energy integration within different vehicle fleet configurations. Hydrogen production for heavy-duty vehicles is crucial in reducing emissions within the transportation sector [50, 51]. As nations move toward decarbonized transportation systems, hydrogen has emerged as a critical enabler, particularly for mobility segments where BEVs face operational constraints such as the heavy-duty segment. These include high bursts of power, payload sensitivity, extended driving ranges, and limited grid accessibility. In such scenarios, HFCVs offer competitive advantages due to higher energy density, faster refueling times, and greater suitability for intensive-duty cycles.

Recent comparative analyses underscore that HRS deployment must be situated within the broader transport–energy system rather than treated in isolation. Ref. [10] shows that while BEVs currently benefit from more extensive charging infrastructure, hydrogen mobility is constrained by limited refueling infrastructure and the high cost of renewable hydrogen production. The study highlights that HFCVs can only achieve competitive well-to-wheel performance when supported by low-carbon electricity or carbon capture in hydrogen production, whereas BEVs are more directly tied to grid decarbonization trajectories. This comparison suggests that, in the near term, hydrogen's role will remain concentrated in segments where BEVs face operational constraints such as the heavy-duty segment and buses, but its wider adoption depends on accelerated HRS rollout and cost reductions in renewable hydrogen supply.

Additionally, BEV charging infrastructure exerts high localized demand on electricity networks, requiring significant grid reinforcement, while HRSs redistribute renewable energy via storage and conversion, offering complementary rather than directly competing pathways for decarbonization. This duality suggests that hydrogen demand may act as a stabilizing mechanism in renewable-rich systems by absorbing oversupply, whereas BEV deployment accelerates grid-scale electrification. Together, these findings underline that strategic planning must integrate HRS deployment with BEV infrastructure (as will be seen in Section 5) and grid development, ensuring that the two technologies evolve as synergistic rather than parallel systems in advancing low-carbon mobility.

Heavy-duty freight and transit fleets reveal clear scale effects. For small fleets, such as those modeled for Italy, decentralized on-site electrolysis consistently outperforms centralized supply due to the disproportionate impact of compression, delivery, and storage costs in low-demand scenarios [40]. These localized systems can be closely coupled with renewable resources, enhancing sustainability. As fleet size grows, however, economies of scale shift the balance. The 3Emotion project shows that centralized production serving ~100 buses lowers the levelized cost of hydrogen (LCOH) by optimizing electrolyzer and trailer utilization, though costs still remain above the EU's 2 €/kg target without strong policy and renewable support [41].

Long-haul freight corridors introduce additional complexity. In the UK, a grid-independent supply chain with underground storage ensures reliable supply across long distances, reducing exposure to grid limitations [43]. By contrast, in Ontario's Highway 401 corridor, a grid-connected hybrid of PV, wind, and storage achieved an LCOH of $2.03/kg with ~93 % renewable penetration, highlighting the potential of corridor-scale systems when grid backup and hybrid renewables are combined [44].

Urban bus and taxi networks highlight the sensitivity of outcomes to electricity prices and station scale. In Ireland, on-site electrolysis for buses proved economically viable when paired with low-cost electricity and high electrolyzer utilization, pointing to the importance of tariff structures and utilization rates [42]. In Brazil, a solar-powered HRS for taxis reported hydrogen costs between $8.96 and $13.55/kg, with feasibility heavily dependent on station sizing and the cost of grid electricity backup [39].

Across these cases, consistent patterns emerge: 1) On-site production is more cost-effective for small, dispersed fleets (e.g., localized bus or taxi systems) where delivery costs are prohibitive. 2) Centralized production becomes advantageous for large, clustered fleets (e.g., >100 buses) where economies of scale outweigh delivery costs. 3) Freight corridors demand either resilient off-grid solutions (UK) or hybrid grid-linked systems (Canada) to ensure supply security. 4) Urban deployments are especially sensitive to electricity price regimes and policy incentives, with feasibility hinging on carbon credits or tariff design.

These findings suggest that techno-economic viability is not determined by technology choice alone but by fleet scale, geography, and energy price regimes. In practice, decentralized systems suit low-demand or geographically dispersed fleets, while centralized hubs align with large urban depots and freight corridors. This comparative framework clarifies why outcomes diverge across regions and provides a strategy for tailoring HRS deployment to specific mobility contexts. Table 3 synthesizes these findings, presenting comparative insights into the suitability of various HRS configurations across case studies.

4.3. Strategic synthesis: grid integration and the evolution of hydrogen refueling infrastructure

As HRSs expand in alignment with decarbonization goals, grid integration emerges as a central axis of technical design and strategic planning. Linking HRSs to electricity networks provides multiple

Table 3
Centralized vs. Onsite Hydrogen Production: Evidence from Case Studies.

