energies

Review

Optimal Planning of Electric–Hydrogen Coupled Integrated Energy System: A Comprehensive Review

Hongbo Ren [1], Lili Miao [1], Qiong Wu [1,*], Xinyu Liu [1] and Weisheng Zhou [2,*]

[1] College of Energy and Mechanical Engineering, Shanghai University of Electric Power, Shanghai 200090, China; tjrhb@163.com (H.R.); lilimiao@163.com (L.M.); xinyu@163.com (X.L.)
[2] School of Architecture and Design, Harbin Institute of Technology, Harbin 150001, China
* Correspondence: wuqiongrff@163.com (Q.W.); zhou@g-eee.org (W.Z.)

Abstract

Against the backdrop of climate change, the volatility of energy supply and demand in integrated energy systems (IESs) has intensified, resulting in heightened scheduling challenges. Electric–hydrogen coupling has emerged as a pivotal approach to fostering multi-energy complementarity while enhancing the flexibility and stability of IES. Rational planning of an electric–hydrogen coupled integrated energy system (EH-IES) can further strengthen energy interconnection and mutual support. First, the architecture and diverse coupling modes of the EH-IES are outlined based on key technologies and coupling mechanisms. Accurate modeling serves as the "cornerstone" of planning, with electric power and hydrogen energy equipment acting as the foundational "carriers" and electric–hydrogen coupling devices as the critical "link." By examining application scenarios across the transportation, building, and industrial sectors, the study analyzes EH-IES planning scenarios, objectives, and modeling methodologies. Sector-specific planning primarily focuses on equipment configuration and layout, evaluated from economic and/or environmental perspectives. Finally, future research directions for EH-IES planning are proposed, addressing multiple uncertainties, energy demand dynamics, and market mechanisms. These insights aim to provide a reference for subsequent studies.

Keywords: electric–hydrogen coupling; integrated energy system; optimal planning; transportation; buildings; industry

1. Introduction

Hydrogen energy, a zero-carbon secondary energy carrier, offers significant advantages such as pollutant-free emissions, carbon neutrality, long-term storage potential, and versatile applications. These attributes position hydrogen as a key driver in the transition toward green and low-carbon energy systems, especially in end-use sectors. The EH-IES is poised to play a pivotal role in boosting renewable energy adoption, improving power system flexibility, and optimizing the operational efficiency of integrated energy systems. Consequently, EH-IES is rapidly becoming one of the primary frameworks for leveraging hydrogen as a secondary energy source.

As an innovative energy paradigm, electric–hydrogen coupling in integrated energy systems has attracted extensive research across multiple sectors, including transportation, buildings, and industry. This approach enhances power system flexibility through hydrogen fuel cell power generation and hydrogen-doped gas-fired power plants [1–3]. In the

Academic Editor: Giovanni Esposito

Received: 15 May 2026
Revised: 30 May 2026
Accepted: 2 June 2026
Published: 4 June 2026

transportation sector, integrated hydrogen production–refueling–charging–switching stations significantly improve energy supply efficiency [4–6]. Moreover, water electrolysis for hydrogen production enables large-scale energy storage [7,8], offering substantial potential for expanding energy storage capacity. By synergistically integrating electric and hydrogen energy, EH-IES presents an efficient and sustainable energy utilization model, establishing itself as a fundamental component of future clean energy systems.

However, the practical deployment of EH-IES is increasingly constrained by real-world regional energy transition risks and hard grid boundaries, which are often overlooked in idealized planning studies. Recent European practice highlights this gap: the EU's push for 55% emissions reduction by 2030 has driven rapid RES penetration, yet insufficient energy storage and lagging grid upgrades have triggered frequent renewable curtailment and frequency stability risks. Taking Greece as a regional case, the interconnected system curtailed 860 GWh of wind and solar power in 2024 alone due to limited cross-regional transmission capacity and a lack of flexible regulation resources; its revised National Energy and Climate Plan explicitly notes that unconstrained RES expansion without matching storage and grid flexibility will directly threaten supply security. These practical challenges indicate that EH-IES planning cannot be decoupled from actual grid operation constraints [9]—including transmission interconnection limits, inertia support shortages, and time-varying supply–demand mismatches—otherwise even technically optimal configurations may face implementation failures.

EH-IES enables the interconnection of diverse energy forms [10], significantly expanding its potential applications. The system achieves bidirectional energy conversion between electricity and chemical energy through water electrolysis for hydrogen production and subsequent power generation via fuel cells. A typical operational cycle involves converting surplus renewable energy into hydrogen during periods of excess generation, storing it, and then converting it back to electricity during supply shortages. This closed-loop energy management approach substantially improves overall energy utilization efficiency and system performance.

EH-IES demonstrates robust compatibility with both conventional and renewable energy sources, effectively mitigating the risks inherent in single-source energy dependence. This multi-energy integration diminishes reliance on specific energy carriers, consequently enhancing the stability and reliability of the overall energy infrastructure [11–13]. In terms of application diversity, the transportation sector benefits from technologies like integrated electric–hydrogen energy stations and hydrogen fuel cell vehicles (HFCV), which provide significant decarbonization potential and actively facilitate the ecological transformation of mobility systems [14–17]. For industrial applications, hydrogen fulfills dual roles as both a clean combustion fuel and an essential industrial feedstock, yielding substantial reductions in both operational expenditures and environmental emissions. In the built environment, EH-IES contributes to improved energy self-sufficiency and system efficiency [18]. Regarding energy storage solutions, EH-IES enables large-capacity storage capabilities that effectively compensate for the inherent intermittency and volatility of renewable energy sources, thereby establishing a comprehensive, multi-dimensional storage framework.

Consequently, meticulous planning of EH-IES is imperative. This system embodies not only a multi-system coupling configuration but also exhibits sophisticated multi-process interdependencies. As EH-IES directly interfaces with end-user sectors, it profoundly impacts both energy consumption patterns and production dynamics. The complex interplay among generation sources, distribution networks, load demands, and storage systems in EH-IES necessitates continuous, multidimensional coordination [19,20].

Significant research efforts worldwide have focused on investigating and strategically planning EH-IES, yielding customized solutions for diverse application scenarios. Despite the growing body of research in recent years, there remains a conspicuous absence of systematic planning frameworks for EH-IES. Particularly, planning methodologies that comprehensively account for electric–hydrogen coupling dynamics remain insufficiently developed. This critical gap underscores the pressing need for sophisticated approaches that can effectively navigate the complex challenges and leverage the opportunities inherent in EH-IES implementation, thereby ensuring its optimal performance and long-term viability within evolving energy systems.

To summarize, there exists a pressing need for a systematic examination and synthesis of EH-IES planning methodologies. The principal objectives and scholarly contributions of this research are delineated as follows:

(1) Unlike existing reviews that focus solely on equipment-level optimization, this study establishes a framework that shifts the research focus from "single-component optimization" to "system-level multi-sectoral synergy". By systematically reviewing the coupling mechanisms across transportation, building, and industrial sectors, this review reveals the distinct planning logics required for different end-use applications.
(2) This study first presents a comprehensive analysis of EH-IES's typical configurations and coupling mechanisms, while detailing hydrogen energy's multifaceted applications. This approach facilitates a paradigm shift in research focus from "equipment-level optimization" to "system-level synergy" through hydrogen-based integration.
(3) This study systematically examines EH-IES planning methodologies across three key sectors: transportation, buildings, and industry. The analysis elucidates both the fundamental principles governing electric–hydrogen coupling in end-use energy applications and the scenario-specific strategic variations that emerge across different operational contexts.
(4) This study proposes future research directions across three critical dimensions: system resilience, energy demand dynamics, and market mechanisms. These proposed directions may facilitate an evolution in planning objectives from singular cost optimization toward achieving a tripartite equilibrium encompassing economic viability, low-carbon sustainability, and system resilience.

This study focuses on the planning of EH-IES; the whole research framework is shown in Figure 1. First, it outlines the characteristics of EH-IES, its key technologies, and typical electric–hydrogen coupling mechanisms. Second, it analyzes and discusses the modeling of electric power and hydrogen energy equipment within EH-IES. Third, it systematically reviews the planning scenarios, methods, and uncertainty management strategies for EH-IES. Finally, the future research directions for the EH-IES are discussed.

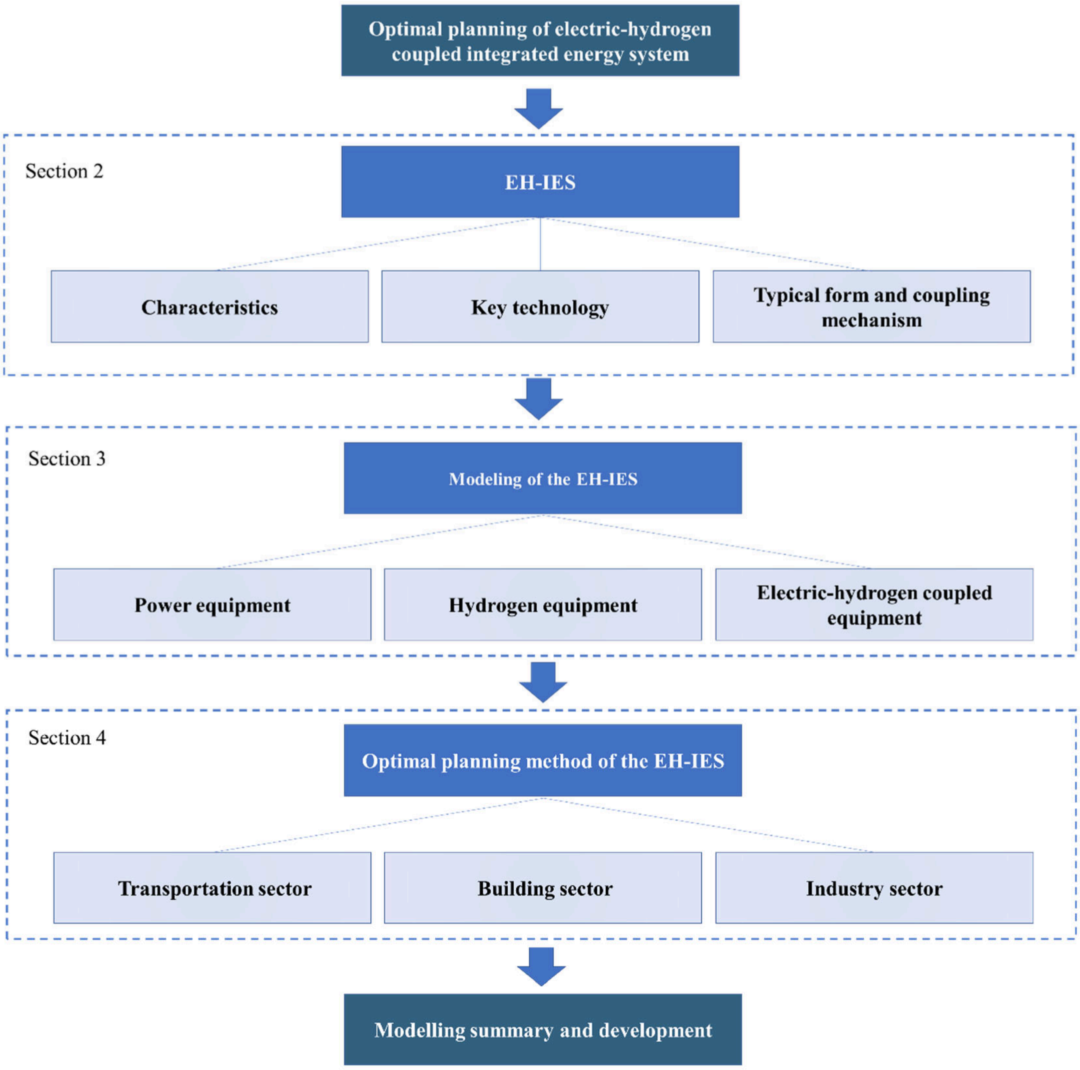

Figure 1. Overall research framework of this review on EH-IES planning.

2. Typical Form and Coupling Mechanism of EH-IESs

The EH-IES is designed to enhance renewable energy dispatchability while significantly reducing system carbon emissions. As illustrated in Figure 2, the EH-IES architecture comprises three core components: renewable-powered hydrogen production systems, hydrogen storage infrastructure, and hydrogen fuel cell power-generation units. These components are intelligently interconnected with the electrical grid and downstream applications through bidirectional energy flows, enabling seamless electricity–hydrogen synergies.

The system's operational scope encompasses demand-side applications across three primary sectors—transportation, buildings, and industry—which are powered by a diversified energy portfolio comprising renewable generation, hydrogen fuel cells, gas turbines, and direct grid connections, collectively delivering both electricity and thermal energy to end users. During periods of renewable energy surplus, excess electricity is converted into hydrogen via electrolysis, after which the produced hydrogen is compressed and stored in high-integrity containment systems for future utilization.

The EH-IES addresses thermal energy requirements principally through electric heating systems while strategically storing any excess thermal output in dedicated thermal storage units, exemplifying the system's comprehensive energy management capabilities and underscoring its critical function in facilitating a sustainable, decarbonized energy infrastructure.