Authors	Production Mode Analyzed	Key Findings
[40]	On-site electrolysis for small fleets	On-site more cost-effective for small fleets (2–8 buses); delivery costs not justified at low demand
[44]	Solar-powered on-site electrolysis on highway	On-site production avoids transport costs; suitable for dispersed or remote regions
[39]	Solar-powered on-site electrolysis for light-duty	On-site solar HRS can be cost-competitive in high-solar regions with proper sizing
[41]	Centralized vs. on-site for large bus fleets	Centralized production cost-effective for large fleets (~100 fuel cell buses) due to economies of scale
[43]	Centralized production with distribution model (spatially optimized)	Centralized best for clustered demand; decentralized suits remote areas
[42]	Decentralized supply chain	Decentralized viable with low-cost electricity; sensitive to scale and power price

benefits—greater energy reliability, the ability to exploit dynamic pricing, and opportunities to export surplus renewable generation. Yet it also introduces trade-offs, especially where grids remain carbon-intensive or structurally weak. The interaction between HRSs and grids is thus best understood not as a binary (connected vs. off-grid) but as a continuum of design configurations shaped by local resource profiles, regulatory conditions, and infrastructure maturity. Across the reviewed literature, four major system types are evident: grid-augmented, market-responsive, grid-independent, and hybrid/composite configurations. Each presents distinct pathways for operational optimization, resilience, and cost competitiveness.

4.3.1. Grid-augmented systems: stability through hybridization

[37,44] and [39] exemplify the benefits of grid-augmented HRSs, in which renewables (solar PV, wind) are coupled with grid connectivity to alleviate intermittency constraints and sustain a continuous supply. [37] models a HRS co-located with a solar plant, where the grid serves dual roles: supplying power during solar deficits and acting as a recipient for surplus energy, thereby stabilizing system operation and generating economic returns. Similarly, [44] demonstrates a hybrid highway refueling design along Canada's Highway 401, demonstrating that grid interactions enable optimized energy use and GHG mitigation in heavy-duty freight refueling. Ref. [39] highlights how grid access stabilizes solar-powered taxi HRSs in Brazil during periods of low irradiance. These examples underscore that grid augmentation reduces cost volatility and enhances resilience, but their long-term viability depends heavily on tariff structures, carbon intensity of the grid, and fair compensation for electricity exports.

4.3.2. Market-responsive systems: leveraging energy market dynamics

Market-responsive configurations exploit electricity market structures by timing hydrogen production to coincide with off-peak or low-cost hours. Ref. [29] and related modeling studies [33,38] show that predictive, price-driven electrolyzer scheduling can cut hydrogen production costs substantially while raising renewable utilization. Such systems rely on advanced forecasting of electricity prices, renewable availability, and hydrogen demand to dynamically adjust operations. While these architectures lower one of the largest cost components—electricity—they are vulnerable to market volatility and require transparent, stable regulatory frameworks to scale effectively. Their promise lies in mature electricity markets with dynamic tariffs and demand-response mechanisms.

4.3.3. Grid-independent models: enhancing resilience and localization

At the other end of the spectrum, grid-independent HRSs are designed for locations where grid extension is either infeasible or uneconomical. Ref. [32] models a standalone DC microgrid integrating hydrogen production with battery and renewable storage, showing that such islanded systems can autonomously regulate energy flows and maintain refueling reliability under variable loads. Ref. [43] proposes an off-grid hydrogen supply chain for UK freight corridors, combining renewable generation with underground storage to ensure consistent supply independent of grid infrastructure. These models enhance resilience and spatial adaptability, but they incur higher upfront costs and depend on sophisticated storage and management frameworks to maintain competitiveness.

4.3.4. Hybrid and composite models: flexibility through integration

Hybrid systems that combine grid electricity with alternative energy vectors—such as methanol or biomethane—introduce additional dimensions of flexibility. In [34,35], such composite systems are shown to enhance cost-effectiveness by balancing variable energy inputs while maintaining operational reliability. These designs also highlight the growing interdependence between hydrogen infrastructure and broader decarbonization strategies.

4.3.5. Toward a system-oriented future

The evidence highlights that grid integration is not a technical afterthought but a strategic choice that shapes the viability of HRS infrastructure. In low-carbon electricity systems with dynamic pricing and supportive policy frameworks, grid-augmented and market-responsive configurations deliver strong cost and stability gains. Where grid reliability is limited or autonomy is critical, off-grid models become preferable. Hybrid hydrogen valleys point toward a future in which HRSs operate as multi-vector energy hubs, reinforcing synergies between transport, electricity, and gas networks. On a normalized basis, cost competitiveness aligns more with electricity price stability, renewable resource complementarity, and policy design than with a single "best" technology pathway. Table 4 summarizes the studies related to HRS grid integration and configurations.

Although direct benchmarking is difficult given the diversity of geographies and typologies, the studies collectively provide a robust sample. This synthesis, despite its challenges, offers comparative insights not previously articulated in the literature.

4.4. Safety and risk assessment in hydrogen refueling stations

Safety in HRS design centers on managing the risks of high-pressure hydrogen storage, leakage, and explosion. Studies emphasize that effective risk mitigation measures—such as advanced leak detection, ventilation, and standardized safety protocols—are essential both for regulatory compliance and for building public trust in hydrogen infrastructure.

Ref. [45] identifies leakage from 90 MPa storage tanks as a significant risk and recommends removing hydrogen tube trailers when on-site production is sufficient to minimize hazards. The findings highlight the importance of reducing the amount of high-pressure hydrogen stored on-site to lower the potential for accidents. Similarly, [46] emphasizes that environmental factors, such as wind direction and the presence of obstacles, are critical in hydrogen gas dispersion for minimizing risks.

Ref. [48] demonstrates that installing protective barriers can effectively mitigate explosion overpressure, though precise implementation is essential for these barriers to perform as intended. This precision may present challenges in regions with limited resources or technical expertise. For mobile hydrogen refueling stations (MHRS), [47] highlights the critical need to identify combustible zones due to the rapid dispersion of hydrogen in open spaces, ensuring safety in mobile infrastructure. Ref. [49] proposes an integrated approach that combines inherently safer design (ISD) principles with quantitative risk assessment and economic considerations. The study demonstrates that optimizing storage capacity and adjusting dispenser designs can significantly improve safety while maintaining cost-effectiveness.

The reviewed studies show that effective HRS safety depends on addressing specific technical risks—such as high-pressure hydrogen leaks, localized explosion overpressure, and dispersion influenced by wind and structural barriers—through targeted design choices. Strategies such as removing tube trailers when on-site production suffices, installing precision-calibrated blast barriers, and redesigning dispenser layouts all reduce incident severity. These measures require accurate modeling and implementation. Integrated approaches that combine ISD with quantitative risk and cost analysis enable optimization of storage volumes and zone layouts without compromising performance. These findings point to the need for tailored, site-specific safety protocols, especially as HRS networks expand into varied urban and regional environments.

5. Review of category three: management and optimization of integrated energy systems

This section examines the deployment of integrated energy systems (IES) for HRSs, highlighting their role in mitigating renewable energy intermittency, enhancing system resilience, and advancing sustainable

Table 4
Comparative summary of HRS grid integration models.

Authors	Region	Grid Connection	Renewable Integration	Model Type	Energy Export	Cost Optimization	Key Features and Findings
[32]	China	No	Solar + Wind	Off-grid Microgrid	No	Yes	Islanding DC microgrid with hybrid H_2–electric storage; ensures resilience under variable loads
[33]	Germany	Yes	Wind + Grid	Market-Responsive	Yes	Yes	Spot market participation, forecast-driven scheduling lowers costs
[34]	China	Yes	Solar + Methanol + Grid	Two-Layer Optimization	No	Yes	Integrates methanol reforming + grid; balances energy for cost minimization
[35]	Italy	Yes (via PPA)	Wind, Solar, Biomethane	Hydrogen Valley	No	Yes	Biomethanation integrated with renewables and PPA; grid fees may limit gain
[37]	Italy	Yes	Solar + Grid	Grid-Augmented HRS	Yes	Yes	Exports surplus, imports when needed; improves economics and stability
[38]	China	Yes	Solar + Wind + Grid	Price-Responsive HRS	No	Yes	Uses dynamic pricing and day-ahead scheduling for optimized electricity sourcing
[39]	Brazil	Yes	Solar + Grid	Grid-Augmented HRS	Yes	Yes	Taxi fleet HRS with grid backup and surplus export; sensitive to rising power costs
[43]	UK	No	Solar + Wind + Grid	Off-grid Supply Chain	No	Yes	Underground H_2 storage for off-grid freight routes; enhances resilience
[44]	Canada	Yes	Solar + Wind + Grid	Highway HRS Feasibility	Yes	Yes	Achieves 93 % renewable share, LCOH $2.03/kg; uses import/export under favorable prices

hydrogen infrastructure. Empirical studies across various geographical contexts demonstrate the effective integration of renewable sources, such as solar, wind, and hybrid configurations, to ensure energy stability and optimize utilization in both isolated and urban settings. Advanced optimization strategies, including bilevel energy management, multi-vector approaches, and coordinated capacity sizing, significantly improve system efficiency and reduce costs, particularly in regions with variable renewable energy supply.