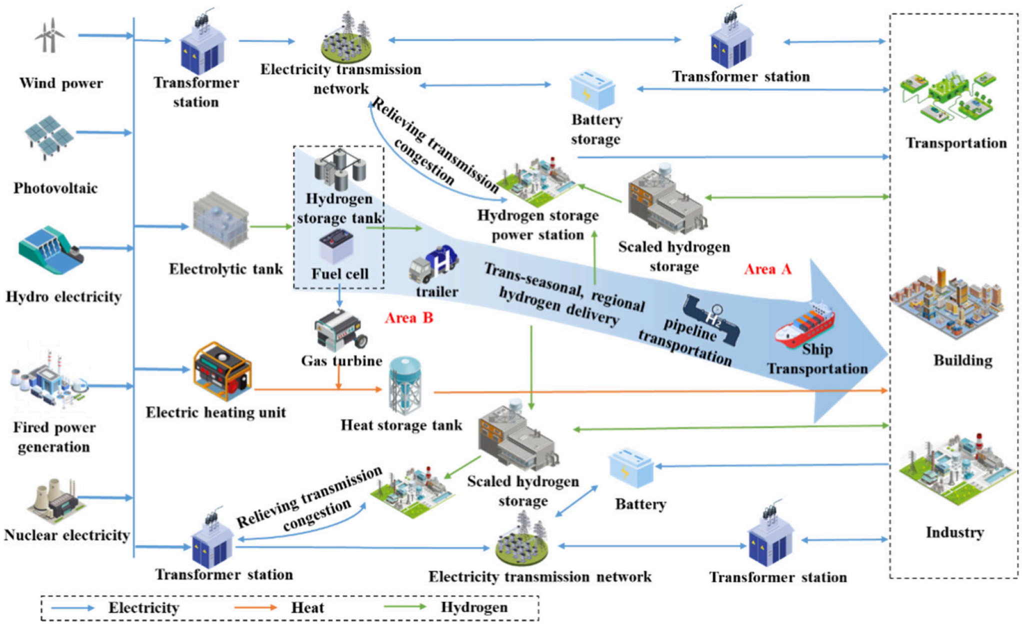

Figure 2. Typical architecture of the EH-IES and sectoral interconnections.

Leveraging abundant renewable resources including wind and solar power, the system implements cutting-edge electrolysis technology to transform surplus electricity into high-purity hydrogen, which undergoes compression and secure storage in advanced containment systems for reliable deployment during peak demand cycles. This innovative approach marks a substantial advancement in sustainable hydrogen production efficiency while effectively mitigating the longstanding issue of renewable energy curtailment.

The EH-IES represents a significant advancement in thermal energy management through its integrated approach. The system utilizes electric heating systems to meet thermal demands while intelligently capturing and storing excess thermal energy in specialized thermal storage units. This comprehensive energy management strategy not only demonstrates remarkable efficiency in resource utilization but also embodies the system's strong commitment to sustainable energy practices [21].

Hydrogen's multifunctional capacity enables critical ancillary grid services, including peak load shaving and dynamic frequency regulation across fluctuating demand cycles. These operational capabilities play a pivotal role in ensuring grid resilience while enabling large-scale, spatiotemporal energy storage solutions that transcend geographical and seasonal constraints [12,22,23]. For decarbonizing hard-to-abate sectors such as transportation and heavy industry, the system integrates Power-to-Gas (P2G) infrastructure with advanced fuel cell technologies. This integrated framework enables bidirectional electricity–hydrogen conversion, thereby powering zero-emission mobility solutions and facilitating sustainable industrial processes. The implementation of this system architecture demonstrates substantial co-benefits, including dramatic reductions in criteria air pollutants and measurable improvements in urban atmospheric quality.

2.1. Characteristics of the EH-IES

The EH-IES embodies the next-generation multi-energy complementarity framework, integrating renewable electricity generation through cutting-edge technologies with hydrogen production via water electrolysis and methane-reforming processes. By coupling these electricity and hydrogen systems with renewable generation infrastructure, the EH-IES achieves coordinated operation that dynamically compensates for the inherent variability and stochastic fluctuations characteristic of renewable power generation [24]. This deeply integrated synergy significantly boosts the energy system's operational flexibility and dependability, providing robust compensation for renewable energy's inherent intermittency and volatility while maintaining stable energy supply.

The EH-IES demonstrates exceptional regulatory flexibility through its multi-timescale energy management capabilities. The system employs battery storage solutions to address diurnal and short-term electricity demand fluctuations, while hydrogen storage infrastructure provides seasonal energy-buffering capacity. During peak demand periods, stored electricity is strategically dispatched to maintain grid balance, with excess renewable energy being converted to hydrogen through power-to-gas technology for long-term storage [25]. This dual-storage approach creates a versatile energy reserve that can be activated during supply deficits. By enabling such dynamic energy allocation across different timescales, the EH-IES not only enhances system stability but also maximizes resource efficiency, effectively mitigating variability in both generation and load profiles.

The environmental advantages of the EH-IES are scientifically validated, with its clean energy profile demonstrating exceptional decarbonization potential. As a zero-emission energy carrier, hydrogen's combustion yields only water vapor, eliminating particulate and greenhouse gas emissions. When synergistically combined with advanced fuel cell technologies, the system enables completely emission-free energy conversion processes. By harnessing renewable electricity generation and systematically replacing fossil fuels with hydrogen across energy sectors, the EH-IES achieves dramatic lifecycle carbon reductions exceeding 80% compared to conventional systems [26]. This transformative approach represents a critical pathway for climate change mitigation while simultaneously addressing urban air pollution challenges, positioning the EH-IES as an indispensable component in the transition to carbon-neutral energy systems.

2.2. Key Technology of the EH-IES

A technical examination of the EH-IES reveals several groundbreaking innovations that form the foundation of this integrated energy system. Chief among these are fuel cell technology and P2G systems, which serve as the technological pillars enabling efficient energy conversion and storage. The continuous advancement and optimization of these core technologies play a pivotal role in accelerating the transition to clean energy systems and realizing carbon neutrality targets.

2.2.1. Fuel Cell Technology

Fuel cell technology can be systematically classified into high- and low-temperature variants, each engineered to address specific operational requirements and application domains. Low-temperature fuel cells, including Proton Exchange Membrane Fuel Cells (PEMFCs) and Alkaline Fuel Cells (AFCs), demonstrate superior performance characteristics for particular use cases. Conversely, high-temperature systems such as Solid Oxide Fuel Cells (SOFCs) and Molten Carbonate Fuel Cells (MCFCs) exhibit distinct advantages in alternative applications. Comprehensive comparative analyses, as presented in Table 1, quantitatively evaluate the relative efficiencies, operational parameters, and application suitability of these technologies, offering critical insights for their optimal deployment in practical implementations.

Table 1. Comparison of different fuel cell technologies.

Type	Operating Temperature	Output Capacity	Investment Costs	Degradation Rate	Application Field
PEMFC	<120 °C	<250 kW	1500–4000 $/kW	0.5–1.0%/1000 h	Backup power supply/Mobile power supply/Transportation/Distributed power generation
AFC	<100 °C	10–100 kW	200~700 $/kW	1–2%/1000 h	Backup power/Transportation
SOFC	500–1000 °C	5–3000 kW	3000–5000 $/kW	0.2–1.0%/1000 h	Distributed power generation/Cogeneration
MCFC	600–700 °C	<1000 kW	4000–5000 $/kW	0.5–1.5%/1000 h	Distributed generation/Cogeneration

PEMFCs have emerged as a technologically advanced alternative to conventional internal combustion engines, demonstrating superior performance attributes that align with contemporary energy demands [27]. These systems exhibit multiple competitive advantages, including high energy conversion efficiency, zero operational emissions, exceptional fuel flexibility, and modular design capabilities—characteristics that position them favorably within the modern energy paradigm. Particularly noteworthy are PEMFCs' remarkable operational efficiencies and rapid hydrogen-refueling capacity, which enable driving ranges comparable to traditional fossil fuel systems, thereby driving their rapid adoption in transportation applications [28]. However, despite these significant benefits, PEMFC technology development faces several critical challenges. A primary technical limitation involves their susceptibility to fuel impurities, which can substantially compromise cell performance and operational lifespan. Furthermore, the dependence on expensive components, notably platinum-based catalysts and specialized proton exchange membranes, creates substantial economic barriers. These cost factors may potentially constrain widespread commercialization by maintaining prohibitively high production expenses.

In contrast, AFCs offer a cost-effective solution with versatile applications in both distributed energy systems and stationary power generation. As the most technologically mature and commercially established fuel cell type, AFCs demonstrate distinct advantages through their ability to utilize non-precious metal catalysts in alkaline operating conditions. Nevertheless, these alkaline environments present notable technical challenges, as the highly corrosive electrolyte may accelerate stack component degradation, potentially compromising long-term durability and system performance. Despite these limitations, AFCs maintain competitive advantages including exceptional start–stop responsiveness, making them particularly suitable for hydrogen FCVs and as dependable backup power sources in electrical grids.

At the higher-temperature range of fuel cell technologies, SOFCs and MCFCs find their primary applications in stationary power generation and combined heat and power (CHP) systems. MCFCs demonstrate particular environmental advantages through their compatibility with conventional thermal power plants, featuring unique carbon capture capabilities both pre- and post-combustion that can dramatically reduce facility emissions. When configured for CHP applications, these high-temperature fuel cells achieve remarkable combined efficiencies up to 85%, significantly outperforming their approximately 60% efficiency in electricity-only generation modes [29].

2.2.2. P2G Technology

Power-to-X (P2X) represents a transformative approach to energy management by harnessing surplus renewable electricity for hydrogen production through electrolysis. The generated hydrogen serves dual purposes as both an efficient energy storage vector and a versatile industrial raw material [30]. This conversion pathway enables multi-sectoral energy distribution and utilization, significantly improving the operational flexibility and economic viability of renewable energy systems through cross-application repurposing of stored energy.

Among various P2X system configurations, P2G has emerged as the most efficient solution, owing to its unique capability to integrate electrical energy conversion with gas production [31]. This technology effectively utilizes surplus renewable electricity for hydrogen or synthetic natural gas (SNG) generation, offering a scalable approach to mitigate the challenges posed by renewable energy intermittency [32]. P2G systems can be broadly classified into two main categories: electric-to-hydrogen (E2H) and electric-to-natural gas (E2NG, also referred to as electric-to-SNG). The conversion efficiency of electrolytic hydrogen production typically ranges between 75% and 85%, whereas methanation processes exhibit slightly lower efficiencies of 75% to 80%. When these processes are combined in integrated P2G systems, the overall conversion efficiency falls within the range of 49% to 65%. Notably, electric hydrogen production consistently demonstrates higher efficiency compared to electric methane synthesis [25].

Despite its advantages, the widespread adoption of P2G technology faces several key challenges. First, the high capital and operational costs of P2G infrastructure pose a significant barrier, driven by the need for advanced, high-performance equipment to support its complex processes. These substantial investments, coupled with inherent energy conversion inefficiencies, hinder the scalability of P2G systems. Additionally, energy losses during the electricity-to-gas conversion further diminish overall system efficiency. Beyond technical limitations, logistical hurdles—particularly in the storage and transportation of gaseous fuels like hydrogen, which demands stringent safety measures—compound operational complexities and undermine the economic viability of P2G projects.

To address these challenges, P2G technology is undergoing continuous advancement, fostering innovations in renewable energy integration and storage. As these systems mature and achieve economies of scale, they hold transformative potential for modern energy infrastructure. By delivering reliable, flexible, and low-carbon energy solutions, P2G could fundamentally redefine global energy paradigms. This evolution will play a pivotal role in establishing more sustainable energy systems, significantly reducing carbon emissions while accelerating the transition toward a cleaner, more sustainable energy future.

2.3. Typical Coupling Forms and Coupling Mechanisms

The EH-IES exhibits complex and diverse coupling forms and mechanisms. This system achieves deep integration with various sectors, including transportation systems (e.g., electric vehicles), building systems, industrial systems, and electric–hydrogen integrated energy stations. Furthermore, multiple stakeholders can participate in the EH-IES across different operational segments, spanning generation, transmission, consumption, and storage components of the energy system.

In this study, the terms multi-system coupling and multi-link coupling are used to describe two complementary but distinct levels of integration within EH-IES. Multi-system coupling refers to the interconnection and coordinated operation of different energy systems, such as the power system, hydrogen network, thermal network, transportation system, and industrial energy users. It emphasizes cross-sectoral energy exchange and infrastructure sharing. Multi-link coupling describes the coordinated interaction among internal functional links within a single EH-IES, specifically covering the generation, transmission, consumption, and storage links. It focuses on intra-system synergy across the energy conversion chain. While multi-system coupling addresses "how EH-IES connects with other sectors," multi-link coupling addresses "how different functional components collaborate within EH-IES".

2.3.1. Multi-System Coupling

(1) Electric–hydrogen coupling in the transportation sector

The transportation sector is undergoing a significant shift from conventional fossil fuels—primarily used in traditional vehicles that emit substantial amounts of carbon dioxide and other pollutants—toward cleaner, sustainable energy sources like electricity and hydrogen [33]. This transition is fueled by growing environmental concerns and a global commitment to sustainability. New energy vehicles, powered by these clean alternatives, are set to redefine mainstream transportation systems [34]. Hydrogen, in particular, offers distinct advantages due to its versatility in powering diverse vehicle types—from light-duty cars to buses and heavy-duty trucks—via efficient refueling infrastructure [35–37]. Compared to battery electric vehicles (EV), HFCV eliminate self-discharge concerns while providing higher energy density, extended driving ranges, and significantly faster refueling times [38].

The integration between the EH-IES and transportation network is facilitated through the deployment of specialized transportation and charging infrastructure, as illustrated in Figure 3. The strategic placement of hydrogen-refueling stations and electric–hydrogen integrated energy stations is optimized using geographic information systems (GIS) and big data analytics. Key planning considerations include regional energy demand patterns, traffic flow dynamics, and land acquisition costs. Furthermore, comprehensive economic and technical analyses are conducted to determine optimal facility capacities for energy production, storage, and distribution. These analyses incorporate critical parameters such as projected traffic demand, energy production costs, storage efficiency metrics, and associated storage costs [39–42].

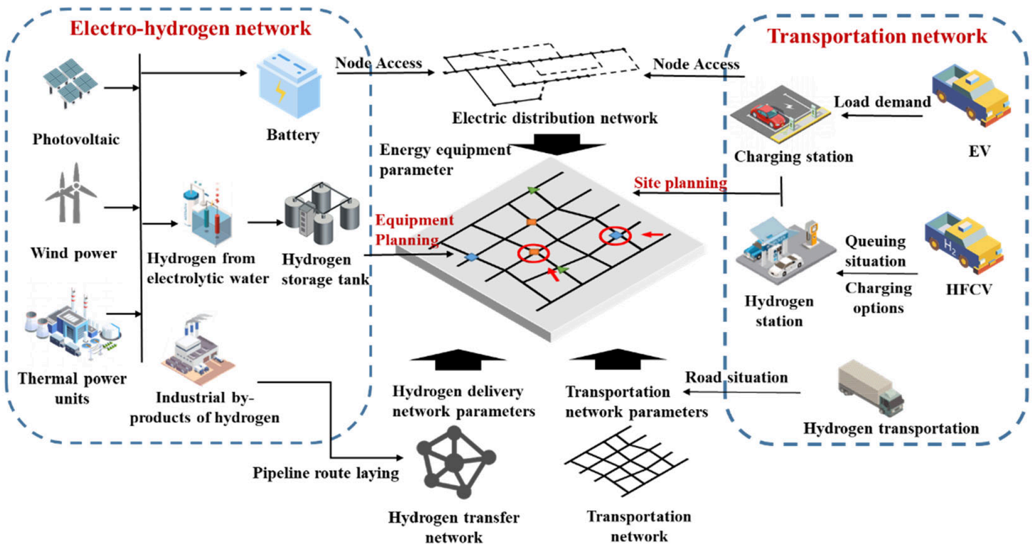

Figure 3. Electric–hydrogen coupling in the transportation sector.

Governments serve as pivotal enablers in this transition by implementing dynamic energy pricing strategies for vehicle-charging and hydrogen-refueling infrastructure, carefully calibrated to align with load demand patterns. These policy measures simultaneously optimize energy utilization while advancing economic and environmental sustainability goals. Through such well-designed systems, end users gain the capacity to make informed choices about their energy consumption, travel planning, and refueling behaviors, thereby reducing energy waste and enhancing overall system efficiency. This synergistic interplay between technological innovation, policy frameworks, and consumer participation forms the foundation for accelerating EH-IES adoption, paving the way for a sustainable and economically robust energy ecosystem.

(2) Electric–hydrogen coupling in the building sector

The implementation of electric–hydrogen coupling technology in the building energy sector, as illustrated in Figure 4, offers an innovative approach to addressing the complex challenges of heterogeneous energy loads and their significant seasonal fluctuations. Within this sector, energy consumption patterns demonstrate stochastic characteristics that require sophisticated coordination among diverse energy conversion systems. Such coordination is crucial for effectively balancing short-term supply–demand variations at the residential scale while simultaneously guaranteeing stable long-term energy provision at the community level. The integration of electric–hydrogen coupling technology has the potential to transform conventional energy management paradigms in the built environment, ultimately improving both energy utilization efficiency and overall system sustainability.

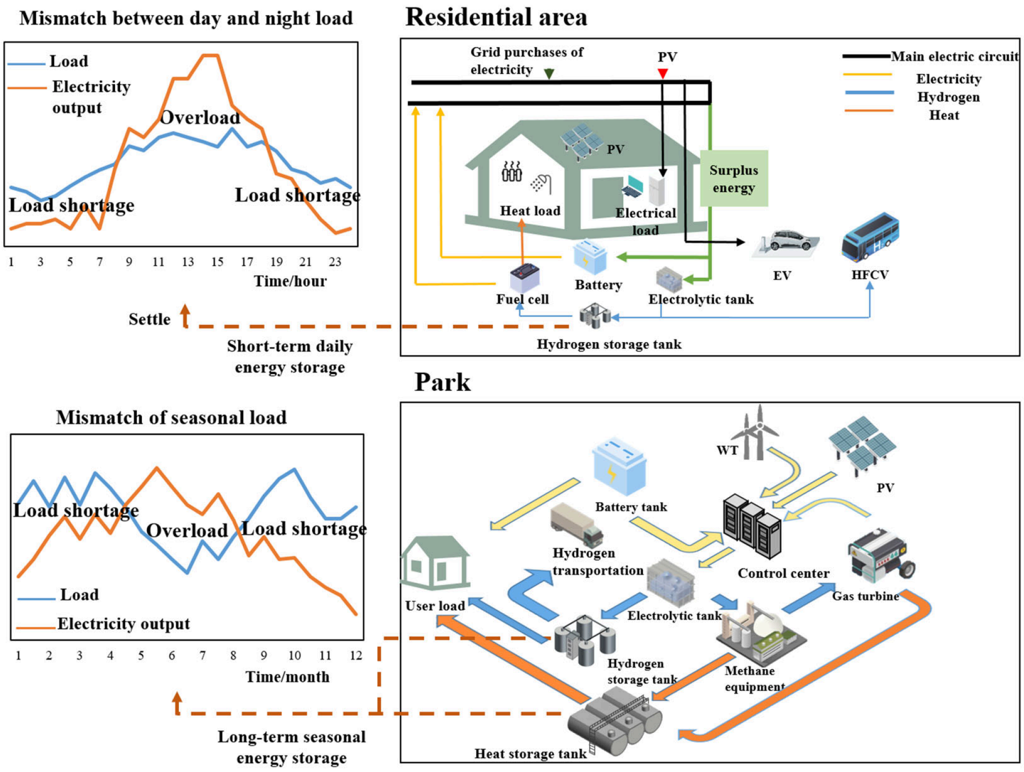

Figure 4. Electric–hydrogen coupling in the building sector.

At the residential area, electric–hydrogen coupling systems primarily optimize energy supply and utilization for individual dwellings or small residential communities. These systems employ compact electrolyzers for on-site hydrogen production and small-scale fuel cells to enable efficient, clean energy conversion. Beyond providing low-carbon electricity, the integrated systems offer sustainable charging solutions for electric vehicles while maintaining seamless interoperability with distributed renewable energy sources—particularly solar PV arrays and WT. This configuration creates a diversified renewable energy portfolio that effectively displaces fossil fuel-based generation. By implementing this approach, households can significantly decrease dependence on centralized power grids while achieving greater energy self-sufficiency. The systems comprehensively address residential energy demands—including electricity, space heating, and cooling—with markedly lower carbon emissions compared to conventional energy solutions.

At the district level, park-scale EH-IES integrate large-capacity water-electrolysis hydrogen production facilities with extensive fuel cell arrays. These systems are synergistically coupled with existing energy infrastructure—including electrical grids and district heating networks [4,43]—to establish a fully integrated hydrogen value chain. This comprehensive approach optimizes the entire hydrogen lifecycle, from production and storage to distribution and end-use applications, thereby creating a foundation for a sustainable hydrogen economy within the park's energy ecosystem.

A particularly impactful innovation involves the progressive blending of hydrogen with natural gas at concentrations up to 20%, representing a strategic transition away from conventional fossil fuel-based CHP systems. The implementation of advanced CHP technologies—utilizing either hydrogen-capable gas turbines or high-efficiency fuel cells—leverages existing building and energy network infrastructure to deliver reliable, on-demand heat and power generation. This technological integration not only enhances system flexibility but also makes significant contributions to decarbonization efforts, supporting the transition toward a more sustainable and resilient energy paradigm.

In conclusion, the strategic implementation of electric–hydrogen coupling technology across both residential and district scales presents a comprehensive solution to the inherent volatility and complexity of building energy systems. This innovative approach not only facilitates optimized energy flow management but also represents a paradigm shift in sustainable infrastructure development for the built environment. By modernizing energy systems at multiple scales, this technological advancement demonstrates transformative potential in redefining conventional energy frameworks. The successful dual-scale application provides compelling empirical support for transitioning toward more integrated, low-carbon energy solutions in building operations and management, marking a significant step forward in achieving sustainable urban development goals.

(3) Electric–hydrogen coupling in the industry sector

The industrial sector is witnessing a paradigm shift through the incorporation of electro-hydrogen technology in manufacturing key chemical compounds, particularly ammonia and methanol [18]. This innovative integration is creating novel pathways for hydrogen energy utilization, fundamentally transforming conventional chemical production methods toward more sustainable and energy-efficient processes (Figure 5). The application of electro-hydrogen coupling demonstrates particular transformative potential in chemical synthesis, where it facilitates the production of critical industrial feedstocks and clean fuels while significantly reducing the carbon footprint of traditional manufacturing approaches.

The production of "green ammonia" and "green methanol" via electro-hydrogen technology, utilizing renewable-derived green hydrogen, marks a transformative leap in sustainable industrial manufacturing [44]. As fundamental industrial commodities—with ammonia serving as the cornerstone of agricultural chemicals and methanol functioning as both a versatile fuel and essential chemical precursor—these products demonstrate green hydrogen's disruptive potential in chemical process engineering. This technological transition achieves dual benefits: it dramatically reduces the carbon intensity of conventional production methods while establishing a scalable framework for green hydrogen adoption in other carbon-intensive industries, particularly metallurgical processes and petroleum-refining operations [45].

The metallurgical sector stands at the brink of a technological revolution through the adoption of hydrogen-rich and pure hydrogen-based processes. These innovative approaches utilize hydrogen as a primary reducing agent, offering a viable pathway to displace conventional carbon-intensive metallurgical operations and enable sustainable, low-emission metal production. This transformation not only supports global climate mitigation initiatives but also underscores hydrogen's pivotal role in facilitating the deep decarbonization of heavy industries.

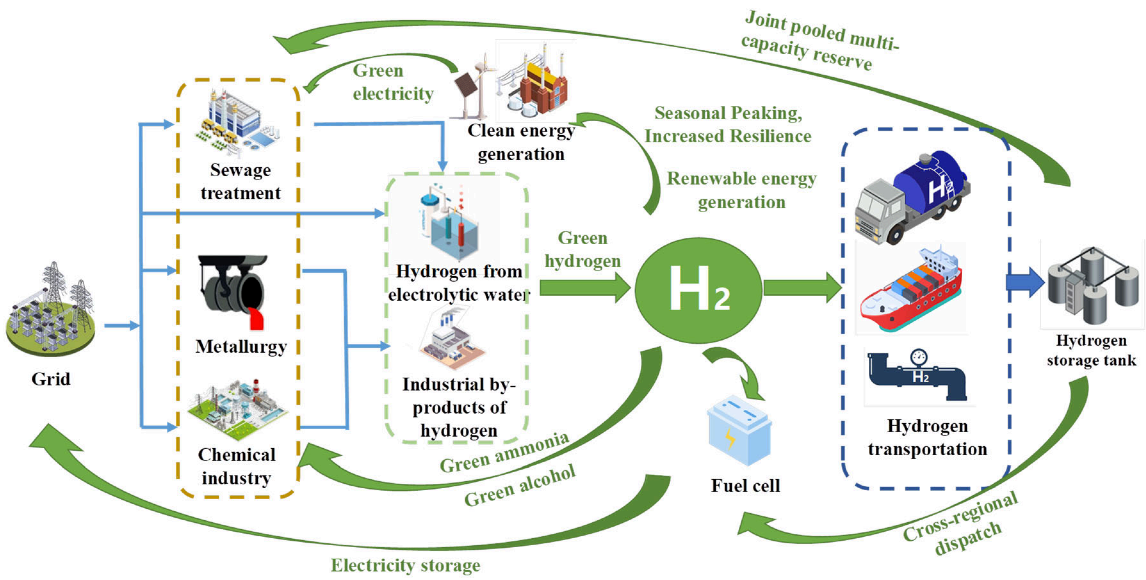

Figure 5. Image of electric–hydrogen coupling in the industry sector.