The analysis extends the region-specific comparative framing to integrated, multi-vector energy systems, identifying when centralized pipelines or multi-hub depots dominate versus when decentralized microgrids or onsite models are more appropriate. Outcomes are benchmarked against contextual drivers—grid accessibility, demand clustering versus dispersion, and policy or investment frameworks—providing system-planning guidance that moves beyond prior technology-focused reviews. Table 5 synthesizes these studies, summarizing key aspects and regional adaptations to enhance the sustainability and resilience of IES for HRSs.

5.1. Innovative integration and strategic management of integrated energy systems

Integrated energy systems (IES) that embed hydrogen refueling stations (HRSs) with electricity, heating, cooling, and storage provide quantifiable efficiency and cost advantages over standalone configurations. The reviewed studies show that aligning HRSs with local demand profiles and renewable availability improves utilization rates, reduces operating costs, and enhances energy security.

A notable strategy involves coupling HRSs with energy-intensive, continuous-demand applications such as data centers. In California, [52] models a shared system where curtailed wind and solar energy support both HRS operations and a data center. This co-location significantly reduces energy costs and emissions, while enhancing grid stability. The dual-use paradigm not only improves asset utilization but also illustrates how HRSs can serve as balancing mechanisms in renewable-heavy grids—particularly as artificial intelligence accelerates electricity demand growth in the digital economy.

In climates where battery electric vehicles underperform—such as in Eastern Mongolia—hydrogen becomes a strategic asset. Ref. [54] examines Eastern Mongolia's multi-park IES with a shared storage station. The system achieves 99.47 % renewable penetration and 32.7 % CO_2 reduction, while hydrogen fuel cell vehicles (HFCVs) outperform BEVs in sub-zero conditions, reinforcing hydrogen's role where electrification faces environmental constraints.

For off-grid regions, [53] proposes a solar–wind–hydrogen system for an isolated HRS that also serves building loads, while [59] model a hydrogen-based microgrid for Rakiura–Stewart Island, New Zealand, replacing batteries with hydrogen and supercapacitors. Ref. [60] further optimizes a wind–solar–microhydro hydrogen microgrid in Feilding, New Zealand, achieving electricity at $0.09/kWh and hydrogen at $4.61/kg—both below national averages. These cases show that off-grid development credits, diesel replacement subsidies, and feed-in tariffs for renewable-to-hydrogen conversion are the most effective levers to support remote autonomy.

Urban deployment adds another dimension. Ref. [55] presents a campus-based solar-hydrogen system integrating HRSs, BEV charging, vehicle-to-grid (V2G), and power-to-gas (P2G) functionalities. Demand-response cuts costs by 27.5 % and reduces peaks, proving the value of hydrogen as an urban grid stabilizer. Evidence from the UBC deployment indicates that adoption can be accelerated through demand-response pricing reforms and mandatory provisions for P2G integration.

[65] applies a genetic algorithm-based scheduler in a Spanish technology park, optimizing electrolyzer operation with HVAC, EV charging, and HRS loads. The system shifts demand to renewable peaks, maximizing self-consumption and reducing external procurement. This real deployment suggests digitalization incentives and regulatory approval for advanced scheduling algorithms as practical enablers.

In aggregate, the reviewed evidence underscores that integration strategies must be differentiated according to regional and system-specific conditions. In renewable-heavy grids, co-location of hydrogen refueling stations with other energy-intensive loads, combined with grid-balancing contracts, has been shown to maximize the utilization of variable renewable energy. In cold-climate regions, where battery degradation reduces the effectiveness of electric vehicles, targeted incentives for hydrogen vehicle deployment and differentiated carbon pricing provide more accurate reflections of comparative technology performance. For remote and off-grid contexts, concessional finance mechanisms and diesel displacement credits emerge as critical instruments to support hydrogen-based autonomy, as demonstrated in island and rural case studies. In urban energy systems, hydrogen's role as a stabilizing vector is best enabled through demand-response pricing reforms and regulatory mandates for power-to-gas (P2G) integration.

5.2. Optimization and risk management in integrated energy systems

As hydrogen-based mobility expands in tandem with renewable energy deployment, the imperative to coordinate electricity, hydrogen, and transportation systems necessitates sophisticated strategies grounded in spatial planning, technological integration, and risk-informed

Table 5
Overview of key aspects in category three studies.