Beyond its direct application in industrial processes, hydrogen demonstrates versatile potential through its integration with existing energy infrastructure. A prime example is the blending of hydrogen with natural gas for transportation and storage, which offers a pragmatic transition strategy. This approach capitalizes on established pipeline networks, minimizing capital expenditures for new infrastructure while simultaneously expanding hydrogen's distribution capabilities as a clean energy vector. Such integration not only enhances the scalability of hydrogen deployment but also optimizes the utilization of current energy assets during the transition to low-carbon systems.

2.3.2. Multi-Link Coupling

Hydrogen energy demonstrates extensive application potential across multiple sectors, including transportation, construction, and industrial systems, while also serving as a pivotal medium for energy interconnection and transition. Its adoption facilitates large-scale deep decarbonization and significantly enhances clean and efficient energy utilization. Within EH-IES systems, diverse resources and multifaceted approaches enable comprehensive coupling participation across all components—generation, transmission, consumption, and storage. As illustrated in Figure 6, these developments clearly showcase the emerging trends in electric–hydrogen integration.

(1) The source side

During the development of EH-IES, the share of renewable energy in power generation is expected to grow steadily. The conversion of wind and solar energy into both electricity and hydrogen enables efficient utilization of clean energy while reducing reliance on conventional energy sources and lowering carbon emissions. Regarding hydrogen production, electrolysis offers superior hydrogen purity compared to traditional methods like coal gasification and methane reforming. However, it currently faces challenges such as higher production costs. Additional technical hurdles include ensuring system safety, improving electrolysis conversion efficiency, and optimizing integrated system operations—all of which represent critical barriers to advancing electrolytic hydrogen technology. A key advantage of EH-IES lies in the complementary relationship between electricity and hydrogen. When renewable generation exceeds grid demand, surplus electricity can be utilized for water electrolysis, producing hydrogen and oxygen for storage. This stored hydrogen can then be deployed across industrial, construction, and transportation sectors, enhancing overall system flexibility and energy utilization efficiency.

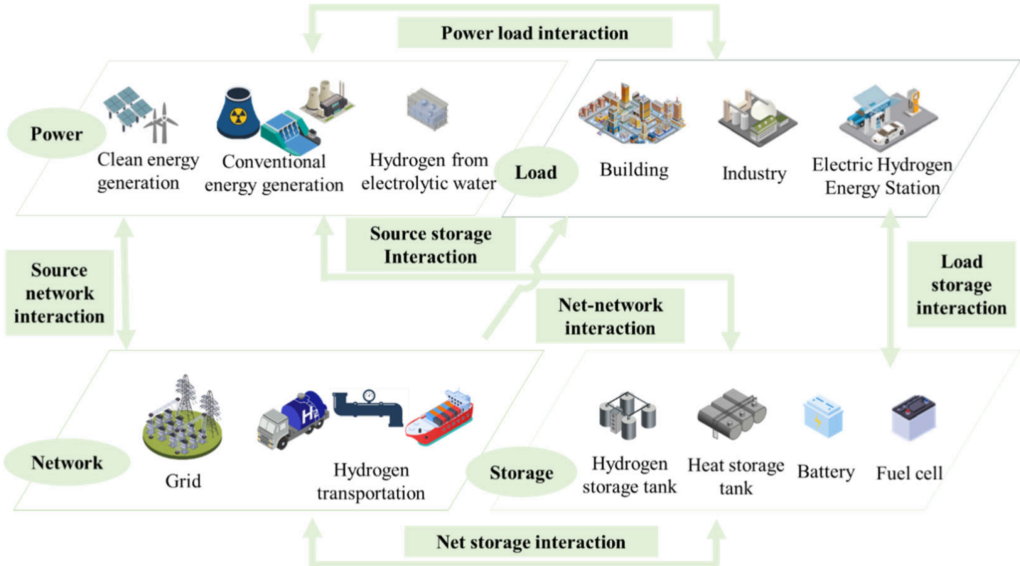

Figure 6. Electric–hydrogen coupling in source–network–load–storage segments.

(2) The network side

Within EH-IES frameworks, the power grid assumes an expanded role that transcends conventional electricity transmission functions. Through synergistic integration with hydrogen infrastructure, it enables cross-seasonal and long-duration energy storage capabilities. Hydrogen serves as an optimal medium for extended energy storage, facilitating electrical energy conversion and retention through multiple technological pathways [46]. These encompass physical storage methods including high-pressure gas containment and cryogenic liquid hydrogen systems, and chemical conversion approaches such as hydrogen-based ammonia synthesis and methanation processes.

Hydrogen energy serves multiple critical functions in power grid operations. It enables large-scale energy storage that facilitates peak load management, frequency modulation, transmission congestion relief, voltage control, and emergency black-start functionality [32]. The intermittent nature of wind and solar power generation induces considerable frequency variations, which jeopardize grid stability and compromise power quality for consumers [47]. Hydrogen-based energy storage systems, however, demonstrate exceptional frequency regulation capabilities with response times measurable in seconds, presenting a viable solution to these grid stability challenges.

Hydrogen grids significantly improve the resilience and operational flexibility of modern power systems. These systems serve a dual function: providing essential backup power during grid outages to maintain energy security, and offering rapid frequency regulation capabilities with response times measured in seconds [48]. This unique combination of attributes—instantaneous grid stabilization and reliable emergency power supply—ensures uninterrupted energy delivery even during system disturbances. By substantially enhancing grid robustness, hydrogen infrastructure emerges as a pivotal component in the development of sustainable and resilient energy networks for the future.

(3) The demand side

Amid growing global demand for sustainable transportation fuels, the convergence of innovative technologies offers a transformative approach to clean energy generation and utilization. The development of fully integrated PV charging and hydrogen-refueling stations represents a significant technological advancement, simultaneously addressing the distinct requirements of both electric and fuel cell vehicles [49]. This irreversible shift toward dual-function infrastructure not only demonstrates remarkable technological synergy but also embodies the optimization of renewable energy systems through integrated design.

A closer examination of fuel cell operation reveals that these systems produce significant thermal energy alongside electricity. Strategically recovering and utilizing this waste heat through cogeneration systems yields dual advantages: it substantially improves overall energy efficiency while simultaneously reducing carbon emissions [50,51]. This approach highlights the essential role of optimized energy conversion in achieving advanced eco-sustainability benchmarks.

(4) The storage side

The advantages of hydrogen as an energy carrier become particularly apparent when evaluating its inherent characteristics against alternative energy storage technologies, including pumped hydro storage and electrochemical batteries. Hydrogen distinguishes itself through three key attributes: superior energy density, zero-emission operation, and unique capability for seasonal-scale energy storage [52,53]. These properties collectively establish hydrogen as the optimal solution for large-capacity, long-duration energy storage requirements—a critical component for maintaining grid stability in renewable-dominated energy systems.

In the context of energy storage, EH-IES emerges as a key solution to the challenges posed by the variability of power sources, particularly intermittent renewable resources like wind and solar. By integrating electrical and hydrogen storage technologies, hybrid systems effectively manage fluctuations across different time scales. This integration significantly reduces the risk of imbalance within the power grid [14,54,55]. When incorporated into microgrid frameworks, these hybrid systems provide additional benefits [56]. They enhance the adaptability and resilience of local energy systems, enabling better management of the unpredictability associated with distributed renewable resources. As a result, these systems reinforce overall grid stability and security.

Ultimately, combining advanced hydrogen storage solutions with sophisticated grid management techniques marks a new era in grid efficiency and reliability. This development sets a benchmark in the pursuit of zero-emission energy systems [47,57].

2.4. Comparison Between EH-IES and Other Low-Carbon Energy Systems

Battery-only energy storage systems and electro-hydrogen hybrid energy systems are complementary: battery-only systems are more cost-effective for short-term regulation, while electro-hydrogen systems are indispensable for medium- to long-term applications and scenarios where decarbonization is particularly challenging. In practical planning, a hybrid model that uses batteries for short-term storage and hydrogen for long-term storage can be adopted. The following Table 2 compares EH-IES with other low-carbon energy systems:

Table 2. Comparison of EH-IES with other low-carbon energy systems.

Comparison Criteria	Battery-Only Energy Storage Integrated Energy System	Electricity–Hydrogen Coupled Integrated Energy System
Energy Storage Duration	Hourly/daily scale, not suitable for cross-seasonal storage	Weekly/seasonal scale; suitable for long-term fluctuations in wind and solar power
Application Scenarios	Small-scale buildings, short-distance transportation	Heavy industry decarbonization, heavy-duty transportation, cross-seasonal peak shaving
Carbon Emissions	Depends on the cleanliness of the grid	Can achieve net-zero carbon emissions across the entire process (assuming green electricity is used for hydrogen production)
Cost Trends	Costs of lithium-ion batteries are declining at a slower pace	Costs of electrolyzers and fuel cells still have room to decrease by 30–50%

3. Modeling of the EH-IES

The integration of different systems and components in the EH-IES requires various electric power and hydrogen energy equipment. Therefore, accurate modeling of power and hydrogen devices forms the foundation for EH-IES planning.

3.1. Modeling of Power Equipment

3.1.1. Renewable Energy Equipment

In the EH-IES, renewable energy equipment plays an important role in providing clean, renewable power for the system and promoting the coupling of hydrogen energy with renewable energy on the power side to facilitate large-scale renewable energy consumption.

(1) Wind power

Various types of mathematical models for wind turbines exist. One is statistically based models, such as autoregressive moving average model (ARIMA), generalized ARCH model (GARCH), grey forecasting, empirical modal decomposition, Kalman filtering model and so on. These models are based on historical data or real-time data, and utilize statistical principles and methods to predict or describe the output of wind power. The second is the use of artificial intelligence technology, using algorithms, learning and training through a large amount of data to establish the relationship between input and output, which is more adaptable to the nonlinear change process of wind speed.

The power output of a wind turbine (WT) is related to the wind speed as follows:

$$P = \begin{cases} 0, v < v_{ci}; v > v_{co} \\ av^3 - bP_r, v_{ci} \le v \le v_r \\ P_r, v_r \le v \le v_{co} \end{cases} \tag{1}$$

$$a = \frac{P_{\rm r}}{{\rm v}_r^3 - v_{ci}^3} \tag{2}$$

$$\rm{b} = \frac{v_{ci}^3}{{\rm v}_r^3 - v_{ci}^3} \tag{3}$$

where v_{ci} and v_{co} are the cut-in and cut-out wind speeds, respectively, v is the actual wind speed, v_r is the rated wind speed, P is the rated power of the fan, and a and b are two coefficients.

(2) PV system

The mathematical model of the PV power-generation system can be expressed as:

$$P_{pv} = P_{pv\_STC} f_{pv} \left(\frac{R_T}{R_{STC}} \right) [1 + \alpha_P (T_c - T_{STC})] \tag{4}$$

where P_{pv}, P_{pv_STC} are the actual output power of the PV power supply and the rated power under the standard test conditions in kw, R_T and R_{STC} are the actual light intensity and the light intensity under the standard test conditions in kw/m^2, f_{pv} and α_P are the loss coefficients and power temperature coefficients of the PV panels, T_c and T_{STC} are the actual cell temperature and the cell temperature under standard test conditions, and here T_{STC} is taken as 25 °C.

3.1.2. Storage Device

As an electrochemical device, the battery can convert electrical energy into chemical energy for storage, and convert chemical energy into electrical energy output when needed. The batteries used in the current scale are mainly lead–acid batteries, nickel–metal hydride batteries and lithium iron phosphate batteries. The battery charging and discharging state formula is as follows:

$$SOC(t) = SOC(t-1) \cdot (1 - \mu_{es}) + \eta_{in} \cdot \frac{P_{in}(t)}{T^{MAX}} \tag{5}$$

$$SOC(t) = SOC(t-1) \cdot (1 - \mu_{es}) + \frac{P_{dis}(t)}{\eta_{dis} \cdot T^{MAX}} \tag{6}$$

where $SOC(t)$ represents the actual capacity of the battery at time t, μ_{es} is the self-discharge rate of the battery, T^{MAX} is the maximum capacity of the battery, $P_{in}(t)$ and $P_{dis}(t)$ represent the charging and discharging power of the battery at time t, and η_{in} and η_{dis} are the charging and discharging efficiencies of the battery, respectively.

3.2. Models of Hydrogen Equipment

The hydrogen energy system (HES) is an important part of the EH-IES, including hydrogen production facilities, such as electrolyzed water hydrogen production equipment, and hydrogen storage facilities, such as hydrogen storage tanks. In addition, the HES includes hydrogen transportation pipelines and hydrogen use equipment, such as hydrogen fuel cells and hydrogen-to-ammonia equipment.

As a two-way device, the hydrogen storage tank can store hydrogen produced by electrolyzing water in the electrolysis tank, and at the same time, it can provide hydrogen for the fuel cell to produce electricity, so as to improve the flexibility of the system, and its mathematical model can be expressed as follows.

$$E_{store}(t) = E_{store}(t-1) + P_{e-in}(t-1) \cdot \eta_e \cdot \eta_{e_{-DC-DC}} - \frac{P_f(t-1)}{\eta_f \cdot \eta_{store} \cdot \eta_{f_{DC-DC}}} \tag{7}$$

where $E_{store}(t)$ is the energy stored in the hydrogen storage tank at time t, $\eta_{e_{-DC-DC}}$ is the converter efficiency of the electrolyzer, $\eta_{f_{DC-DC}}$ is the converter efficiency of the fuel cell, which can be taken as 90% in general, and η_{store} is the efficiency of the hydrogen storage tank, which can be taken as 50% in general.

3.3. Modeling of Electric–Hydrogen Coupled Equipment

P2G equipment and fuel cell equipment are important components of electric–hydrogen coupling equipment, which together realize the conversion and synergy between electric energy and hydrogen energy, improving the flexibility, stability and sustainability of the energy system.

(1) P2G equipment

The P2G is a device that efficiently utilizes excess renewable energy to convert CH_4. The process of synthesizing CH_4 in the P2G is divided into two steps: firstly, the excess renewable energy is utilized to electrolyze water into hydrogen and oxygen by means of electrolysis in an electrolysis cell, and secondly, the hydrogen produced is used in a Sabatier reaction with CO_2 for the final synthesis of CH_4. The P2G principle is shown in Figure 7.

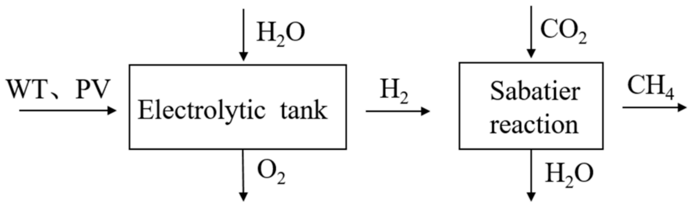

Figure 7. P2G principle.

(2) Fuel cell

The mathematical modeling of the fuel cell's power generation and heat-production power is as follows:

$$P_{HFC-e}(t) = \frac{V_H(t) \cdot Q_H \cdot \eta_{HFC-e}}{\Delta t} \tag{8}$$

$$P_{HFC-h}(t) = \frac{V_H(t) \cdot Q_H \cdot \eta_{HFC-h}}{\Delta t} \tag{9}$$

$$P_{HFC-H}(t) = \frac{V_H(t) \cdot Q_H}{\Delta t} \tag{10}$$

where $P_{HFC-e}(t)$, $P_{HFC-h}(t)$, $P_{HFC-H}(t)$ represent the power generation, heat production and hydrogen consumption of the fuel cell at time t, $V_H(t)$ represents the consumption of hydrogen at time t, Q_H represents the calorific value of hydrogen, and η_{HFC-e}, η_{HFC-h} represent the power-generation and heat-production efficiencies of the fuel cell, respectively.

4. Optimal Planning Method of the EH-IES

The primary objective of EH-IES planning is to facilitate the seamless interconnection and mutual optimization of diverse energy modalities, alongside the deep integration of generation, grid, demand, and storage systems. This integrated approach is crucial for effectively addressing the inherent characteristics of renewable energy sources, such as their high volatility and uncertainty. Depending on the specific planning focus, EH-IES planning can be categorized into transportation, building, and industrial applications. Consequently, the planning process must consider a multitude of factors in a holistic manner to ensure the system's overall efficiency, robustness, and sustainability. The strategic planning of EH-IES, encompassing various planning scenarios, objectives, and modeling techniques, aims to achieve an optimal equilibrium among economic, technological, and environmental considerations. Such planning facilitates the clean and efficient utilization of energy, while driving large-scale decarbonization initiatives. Moreover, due to the inherent complexity of the planning variables, a variety of models exist for EH-IES planning. Therefore, the selection and construction of the appropriate planning model should be tailored to the specific decision-making requirements and challenges, as illustrated in Figure 8.

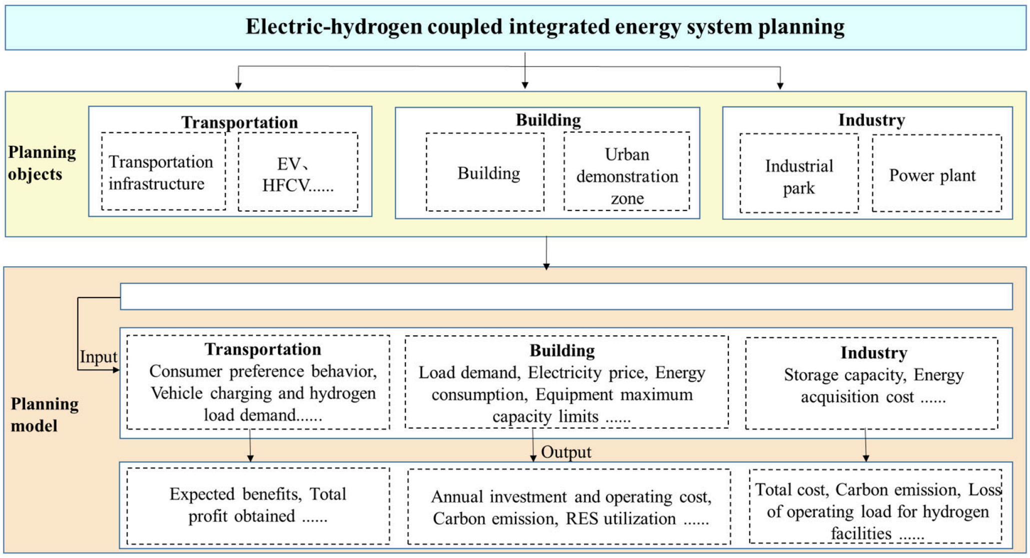

Figure 8. Planning framework for EH-IESs.

4.1. Optimal Planning of EH-IES in the Transportation Sector

The planning of electric–hydrogen coupled integrated energy systems in the transport sector can be divided into two categories, as shown in Figure 9. The first one is the planning of charging/hydrogen supply infrastructure, such as the layout planning of the integrated electric–hydrogen charging station [52,58] and the sizing problem of the production, storage and dispensing facilities of electricity and hydrogen. The efficient and stable supply of electricity and hydrogen can be ensured by planning the site selection, layout and scale of the hydrogen-refueling station and the integrated electric–hydrogen energy station so that the energy demand of the transportation system can be met. The second one is the choice of transportation means and transportation operation strategy. For example, when users travel, they usually consider suitable transportation means. After the electric–hydrogen coupling is taken into account, the modeling methods, power balance equations and optimization variables in the EH-IES planning model in the transportation field will be changed correspondingly [59].

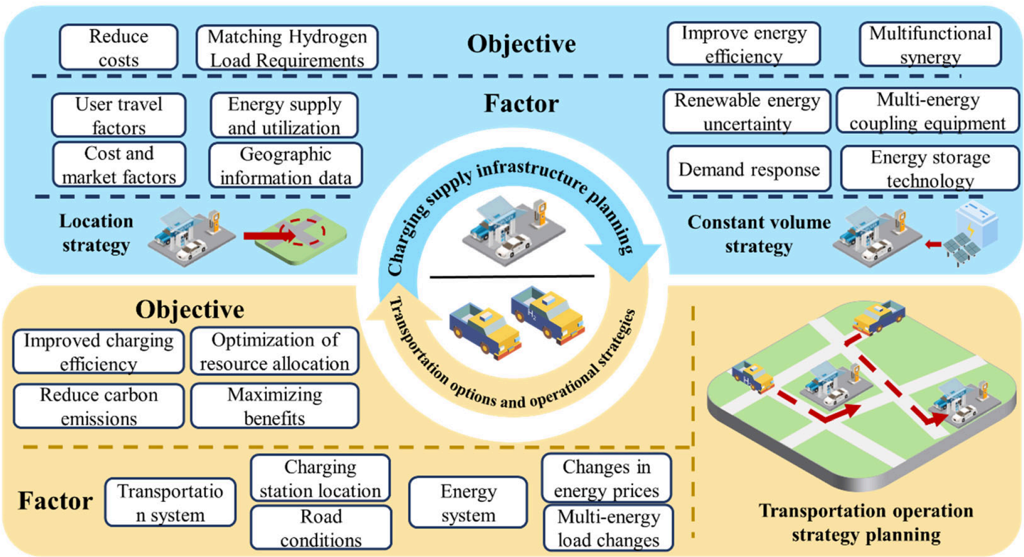

Figure 9. Planning of EH-IES in the transportation sector.

(1) Charging/hydrogen infrastructure

In the context of EH-IES, meticulous planning is critical, particularly in relation to the infrastructure for charging and hydrogen supply. This aspect includes determining the optimal layout for integrated electric–hydrogen charging stations [60]. A key factor underpinning these strategic decisions is the understanding of user travel behavior. This necessitates innovative solutions that enhance the utilization of renewable energy sources and stabilize the energy supply network [61]. The integration of battery replacement facilities and the establishment of hydrogen-refueling stations (HRS), especially those employing on-site renewable energy production, has proven effective.

Significant advancements have been documented in the development of eco-friendly layouts for IES, which combine electric, gas, and hydrogen networks. These systems often feature fast charging stations (FCSs) and hydrogen production stations (HPSs), designed to meet the electricity and hydrogen demands of EVs and hydrogen FCVs [62,63]. Moreover, refined site selection models for HRS have been proposed, leveraging GIS data and demographic analytics. These models provide strategic insights into optimal station locations, coverage distances, and station density [64].

Hydrogen stations are recognized as crucial nodes in the energy infrastructure. Recent studies have proposed advanced models for the planning of integrated energy systems, taking into account the multi-faceted utilization of hydrogen energy. These models aim to optimize the placement of HRSs and assess the impact of hydrogen transmission pathways on the broader energy infrastructure.

In summary, the layout planning for integrated electric–hydrogen charging stations requires a holistic approach. Critical factors include market demand, construction costs, geographic positioning, compatibility with charging facilities, and urban planning constraints [61]. The integration of HRS with electric charging stations creates a synergistic model capable of addressing operational and economic challenges that were previously associated with standalone hydrogen stations.

Looking ahead, long-term planning for electric–hydrogen energy stations must align with the growing demands of the hydrogen energy supply chain [64,65]. Siting decisions for hydrogen facilities should consider risk, cost, and demographic coverage to determine optimal locations [66]. Current methodologies also address the fluctuating demands for hydrogen, adjusting facility size and location to accommodate both short-term uncertainties [67] and long-term growth projections [68].

A model for off-grid charging stations, serving both electric and hydrogen vehicles, has been proposed to optimize the output of solar panels, hydrogen storage systems, water electrolyzers, fuel cells, and diesel generators [69]. Similarly, Wang et al. [70] propose an off-grid solar charging station, incorporating robust optimization within mixed-integer linear programming (MILP) for deterministic models to handle uncertainty. While much existing research on hydrogen supply network design focuses on facility siting, Y. T et al. [71] specifically examine regions where large-scale hydrogen supply is difficult, proposing models for determining the timing and location of hydrogen production bases and refueling stations.

Despite these advancements, the research on infrastructure planning—such as siting and layout of energy stations—still holds considerable potential for improvement, especially in addressing the large-scale demand for hydrogen FCVs. Tao et al. [72] proposed a coordinated planning strategy for HRSs, HPSs, and power grids, while Gan et al. [73] introduced a collaborative planning approach coupling multiple networks, including P2G. Building upon this, the cooperative planning of multiple networks for electro-hydrogen transportation is crucial. Most existing studies rely on single-stage planning methods, which have limitations in addressing the continuous growth of system loads and policy changes. In contrast, multi-stage planning methods offer higher flexibility, adaptability, and global optimization capabilities. These methods are better suited to tackle long-term load changes and construction sequencing issues, making them a more scientific and rational approach for energy station siting and layout [74].

Although considerable progress has been made, there remains significant room for improvement in planning models. Recent studies have proposed coordinated strategies for the integration of hydrogen-refueling stations, hydrogen production facilities, and power grids, highlighting the benefits of a holistic approach. Furthermore, transitioning from static, single-phase planning to dynamic, multi-phase models provides a more adaptable, risk-averse, and progressively optimized framework for energy station siting and layout.

(2) Transportation option and operation strategy

The selection of transportation vehicles and the formulation of operational strategies for transportation systems are significantly influenced by the location, capacity, and pricing of hydrogen charging and refueling infrastructure. These factors directly affect users' charging preferences and driving behaviors, which in turn impact traffic flow distribution. In the context of electric–hydrogen coupled systems, planning extends beyond conventional vehicles to include EVs and hydrogen HFCVs, among others. Moreover, the state of the road network plays a critical role in influencing both driving behaviors and decisions related to charging and hydrogen refueling [71]. This dynamic interaction ultimately affects the load distribution within the electric–hydrogen system, thereby necessitating the development of optimized operational strategies for transportation.