Authors	Focus	Region/Context	Key Findings
[52]	Renewable integration for data centers & HRSs	California, USA	Electrolysis with renewable energy optimizes HRS and data centers. Mixed renewable-fossil approach cuts costs; pure renewable is costly but emission-free
[53]	Coordinated sizing of electricity & hydrogen networks for HFCVs	Isolated HRS settings	Multi-network coordination reduces costs and enhances reliability in isolated systems
[54]	Multi-park integrated energy system (MPIES) for renewable energy use	Eastern Mongolia	Multi-park IES with hydrogen storage improves renewable energy use and emissions reduction
[55]	Solar-hydrogen microgrid for HFCV refueling and BEV charging, and vehicle-to-grid (V2G)	University of British Columbia, Vancouver Campus, Canada	Solar-integrated HRS for HFCV & BEV, using hydrogen storage for stability. Optimization reduces costs by 27.5 %
[56]	Multi-network planning for HRS	Australia	Coordinated hydrogen production and storage support scalable IES
[57]	Integrated planning of green hydrogen supply chain for HFCVs	Xi'an, China	Centralized hydrogen production with pipelines is cost-effective for urban transport
[58]	Multi-hub HRS for public buses	Lazio, Italy	Multi-hub HRS network reduces LCOH by up to 40 %, benefiting fleet operations and cutting CO2 emissions
[59]	Optimization of off-grid multi-carrier microgrid for remote energy	Rakiura-Stewart Island, New Zealand	Hydrogen and super-capacitors reduce diesel dependency and costs by 54 % for isolated communities
[60]	Standalone hydrogen microgrid optimization	Feilding area, New Zealand	Hydrogen-based microgrid design lowers electricity costs and enhances system feasibility
[61]	Integrated multi-stage network planning for HRS	Australian networks	Multi-stage model optimizes HRS siting, reduces costs, and increases renewable usage
[62]	Energy management for HRS with bilevel optimization	General	Cooperative scheduling maximizes profits, balances costs amid energy price fluctuations
[63]	Risk-averse electric vehicle charging and HRS	Local multi-energy systems	Integrated demand response (IDR) and P2H manage flexibility, reducing renewable variability risks
[64]	Integrated BEV charging and HRS for highway stations	Highway stations	Co-location of BEV charging and HRS improves renewable profitability and dynamic energy use
[65]	Multi-vector energy management for BEV charging and HRS	Spanish technology park	Multi-vector system maximizes renewables, reduces costs, and minimizes grid reliance

management.

Spatial coordination emerges as foundational: [56] introduces a tri-network planning framework that aligns hydrogen production in solar-abundant rural zones with refueling demand in urban centers. This is operationalized via a hybrid logistics system—pipelines for densely populated areas and truck delivery for peripheral zones—balancing cost-efficiency with supply reliability. Extending this approach, [61] presents a multi-stage, multi-zone expansion model across a 100-node grid, co-optimizing renewable energy deployment, grid reinforcements, and hydrogen production facilities. The study demonstrates how phased rollout strategies can minimize long-term costs while supporting resilience and decarbonization targets.

Technological hybridization offers a complementary pathway to optimize infrastructure performance. Refs. [57,58] examine multi-hub hydrogen networks that fuse centralized and decentralized production. Ref. [57] optimizes urban-scale hydrogen pipelines using routing algorithms that account for vehicle movement patterns, while [58], in the context of Lazio, Italy, combines centralized steam methane reforming with decentralized solar electrolysis, revealing a 46 % CO_2 reduction with marginal cost implications. These hybrid models underscore how strategic blending of production modalities can harness both renewable intermittency and infrastructure synergies.

Temporal and behavioral factors introduce additional layers of complexity. Ref. [64] integrates evolving demand projections, electric vehicle travel patterns, and investor return timelines to propose a phased rollout of battery-electric and hydrogen refueling infrastructure along transportation corridors. Their results emphasize that infrastructure deployment must align not only with technical efficiency but also with adoption patterns and investor return expectations, particularly in transport corridors where traffic growth and technology uptake evolve simultaneously.

While spatial and temporal optimization strategies are critical, they alone do not guarantee system robustness under the inherent variability of renewable energy sources. To address this, probabilistic risk management becomes essential. Ref. [63] introduces a tri-level, risk-averse optimization framework tailored for local multi-energy systems, integrating electricity, thermal, and hydrogen vectors. This model proactively manages uncertainty in wind energy generation, hydrogen demand, and market price fluctuations through adaptive day-ahead scheduling and demand-side response mechanisms. In a complementary vein, [62] applies a bilevel optimization approach that captures the decision-making interplay between hydrogen producers and refueling station operators. By incorporating chance constraints, the model ensures operational resilience in the face of fluctuating solar output and varying hydrogen demand, underscoring the importance of uncertainty-aware planning in hydrogen infrastructure deployment.

In sum, the comparative evidence across the IES-focused studies indicates that techno-economic outcomes are shaped less by the choice of optimization algorithm (bilevel, multi-stage, metaheuristic) than by the alignment of system design with local infrastructure and demand conditions. Remote island contexts, such as Stewart Island and Feilding in New Zealand, underscore the role of hydrogen as long-duration storage to replace diesel and achieve near-complete autonomy. In contrast, urban multipurpose systems in California, Spain, and Canada highlight hydrogen's value as a flexibility asset, absorbing renewable surpluses, supporting BEV charging, and stabilizing grids. Centralized supply chains—Xi'an, China, or multi-hub depot networks in Italy—achieve cost reductions for clustered urban fleets, while decentralized models, such as hydrogen microgrids in New Zealand and onsite/grid-integrated production in Australia, improve resilience where centralized infrastructure is uneconomical or technically impractical.

Across these diverse cases, divergences in LCOH and system feasibility are explained primarily by three factors: (i) grid accessibility and tariff structures, (ii) spatial demand distribution (clustered fleets vs. remote communities), and (iii) policy and investment frameworks that determine scale and rollout. Collectively, these findings establish that

HRSs embedded in IES function not as stand-alone refueling assets but as multi-vector energy nodes whose viability depends on contextual integration across electricity, transport, and storage systems. This comparative framing distinguishes this review from prior surveys by clarifying why outcomes converge or diverge across regions and how planners can tailor IES–HRS deployment to resource profiles and infrastructure maturity.

6. Policy recommendations based on the reviewed studies

The following recommendations are sequenced according to policy priority, beginning with immediate, high-impact applications (heavy-duty transport, electrolyzer operation, and grid integration), followed by context-specific solutions (off-grid systems and sectoral stability), and concluding with water sustainability, and emerging applications (data centers). This ordering reflects both the frequency of evidence across the reviewed studies and the scale of impact for near-to long-term deployment.

6.1. Strategic sector-specific policies

Policy initiatives should focus first on mobility segments where hydrogen adoption is both technically advantageous and supported by evidence from case studies. Heavy-duty, long-haul freight and urban public transport consistently emerge as priority applications [42–44]. Urban fleets such as taxis in Brazil [39] and bus networks in Europe and Ireland [40–42,58] demonstrate that aligning HRS infrastructure with transit routes can yield immediate emission reductions. For long-haul freight, hydrogen highways [44] and spatially optimized HRS siting with bulk storage and delivery logistics [43] provide targeted solutions that lower costs and enhance supply reliability.

Complementary measures include co-locating HRSs with BEV charging hubs along major corridors, as shown in integrated planning studies [64]. Such multi-fuel stations reduce infrastructure duplication, spread fixed costs, and accelerate user adoption. To support these deployments, policies should emphasize tariff reform for grid electricity in large hubs, scale-up incentives for bus depots, and infrastructure mandates for corridor-based HRSs, ensuring that investments are directed where hydrogen achieves the highest near-term impact.

6.2. Electrolysis and integrated energy systems

Electrolysis remains the core pathway to green hydrogen for both grid-connected and autonomous stations. Evidence shows that price- and forecast-responsive electrolyzer scheduling can reduce costs and raise renewable utilization: in a Berlin HRS case, predictive operation with co-located wind lifted the renewable share from 62 % to 74 % and cut hydrogen cost by up to ~13 % compared to spot-only scheduling [33]. Integrated designs go further: in Canada, a Highway 401 corridor model combining PV, wind, and grid supply achieved a 93 % renewable share with an LCOH of ~$2.03/kg, underscoring how grid-augmented systems stabilize operations and cut costs [44]. At the University of British Columbia, a solar–hydrogen–BEV microgrid reduced annual operating costs by ~27.5 % under optimized scheduling, illustrating the efficiency gains of multi-functional hubs [55].

For clustered urban fleets, centralized or multi-hub depot networks in Italy have been shown to lower LCOH by up to ~40 % and reduce CO_2 emissions by ~46 % through economies of scale and diversified supply portfolios [58]. Similarly, integrated pipeline planning in Xi'an demonstrates that tariff structures and electricity prices decisively shape optimal siting and sizing, making regulatory design as critical as technology choice [57]. Collectively, these findings emphasize that policy measures must extend beyond standard support for electrolyzers to include three evidence-backed levers: (i) incentives for intelligent, forecast- and tariff-responsive scheduling, (ii) tariff and market reforms that enable cost-efficient operation under dynamic electricity conditions, and (iii) support for integrated multi-vector hubs that co-optimize hydrogen with electricity, storage, and mobility systems.