To address this complexity, the establishment of a multi-objective planning model is essential. Such a model must integrate various objectives and constraints, including those related to transportation network limitations, distribution network capacities, hydrogen balance, and the energy demands of EVs. The aim is to maximize long-term profitability for charging stations while simultaneously enhancing overall system efficiency [75]. For example, an evolutionary game model presented in [76] captures the flexibility of vehicle demand response, driven by lease price settings. This model effectively demonstrates the substitutability between different vehicle types and their implications for the long-term planning of EH-IES within the transportation sector.

Additionally, Y. T et al. [77] propose a synergistic planning model that jointly considers the operation of distribution grids and transportation systems, incorporating the participation of HFCVs. This model tracks carbon emissions from vehicle footprints, aiming to optimize the mix of vehicle types in order to minimize overall carbon emissions. Given the significant uncertainties inherent in electric–hydrogen coupled system planning, factors such as fluctuations in renewable energy generation, changes in multi-energy loads, variability in traffic flow, and energy price fluctuations can introduce stochastic variations in user travel behaviors. To address these uncertainties, stochastic planning models are essential. These models use probability distributions and stochastic variables to assess risks and benefits across different planning scenarios, allowing for the identification of the optimal decision-making strategy under uncertain conditions [78].

Moreover, when conflicts of interest arise between decision-making entities, such as enterprises and vehicle owners, a two-tier planning approach is often employed. This approach addresses the competing interests and decision-making influences of these stakeholders. In summary, effective planning of transportation choices and operational strategies is critical for optimizing resource allocation, reducing system carbon emissions, and enhancing overall system efficiency. As renewable energy generation and hydrogen production technologies continue to improve, the integration of renewable energy into transportation networks becomes more seamless. The coupling of transportation systems with EH-IES is thus becoming increasingly synergistic.

Table 3 provides a summary of the current state of research on the planning of EH-IES in transportation, detailing key planning objectives, methods, models, and the treatment of uncertainties encountered in the modeling process.

4.2. Optimal Planning of EH-IES in the Building Sector

The system planning for EH-IES in the building sector focuses on the flexible use and storage of multiple energy sources. This approach aims to reduce overall building energy consumption and enhance integrated energy efficiency. The optimization of equipment configuration is the key to achieving this goal. As illustrated in Figure 10, the planning process typically begins with an analysis of the building's energy demand. Key system parameters, such as capacity, layout, and operational mode, are then determined. Subsequently, targeted system models are developed and solved based on specific planning objectives. By optimizing equipment capacity, the total initial investment, operational and maintenance costs, replacement costs, and distribution grid power transaction costs of the EH-IES can be minimized. These optimizations ensure that the energy demands of the building sector are met while optimizing the system's economic performance.

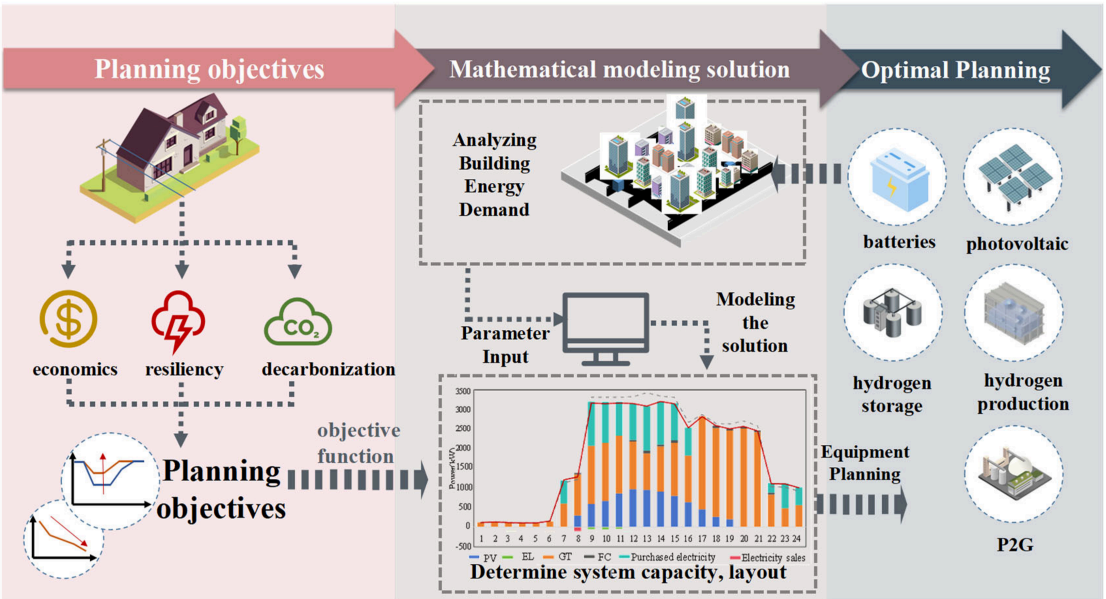

Figure 10. Planning of EH-IESs in the building sector.

The development of the model involves identifying critical system parameters derived from the energy demand analysis. Depending on the system's characteristics and planning objectives, suitable planning methodologies—such as two-layer planning, multi-objective planning, and stochastic planning—are selected. The algorithms employed are designed to account for the system's complexity and inherent uncertainties. This ensures the identification of the optimal energy allocation strategy [71]. A summary of research on the planning of EH-IESs in the building sector is provided in Table 4.

Table 3. Summary of EH-IES planning in the transportation sector.

Literature Number	Transportation Facilities		Planning Objectives	Planning Targets	Planning Methodologies	Uncertainty Considerations
	Hydrogen Station	Electricity–Hydrogen Integrated Energy Station				
[63]		✓	Highway energy stations	Minimize investment costs and maximize net returns	Two-tier planning	✓
[66]	✓		City hydrogen station siting	Minimize total investment cost, hydrogen demand coverage at hydrogen-refueling stations	Multi-objective planning	✓
[69]		✓	Off-grid hydrogen charging station	Minimize investment costs	Stochastic programming	✓
[73]	✓		Hydrogen supply infrastructure	Minimize investment costs	Two-stage randomized planning	✓
[76]		✓	Electricity–hydrogen integrated energy station	Minimize investment costs and maximize expected returns	Two-stage randomized planning	✓
[78]		✓	Electricity–hydrogen integrated energy station	Maximize total profit	Risk-constrained linear planning	✓
[79]	✓		Electricity–hydrogen–transportation coupling network	Minimize total planning costs	Multi-stage planning	
[80]		✓	Electricity–hydrogen integrated energy station	Minimize operating costs	Three-level mixed-integer linear planning	✓
[81]	✓		HFCV green hydrogen supply chain	Minimize total investment and operating costs	Two-stage planning	✓
[82]	✓		Hydrogen station	Minimize risk and total cost, maximize coverage of population areas where hydrogen station locations are problematic	Multi-objective planning	✓

Table 4. Summary of EH-IES planning in the building sector.

Literature Number	Scenarios		Planning Objectives	Coupled Resource				Building Transportation Integration	Planning Methodology
	Residential Area	Park		Electricity	Hydrogen	Heat	Gas		
[83]	✓		Minimizing costs, reducing carbon emissions and improving overall energy efficiency	✓	✓	✓			Multi-objective planning
[75]		✓	Minimize investment cost, operating cost, carbon emission cost	✓	✓	✓		✓	Two-stage stochastic planning
[84]		✓	Minimize operating costs	✓	✓	✓			Stochastic programming
[85]		✓	Minimize investment costs, system operating costs	✓	✓	✓	✓		Multi-objective planning
[86]		✓	Minimize investment costs	✓	✓				Stochastic programming
[87]		✓	Minimizing investment costs and reducing carbon emissions	✓	✓	✓	✓		Multi-objective planning
[88]	✓		Maximize profits, reduce carbon footprint	✓	✓	✓		✓	Multi-objective planning
[89]	✓		Minimizing investment costs, carbon emissions	✓	✓	✓		✓	Multi-objective planning
[90]	✓		Minimizing investment costs, carbon emissions, and improving overall energy efficiency	✓	✓	✓			Multi-objective planning

In terms of the equipment configuration of the system, it should be based on factors such as the energy demand, technicality and economy of the system. Meanwhile, factors like the investment cost, operation efficiency and maintenance cost of the equipment are also considered. This ensures that the expected energy supply demand is met by the system, making it economical and reliable. For small residential buildings, Jung Y et al. [91] proposed a system configuration comprising an electrolyzer, hydrogen storage, and fuel cell to determine the optimal arrangement of system components. The study compared energy system configurations based on two scenarios—hydrogen and electricity and found that these configurations significantly reduce energy consumption and emissions compared to buildings that rely on gas boilers. Similarly, Endo N et al. [92] designed a small low-rise building with a stationary hydrogen system to determine the operating power of each component, based on calculations of the building's PV capacity and energy demand projections. Wang Y et al. [79] extended this work by planning a residential district, verifying the effectiveness of an integrated hydrogen storage energy system that couples electric and thermal energy utilization to reduce system carbon emissions and improve overall energy efficiency.

At the park or residential level, Yu K et al. [85] employed a multi-objective planning model to optimize equipment capacity, considering inter-seasonal thermal storage and electric–hydrogen generation systems. The goal was to minimize the combined annualized investment costs and operating costs of an urban multi-energy flow system. In a similar context, Farahani SS et al. [93] modeled the entire energy supply chain of a building, considering electrical load and heat demand, to determine the optimal system configuration. Mehrjerdi H et al. [86] further investigated a net-zero energy building, aiming to minimize the investment costs associated with PV systems and determining the optimal combination of hydrogen and fuel cell systems.

Hydrogen energy storage technology is pivotal in enabling large-scale and long-duration energy storage. For energy storage capacity planning within the building sector, the rated capacity or power of each system component is determined based on the balance between energy supply and demand, load characteristics, and renewable energy integration [94]. Wang J et al. [87] explored the planning of zero-energy buildings with integrated battery and hydrogen vehicle energy storage. The study demonstrated that hybrid renewable energy and hydrogen vehicle energy storage systems can yield significant economic benefits when applied to campuses and residential complexes. Proper energy storage capacity planning ensures that the storage system can meet the electric power balance requirements of the EH-IES across different time scales.

Further studies have focused on integrated energy systems that incorporate community-level hydrogen storage. For example, Wang J et al. [87] proposed a multi-objective planning model to determine the optimal configuration of a system that facilitates the coordinated supply of cooling, heating, and electricity. In addition, research has delved into the technical integration of zero-energy buildings (ZEBs) with HFCVs, examining the impacts of new EVs on building energy systems. The integration of renewable energy in high-rise residential buildings with hybrid storage systems, combining battery and hydrogen vehicle energy storage, can optimize system configuration and identify the most effective energy management strategies [88]. Additionally, a study on a system combining hydrogen HFCVs with ZEBs found that a net-zero energy balance could be achieved with optimal integration of WT and PV generation, while minimizing power-generation requirements from ground-source heat pump systems [89]. HRES have also been analyzed for their potential to retrofit existing heating systems in buildings, exploring the impact of electric and hydrogen vehicles on the economics and low-carbon performance of HRES [95].

4.3. Optimal Planning of EH-IES in the Industry Sector

The design of EH-IES in the industry sector directly addresses the uncertainties linked to hydrogen production from renewable energy sources. It enables the integrated use of diverse energy sources, which enhances the efficiency and stability of energy conversion processes. This approach not only optimizes energy costs but also contributes to the reduction of carbon emissions. Key components of the system include fixed-capacity hydrogen production equipment, such as hybrid hydrogen gas turbine technology, hydrogen storage tanks, and participation in both electricity and carbon markets. Moreover, the application of hydrogen in chemical production, HFCVs, and various modes of transportation further boosts energy conversion efficiency. It also contributes to cost optimization and supports carbon emission reductions. The ultimate objective is to improve the capacity for hydrogen production, storage, and utilization. Simultaneously, this will enhance economic benefits and contribute to global efforts to mitigate climate change by reducing industrial carbon footprints.

As shown in Figure 11, the EH-IES offers considerable potential and significant development prospects within the industry sector. This system facilitates the conversion of excess electricity into hydrogen, which can be stored and used later. When electricity supply falls short, hydrogen can serve as a fuel through hydrogen fuel cells or be used directly as a fuel source. This ensures a stable energy supply for industrial operations and reduces reliance on the traditional power grid. Additionally, hydrogen, as a clean fuel, can replace fossil fuels in various industrial processes, supporting the green transformation of industries and aligning with global climate change mitigation goals.

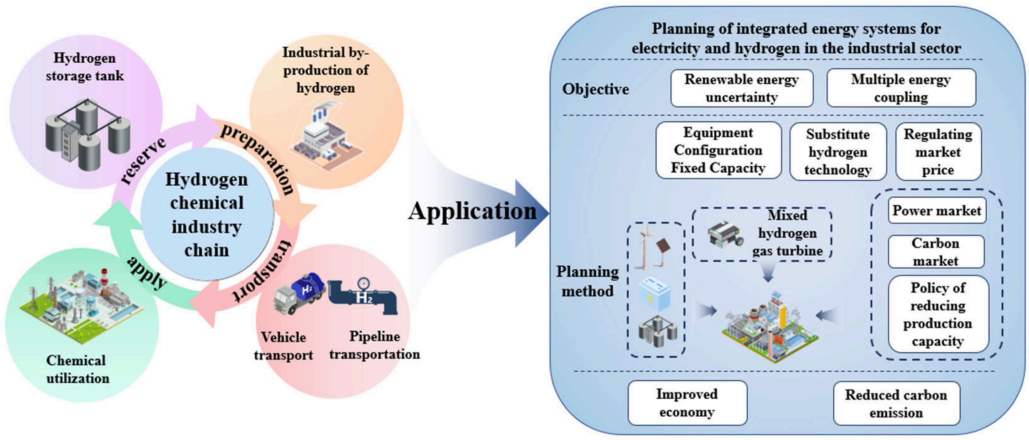

Figure 11. Planning of EH-IESs for the industry sector.

The hydrogen-based chemical industry chain involves several critical stages, including hydrogen production, storage, transportation, and application in chemical manufacturing. The integration of green hydrogen, produced using renewable energy, holds substantial promise for the chemical sector. Notably, ongoing projects are focused on producing green ammonia through the synthesis of ammonia from green hydrogen, as well as generating green methanol through hydrogen-based processes. These initiatives highlight the growing potential of green hydrogen in chemical production.

Currently, several CO_2 hydrogenation-to-methanol technologies have reached the commercialization stage, and industrial-scale demonstrations are underway. Advancements in catalytic technologies are expected to further enhance catalyst performance. At the same time, the costs of essential components, such as PV panels and electrolyzers, are projected to decrease. These cost reductions will drive down the overall costs of green hydrogen production, presenting significant opportunities for the widespread adoption and industrialization of CO_2 hydrogenation pathways for high-value chemical production.

The planning of EH-IES in the industry sector encompasses two main areas of the energy and chemical industry value chain. A comprehensive summary of the planning for EH-IES in the industrial field is provided in Table 5.

Table 5. Summary of EH-IES planning in the industry sector.

Literature Number	Planning Target			Planning Objects	Coupled Resource			Planning Methodology
	Economy	Decarbonization	Resilience		Electricity	Hydrogen	Heat	
[96]	✓			Coal chemical park	✓	✓		Two-tier planning
[97]	✓	✓	✓	Molten carbonate fuel cell power plant	✓	✓	✓	Stochastic planning
[98]	✓	✓		Combined heat and power system	✓	✓	✓	Multi-objective planning
[21]	✓	✓		Combined wind power and hydrogen supply (W-H-CCHP) systems	✓	✓		Multi-objective planning
[99]	✓	✓		Hydrogen-based distributed energy systems	✓	✓	✓✓	Mixed-integer linear planning
[100]	✓	✓		Industrial park	✓	✓	✓	Multi-objective planning
[101]	✓			Industrial park	✓	✓	✓	Two-tier planning

Industrial planning for IES often emphasizes modeling, multi-system coupling, and managing renewable energy variability. Recent studies have focused on improving the energy balance in industrial park energy systems by optimizing hydrogen storage allocation. This optimization increases the revenue for energy system operators. Rizk-Allah RM et al. [102] investigate the application of PV power plants for green hydrogen production at hydrogen-refueling stations, optimizing the sizing of system components by considering capital, operational, and replacement costs. Another study introduces a microgrid configuration that integrates green power generation, energy storage, and heating systems. It optimizes the capacities of PV arrays, hydrogen fuel cells, electrolyzers, and hydrogen storage tanks, thereby reducing redundant equipment configurations and improving economic efficiency.

Zhe et al. [103] demonstrated, through a comparative analysis of IES and HES, that HES achieved a 12% increase in renewable energy penetration. They also effectively prevented load shedding, ensuring a balanced supply and demand between energy sources and consumption loads. Furthermore, Song et al. [104] developed a PV-hydrogen grid-connected IES with hydrogen storage, aiming to improve the system's economic viability, reduce carbon emissions, and enhance energy efficiency. Liu et al. [99] developed a hydrogen-based distributed multi-energy system (DHME) and identified significant cost reductions when integrating hydrogen and hot water storage, alongside multiple energy storage technologies.

Several studies have investigated alternative hydrogen utilization technologies, such as hydrogen injection into natural gas (HING) networks. These technologies effectively enhance wind power generation and hydrogen consumption without necessitating additional investment [105]. One study developed a two-stage planning model to determine the optimal capacity for hydrogen-related infrastructure in an IES incorporating HING technology [106]. The model's results show that coupling the IES with a HES not only reduces carbon emissions but also lowers overall costs and enhances energy efficiency. Another study examined the planning of an IES for an industrial park, which includes hydrogen production, transportation, and storage. The findings demonstrate that integrating these components improves the system's economic viability, mitigates carbon emissions, and reduces power waste [100].

However, the traditional single-stage planning approach faces significant limitations in addressing the dynamic growth of hydrogen demand and evolving policy frameworks within EH-IES. To overcome these challenges, a multi-stage planning methodology is more appropriate. It accounts for long-term load fluctuations and construction timelines, offering more economically advantageous solutions. For example, a combined wind–hydrogen multi-stage capacity planning model has been proposed. This model seeks to maximize the benefits of the IES over the entire planning horizon. It incorporates various hydrogen production techniques, trading models, and load demands across multiple years [54].

Additionally, market dynamics—such as power and carbon markets—and policies like capacity removal and fluctuating equipment prices play a critical role in optimizing the allocation of energy systems in industrial parks. For instance, a hydrogen-driven energy system in the steel industry offers significant opportunities for reducing carbon emissions within this sector. Another study proposed a model to optimize the coupling of wind power with low-energy, low-pollution coal chemical industries, integrating hydrogen energy storage. This model addresses the planning of equipment investment for multi-energy systems. To support this approach, energy management strategies for hydrogen production in coal chemical parks, coupled with renewable energy sources, have been developed. These strategies aim to optimize the capacity configuration of various system components, maximize annual returns on PV investments, and reduce operating costs. Huo et al. [96] developed an annual revenue maximization model that integrates PV generation, hydrogen production, hydrogen storage, and electricity storage, offering an optimal configuration for system components.

Furthermore, the growing impact of climate change presents new challenges to the resilience of energy systems, particularly in the industrial sector, where large-scale operations and long-term planning are typical. As extreme weather events increasingly threaten energy security, it is essential to incorporate resilience considerations into industrial planning. Hybrid EH-IES, when combined with energy storage solutions, hold great potential for improving system resilience and facilitating rapid recovery after disruptions. These systems provide backup energy during power interruptions, thus enhancing the reliability and stability of industrial production processes. Jordehi et al. [107] established an industrial energy center that integrates power, heat, and hydrogen demand. They developed a stochastic mixed-integer linear programming model to address uncertainties, such as transmission line damage, hurricane timing, and emergency repair durations. This model enhances system robustness through hybrid energy storage. Liu et al. [108] proposed a strategy to enhance the resilience of multi-energy industrial parks by integrating electric, hydrogen, and thermal microgrids. This strategy coordinates hybrid energy storage systems, including fuel cells, hydrogen storage tanks, battery storage, and heat units.

4.4. Multi-Timescale Coupling Mechanisms and Planning Methodologies

The core challenge of EH-IES planning lies in coordinating hourly operational constraints (e.g., grid frequency regulation requirements, sub-hourly PV/load fluctuations, hydrogen storage state transitions) with multi-month to multi-year investment decision cycles, while avoiding computational intractability caused by full-time-series simulation.

Most transportation and building sector planning models extract 8–12 typical daily operation scenarios via k-means or hierarchical clustering. This method is computationally efficient for single-sector planning, but may overlook extreme cross-seasonal events (e.g., consecutive cloudy weeks in winter) that drive hydrogen seasonal storage sizing. Gao et al. [109] developed and applied a set of eight representative scenarios with varying time scales and levels of variability to an integrated electricity–hydrogen–heat energy system. The results indicate a practical trade-off between computational burden and planning accuracy. Medium- to long-term scenarios are better able to capture seasonal and diurnal dynamics, thereby enabling a more balanced allocation of generation capacity and lower risk-adjusted costs. Li et al. [110] address the planning and optimization of integrated electricity–hydrogen energy systems that account for energy storage degradation and multi-timescale operations. They propose a two-stage method that derives representative weekly and hourly patterns from meteorological and load data using a limited number of data points, ensuring temporal consistency and preserving long-term trends to validate energy storage constraints and improve planning accuracy. Industrial sector models targeting annual hydrogen production generally retain full-year hourly resolution to capture the coupling between electrolyzer load duration and grid tariff fluctuations. To control complexity, these studies typically simplify equipment degradation and grid dynamic constraints, or adopt rolling horizon optimization to split annual problems into weekly sub-problems.

By revealing the marginal effects of fluctuations in wind and solar power, price volatility, and behavioral variability on system costs and configuration, we can identify differences in sensitivity across various sectors. This allows us to verify whether the stochastic or robust optimization methods employed align with actual risk levels, thereby avoiding overly conservative or aggressive model designs, and ultimately providing quantifiable design benchmarks and risk tolerance thresholds. Ren et al. [111] proposed a two-stage stochastic programming model to address the inherent uncertainties in wind and solar power generation, with the aim of minimizing operating costs and carbon emissions. Yang et al. [112] addressed the uncertainty in renewable energy output during the planning period; the information-gap decision-making theory for extreme scenarios was applied to address system-planning problems involving uncertain parameters. This approach minimizes the impact of uncertainty without exceeding the total budget, and the maximum tolerable fluctuation range for wind and solar power was expanded to 87.65%. Zeng et al. [113] propose a bi-level robust planning model to address the rational configuration of a hydrogen energy system, accounting for the impact of wind power uncertainty in an integrated electricity–heat–hydrogen energy system with increasing wind power penetration. Li et al. [110] propose a two-stage approach to validate storage device constraints and improve planning accuracy. Case studies in southeastern China's IES verify the effectiveness of our planning approach, which lowers equivalent annual costs by 4.5% and reduces battery capacity needs by 12.8%, thereby highlighting its significant economic benefits.

Based on the systematic reviews of the transportation, construction, and industrial sectors presented in Tables 3–5, certain characteristics emerge regarding the selection of planning methods. Although these sectors share the common goal of optimizing electricity–hydrogen synergies, the inherent characteristics of their energy demands and operational constraints lead to differences in the methods chosen.

Stochastic programming is the most widely adopted approach, particularly in the transportation sector. As indicated in Table 3, stochastic programming is frequently employed to address the volatility of traffic flow and user travel behavior [69]. Its strength lies in quantifying probabilistic risks and optimizing expected returns, making it suitable for scenarios with predictable statistical distributions. However, as shown in Tables 4 and 5. In the fields of architecture and industry, multi-objective methods are relatively widely used, where extreme events (e.g., prolonged cloudy periods or sudden production halts) can cause significant deviations from historical averages.

Robust methods and distributionally robust methods are gaining traction, especially in industrial applications (Table 5). These methods prioritize system resilience over cost optimality [70,97,113]. Unlike stochastic programming, robust optimization does not rely on precise probability distributions, making it ideal for heavy industries facing ambiguous uncertainties in renewable generation and market prices. However, the trade-off is often a conservative configuration, leading to higher capital expenditure compared to stochastic programming -based solutions.

Multi-objective planning serves as the foundational framework across all sectors, as evidenced by its ubiquitous presence in Tables 3–5. Multi-objective planning is essential for balancing the trilemma of economy, low-carbon performance, and system reliability [66,82,83,88–90]. In buildings (Table 4), multi-objective planning is often combined with two-stage stochastic models to handle seasonal thermal storage decisions. Two-stage and multi-stage planning are critical for long-term infrastructure development [73,75,76]. In contrast, industrial planning (Table 5) tends to integrate multi-objective planning with bilevel or trilevel models to coordinate the conflicting interests of energy suppliers and industrial consumers [63,96,101].

5. Future Research Perspectives

The EH-IES is an important carrier for realizing the conversion and synergy between electrical energy and hydrogen energy. Reasonable planning is the basic guarantee for realizing the coordinated operation among multiple energies, improving the comprehensive energy utilization efficiency and promoting the consumption of renewable energy. Judging from the current research progress, the following research directions of EH-IES planning still need to be further explored.

(1) Planning of EH-IES considering resilience and adaptability under uncertainty

Under the influence of multiple uncertainties, the planning of the EH-IES considering resilience and adaptability has broad prospects in important fields such as transportation, buildings, and industry. In the transportation field, efforts are made to improve the performance of hydrogen FCVs and actively build a hydrogen-refueling infrastructure network. Uncertain factors such as traffic flow and energy price fluctuations are fully considered, and flexible operation strategies are formulated. In the field of buildings, the focus is on optimizing the energy management system to improve energy utilization efficiency and resilience. The impacts of uncertain factors such as climate change and natural disasters on the building energy supply are fully considered, and the disaster-resistance ability of the building energy system is enhanced. The combination of buildings and distributed energy systems is deeply explored to achieve energy self-sufficiency. In the industry field, the electric–hydrogen coupling technology is deeply integrated with the industrial production process to improve the energy efficiency and sustainability of industrial production. Uncertain demands of industrial production and energy price fluctuations are comprehensively considered, and reasonable energy supply strategies are formulated. The research on the energy utilization of industrial waste is strengthened.