6.3. Grid integration and carbon management

Grid-linked electrolysis strategies can substantially lower hydrogen costs when operations align with tariff structures and carbon policies. Dual-mode electrolyzers that switch between renewable and grid electricity exploit price fluctuations, reducing production costs and improving flexibility [29]. In Canada's Highway 401 case, blending renewable and grid power under peak–valley tariffs proved more economical than renewable-only supply [44]. Similarly, predictive scheduling of on-site electrolysis enhances cost efficiency by matching operation to dynamic electricity markets [29]. Broader analyses of the power-to-hydrogen pathway show that policy levers—particularly carbon pricing and targeted subsidies—are decisive for cost competitiveness in grid-integrated models [37]. Collectively, these findings suggest that the most effective policy support is not generic subsidies but targeted measures that (i) incentivize time-of-use responsive electrolysis, (ii) integrate carbon pricing to reward low-emission hydrogen, and (iii) align tariff structures with renewable variability.

6.4. Off-grid hydrogen refueling stations for remote areas

Evidence from off-grid studies confirms that hydrogen systems are technically viable and economically beneficial for isolated and underserved regions. On Stewart Island (New Zealand), a multi-carrier microgrid achieved a 54 % cost reduction in electricity compared to diesel by combining hydrogen storage with super-capacitors [59], while a battery-less hybrid in Feilding cut electricity costs to $0.09/kWh and hydrogen costs to $4.61/kg—well below national averages [60]. In Canada, a solar–hydrogen–BEV campus hub achieved ~27.5 % lower annual costs through coordinated scheduling [55]. [53] demonstrated that integrated sizing and scheduling of off-grid PV–wind–hydrogen systems prevents over-sizing, reduces costs, and ensures full autonomy for isolated HRSs. Similarly, [24] showed that in remote Greek regions, carefully optimized off-grid HRSs can provide reliable supply despite intermittency challenges.

Off-grid evidence shows that hydrogen-based systems outperform diesel generation on both cost and reliability grounds when properly integrated with local renewables. In contexts such as Stewart Island and Feilding (New Zealand), hydrogen storage cut energy costs by 54 % and delivered electricity and hydrogen at prices below national averages. These results justify dedicated diesel-displacement credits and low-interest financing for electrolyzer and storage deployment in remote communities. To avoid cost escalation from poor system design, policymakers should mandate integrated sizing and scheduling standards for PV–wind–hydrogen microgrids, as demonstrated in New Zealand. In regions with limited renewable predictability, such as remote Greece, risk-sharing mechanisms (e.g., guaranteed offtake contracts or capacity payments) can mitigate intermittency challenges and secure supply reliability. Collectively, the evidence supports targeted policy measures that treat hydrogen not as a marginal add-on but as the primary long-duration storage and autonomy enabler for remote and underserved energy systems.

6.5. Hydrogen's role in power sector stability

Hydrogen enhances power sector stability by mitigating renewable intermittency, balancing supply–demand mismatches, and providing long-duration (seasonal) storage where batteries are insufficient. Evidence from New Zealand's islanded microgrids shows that hydrogen storage can displace up to 54 % of diesel and maintain supply during prolonged renewable shortages, ensuring energy autonomy [59,60]. At the system-integration level, hydrogen enables grid balancing by absorbing excess generation: in California, curtailed solar and wind redirected to a combined HRS–data center hub reduced energy costs and emissions while enhancing grid resilience [52]; similarly, a multi-park system in Mongolia achieved >99 % renewable penetration by coupling HRSs with shared storage [54]. For grid-connected contexts, bilevel and risk-averse scheduling frameworks demonstrate how hydrogen can buffer renewable variability and maintain network stability under price and demand fluctuations [62,63]. Finally, Spain's multi-vector hubs highlight hydrogen's role in sector coupling, where coordinated scheduling across electrolyzers, EV charging, and HRSs reduced fossil reliance and maximized renewable self-consumption [65].

The reviewed evidence suggests that hydrogen should be explicitly recognized in power sector planning as a stability asset, not only a transport fuel. In islanded and off-grid contexts (e.g., Stewart Island, Feilding), hydrogen storage should be prioritized over short-lived battery systems through diesel-replacement credits and concessional finance for electrolysis to ensure autonomy during prolonged renewable shortages. In renewable-heavy grid regions (e.g., California), policy frameworks should incentivize co-located hydrogen hubs with energy-intensive users by extending contracts for grid-balancing services and location-specific capital subsidies. In cold-climate or high-penetration renewable systems (e.g., Mongolia), support for shared storage stations integrated with HRSs should be embedded in capacity-expansion planning, backed by regionally differentiated carbon pricing that reflects hydrogen's comparative resilience. For urban grid-connected contexts (e.g., Spain), regulators should mandate multi-vector scheduling platforms that integrate electrolyzers, EV charging, and HRSs, coupled with demand-response tariff reforms to maximize the usage of renewable surplus of generation.

6.6. Water sustainability in hydrogen production

Water availability is a critical constraint in hydrogen production, particularly in arid regions. As emphasized in [25], producing 1 kg of hydrogen requires substantial water volumes, underscoring the need for innovative water-efficient electrolyzer designs tailored to water-scarce environments. Integrating renewable-powered desalination plants in coastal areas is also significant, though efforts must focus on reducing desalination's energy footprint.

6.7. Data centers and renewable hydrogen

Leveraging curtailed renewable energy to power data centers and HRSs represents a sustainable approach to reducing emissions in the digital infrastructure sector. Utilizing this excess renewable energy for both applications not only mitigates emissions but also stimulates the renewable energy economy [52]. Government incentives for integrating renewable hydrogen in data centers can accelerate decarbonization in this energy-intensive sector, supporting broader renewable energy adoption and fostering sustainable growth.

7. Conclusion

This review synthesized key insights across three thematic categories, providing an evidence-based assessment of HRS development in the context of renewable integration, application-specific deployment, and integrated energy system (IES) optimization.

Category one, focused on renewable-powered HRSs, shows that techno-economic performance is highly dependent on regional solar and wind availability, infrastructure conditions, and grid connectivity. Hybrid PV–wind systems in Riyadh, Saudi Arabia, achieve an LCOH of \$4.23/kg by leveraging seasonal complementarities, while PV-only systems in Tunisia remain viable in grid-constrained settings at ∼ €3.32/kg. Grid-connected configurations in Sweden (€3.5–7.2/kg) and Oman (€6.24/kg) illustrate how grid access supports cost control and operational stability. In South Africa, inland off-grid systems (∼\$8.97/kg) face higher costs due to resource and infrastructure limitations, whereas coastal sites (∼\$6.34/kg) demonstrate more favorable outcomes. In Greece, optimized off-grid designs are technically feasible but economically constrained by limited HFCV uptake and long payback periods. In France, a comparative assessment across twenty urban sites identifies Marseille as the most competitive case, with PV-dominant configurations achieving an LCOH of \$13.5/kg, reflecting the city's high solar yield. Collectively, these findings underscore the importance of context-specific design, spatially resolved resource assessments, and adaptive technology configurations. Future research should prioritize the advancement of high-efficiency electrolyzers, robust storage systems, and real-time forecasting tools.

Category two assessed deployment strategies for HRSs across public transport, heavy-duty freight, and urban fleets, highlighting how production mode and infrastructure scale decisively influence techno-economic outcomes. Decentralized, on-site electrolysis proves more economical for small or spatially dispersed fleets—such as taxi fleets or limited bus depots—where delivery and compression costs dominate. By contrast, centralized systems achieve lower unit costs for large, clustered fleets through economies of scale and coordinated logistics. In both cases, the competitiveness of green hydrogen is contingent on renewable electricity prices, utilization rates, and grid conditions. Grid integration emerges as a critical enabler, providing flexibility, backup capacity, and opportunities to exploit dynamic electricity pricing or hybridized renewable–grid supply. Yet this advantage is conditional on stable regulatory frameworks and clear market signals, without which investment risks remain high. Off-grid configurations offer energy independence but require advanced control mechanisms and storage strategies to ensure reliability under variable renewable supply. These insights suggest that future research should prioritize: (i) dynamic refueling models that reflect heterogeneous vehicle demand profiles, (ii) lifecycle emission analyses that benchmark hydrogen pathways against BEV infrastructure, and (iii) integrated policy frameworks that align fleet-scale deployment with renewable resource and grid development.

Category three emphasized the strategic integration of HRSs into multi-vector energy systems. Evidence from diverse contexts—from island microgrids to urban campuses—demonstrate how co-locating hydrogen infrastructure with renewable generation, storage, and cross-sectoral energy demands improves system resilience, and decarbonization potential. Advanced optimization techniques, such as bilevel and tri-level planning, facilitate infrastructure alignment with temporal energy demand patterns, investment cycles, and spatial resource distribution, while risk-aware scheduling mechanisms help manage variability in renewable supply and fluctuating hydrogen demand. Collectively, these approaches position HRSs not as stand-alone assets but as central nodes within smart, and multi-vector energy networks. Their value extends beyond refueling to include grid balancing, renewable absorption, and cross-sector integration. Future research should therefore concentrate on the development of spatial–temporal co-optimization frameworks that align hydrogen deployment with transport and grid expansion, market mechanisms that incentivize multi-vector flexibility, and planning approaches that ensure scalability. Overall, the sustainable expansion of HRS infrastructure demands a systems-level perspective.

Declaration of competing interest

The author declares that there are no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No data was used for the research described in the article.

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