(2) EH-IES planning based on energy demand and multi-domain integration

The agent planning the EH-IES may be an electric–hydrogen integrated energy station, a building, a comprehensive energy service provider, or a user. Most of the existing research work on the planning of electric–hydrogen, transportation, buildings, and industry is limited to isolated modeling. However, under the energy demand, in order to promote the overall optimization and sustainable development of the system, the limitation of this isolated modeling needs to be overcome and cross-domain collaborative planning research needs to be realized. The unified and cross-domain energy system model is studied, comprehensively considering the energy demand, supply, and storage of transportation, buildings, and industry. Based on the massive amount of system data, the application of big data and artificial intelligence technology in the collaborative planning of electric–

hydrogen, transportation, buildings, and industry is studied. The coordinated policies and standards are formulated, and the cross-domain demonstration projects are implemented to promote the feasibility of the collaborative operation of electric–hydrogen, transportation, buildings, and industry. A reserve system of electricity and hydrogen is established to ensure that energy support can be provided in time in case of energy supply interruption or emergency.

(3) Optimal planning of EH-IES considering multiple stakeholders under market mechanisms

In the planning of the EH-IES, multiple stakeholders need to be considered, including energy suppliers, energy service providers, end users, etc. The roles and interest demands of different stakeholders in the system vary, so it is crucial to construct a multi-stakeholder collaborative planning and dispatching mechanism. Future research should further explore the multi-stakeholder interest coordination mechanism. Tax preferences should be given to enterprises related to the EH-IES to improve their profitability and competitiveness. The balance of interests among different stakeholders should be achieved by introducing market mechanisms such as dynamic electricity prices and demand responses. For example, the construction of hydrogen-refueling stations, etc., needs to be deeply coupled with the power grid. Through the flexible regulation of the power grid, the stable supply of hydrogen energy can be achieved. Consideration should be given to how to improve the efficiency of electrolytic-water hydrogen production equipment and fuel cell power-generation equipment installed inside buildings to achieve self-sufficiency and flexible regulation of building energy.

While current EH-IES planning predominantly focuses on technical optimization and economic feasibility, the practical deployment of such systems is critically constrained by sociotechnical barriers and cybersecurity risks, which warrant deeper investigation in future research.

In the future, attention must be paid to the cybersecurity risks associated with EH-IES. As electro-hydrogen coupling systems involve a large number of IoT devices and energy management platforms, it is necessary to guard against incidents such as data tampering, hydrogen leaks caused by malicious attacks, and grid disconnection. The application of technologies such as blockchain and federated learning in privacy protection and attack attribution should be explored.

It is also necessary to take socioeconomic factors into account: current public misconceptions regarding the safety of hydrogen infrastructure, opposition from residents living near hydrogen-refueling stations, and the lack of an insurance system for the hydrogen industry chain have become non-technical barriers hindering the implementation of these plans. Future research could employ behavioral economics methods to quantify the impact of social acceptance on site selection and refine the design of supporting policies.

6. Conclusions

With the accelerating transition of energy structures, integrated energy systems—characterized by multi-energy complementarity and self-sufficiency—have attracted widespread attention. As a zero-carbon energy carrier, hydrogen is considered the cornerstone of future clean and low-carbon energy systems. The integration of hydrogen energy further enhances heterogeneous energy coupling and facilitates low-carbon transformation in regional integrated energy systems, while simultaneously introducing new challenges for their planning. First, this study analyzes the characteristics and key technologies of hydrogen energy systems, summarizing the coupling mechanisms of typical EH-IESs. Existing planning methodologies and mathematical models for EH-IES components are systematically reviewed. Second, based on current coupling scenarios, the EH-IES planning is categorized into three domains: transportation, buildings, and industry, with comparative analysis against conventional integrated energy system planning. Finally, considering current trends toward low-carbon energy, marketization, and digitalization, potential future research directions for EH-IES planning are proposed.

(1) The planning of EH-IES in the transportation sector primarily encompasses two key aspects. First, regarding charging/hydrogen supply infrastructure planning, the core focus lies in the optimal siting and layout of electric–hydrogen integrated energy stations. This involves comprehensive consideration of multiple factors to ensure efficient and stable operation. Hydrogen supply facilities and renewable energy-based hydrogen production systems are typically co-located with existing charging stations, with particular attention paid to capacity optimization of both electrical and hydrogen facilities to minimize costs while maximizing operational benefits. Second, in terms of vehicle selection and transportation operation strategy planning, customized approaches are developed based on actual conditions. This includes selection of appropriate new energy vehicles, analysis of road network conditions, consideration of charging/refueling facility impacts on user behavior, and incorporation of uncertainty management to develop robust planning solutions. Current EH-IES planning in transportation emphasizes sustainable development through scientific methodologies that holistically address market demand, economic costs, environmental benefits, uncertainty factors, and policy considerations, ultimately enhancing overall energy utilization efficiency.
(2) In the building sector, electric–hydrogen coupling technology is primarily applied to renewable energy utilization, large-scale long-term electrical energy storage, and enhancing building energy system flexibility and reliability. For building system equipment capacity configuration, comprehensive consideration of energy demand, technical characteristics, and economic factors determines equipment rated capacity to achieve optimal balance between cost-effectiveness and reliability. ZEB research has progressively advanced from single photovoltaic system optimization to integrated hydrogen–electric hybrid configurations, significantly reducing both energy consumption and emissions. Modeling methodologies have evolved from deterministic to uncertainty-incorporated approaches, better reflecting real-world operational conditions. The incorporation of seasonal heat storage and electrolytic hydrogen production has improved complementarity and cost-efficiency in urban multi-energy systems. Regarding energy storage planning, hydrogen storage technology has gained prominence due to its large-scale and long-duration storage capabilities. Hybrid renewable energy systems integrating hydrogen vehicle-to-building storage demonstrate favorable economic performance in residential applications, where proper storage capacity planning ensures power-electricity balance. Different storage technologies (hydrogen-based and battery storage) each offer distinct economic and environmental advantages. The integration of zero-energy buildings with new energy vehicles (particularly hydrogen FCEVs) has emerged as a key research focus, with system optimization enabling enhanced energy efficiency and further carbon emission reductions. However, this integration faces challenges in balancing low-carbon objectives with economic viability, necessitating future research to identify optimal equilibrium points between these competing priorities.
(3) In the industrial sector, EH-IES planning encompasses multiple dimensions and has achieved significant progress. Energy-wise, renewable energy-powered electrolytic hydrogen production has emerged as a critical pathway, where wind and photovoltaic power drive water electrolysis to enhance electrical energy conversion efficiency. The integration of hydrogen storage improves energy balance while boosting system reliability and economic viability, particularly in addressing renewable energy intermit-

tency and enabling seasonal storage. Hydrogen infrastructure development, including hydrogen–natural gas blending in pipeline networks, facilitates broader hydrogen energy adoption. Within the hydrogen–chemical industrial chain, green hydrogen demonstrates extensive potential as a clean energy source for chemical manufacturing, with green hydrogen-based ammonia and methanol synthesis projects gaining momentum. Ongoing technological advancements and declining equipment costs are resolving green hydrogen's cost challenges, creating opportunities for industrial-scale technology deployment. Hydrogen storage systems receive particular attention, requiring method selection based on practical application needs. Overall, electric–hydrogen integrated energy planning continues to advance industrial decarbonization, promoting low-carbon, high-efficiency, and sustainable industrial development.

Author Contributions: Conceptualization, H.R. and W.Z.; methodology, Q.W.; validation, H.R., Q.W. and W.Z.; formal analysis, L.M.; investigation, X.L.; resources, W.Z.; data curation, L.M.; writing—original draft preparation, H.R. and L.M.; writing—review and editing, Q.W.; visualization, Q.W.; supervision, W.Z.; project administration, W.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

IES	Integrated energy system
EH-IES	Electric–hydrogen coupled integrated energy system
HFCV	Hydrogen fuel cell vehicles
P2G	Power-to-Gas
PEMFCs	Proton exchange membrane fuel cells
AFCs	Alkaline Fuel Cells
SOFCs	Solid oxide fuel cells
MCFCs	Molten carbonate fuel cells
CHP	Combined heat and power
P2X	Power-to-X
SNG	Synthetic natural gas
E2H	Electric-to-hydrogen
EV	Electric vehicles
ARIMA	Autoregressive moving average
WT	Wind turbine
HES	Hydrogen energy system
MILP	Mixed-integer linear programming
ZEB	Zero-energy buildings
DHME	Distributed multi-energy system
HING	Hydrogen injection into natural gas

References

1. Wang, J.; Wu, W.; Rong, F. Development and tri-objective exergoeconomic-environmental optimization of a novel molten carbonate fuel cell-based system for power, hydrogen and freshwater tri-generation. *Int. J. Hydrogen Energy* **2021**, *46*, 20715–20731. [CrossRef]
2. Elkhatib, R.; Kaoutari, T.; Louahlia, H. Green hydrogen energy source for a residential fuel cell micro-combined heat and power. *Appl. Therm. Eng.* **2024**, *248*, 123194. [CrossRef]

3. Montazerinejad, H.; Eicker, U.; Ahmadi, P. Renewable fuel-powered micro-gas turbine and hydrogen fuel cell systems: Exploring scenarios of technology, control, and operation. *Energy Convers. Manag.* **2024**, *319*, 118944. [CrossRef]
4. He, Y.; Li, N.; Li, N.; Li, J.; Yan, J.; Tan, C. Control behaviors and thermal comfort in a shared room with desk fans and adjustable thermostat. *Build. Environ.* **2018**, *136*, 213–226. [CrossRef]
5. Atabay, R.; Devrim, Y. Design and techno-economic analysis of solar energy based on-site hydrogen refueling station. *Int. J. Hydrogen Energy* **2024**, *80*, 151–160. [CrossRef]
6. Er, G.; Soykan, G.; Canakoglu, E. Designing an optimal multi-energy system with fast charging and hydrogen refueling station under uncertainties. *Sustain. Energy Grids Netw.* **2024**, *39*, 101403. [CrossRef]
7. Emam, A.S.; Hamdan, M.O.; Abu-Nabah, B.A.; Elnajjar, E. A review on recent trends, challenges, and innovations in alkaline water electrolysis. *Int. J. Hydrogen Energy* **2024**, *64*, 599–625. [CrossRef]
8. Dash, S.; Singh, A.; Surapraraju, S.K.; Natarajan, S.K. Advances in green hydrogen production through alkaline water electrolysis: A comprehensive review. *Int. J. Hydrogen Energy* **2024**, *83*, 614–629. [CrossRef]
9. Fotis, G.; Maris, T.I.; Mladenov, V. Risks, Obstacles and Challenges of the Electrical En-ergy Transition in Europe: Greece as a Case Study. *Sustainability* **2025**, *17*, 5325. [CrossRef]
10. Pu, Y.; Li, Q.; Huo, S.; Breaz, E.; Chen, W.; Gao, F. Optimal configuration for shared electric-hydrogen energy storage for multiple integrated energy systems with mobile hydrogen transportation. *Renew. Energy* **2024**, *237*, 121828. [CrossRef]
11. Ye, S.; Wang, J.; Yin, Z.; Kang, J.; Ma, Z. Optimization of a solar-driven community integrated energy system based on dynamic hybrid hydrogen-electric energy storage strategy. *J. Energy Storage* **2024**, *101*, 113917. [CrossRef]
12. Dong, H.; Shan, Z.; Zhou, J.; Xu, C.; Chen, W. Refined modeling and co-optimization of electric-hydrogen-thermal-gas integrated energy system with hybrid energy storage. *Appl. Energy* **2023**, *351*, 121834. [CrossRef]
13. Liu, Z.; Luo, X.; Chen, X.; Huang, Y.; Liu, Y.; Tang, Y.; Kang, Q.; Guo, L. An innovative bi-level scheduling model with hydrogen-thermal-electricity co-supply and dynamic carbon capture strategies for regional integrated energy systems considering hybrid games. *Renew. Energy* **2024**, *237*, 121682. [CrossRef]
14. Xu, W.; Liu, Z.; Li, Z.; Zhang, Z. Low carbon oriented electric-hydrogen system multi-time scale collaborative optimal scheduling strategy considering hybrid energy storage. *Energy Rep.* **2024**, *12*, 4295–4305. [CrossRef]
15. Nagem, N.A.; Ebeed, M.; Alqahtani, D.; Jurado, F.; Khan, N.H.; Hafez, W.A. Optimal design and three-level stochastic energy management for an interconnected microgrid with hydrogen production and storage for fuel cell electric vehicle refueling stations. *Int. J. Hydrogen Energy* **2024**, *87*, 574–587. [CrossRef]
16. Vilberger, M.E.; Popov, N.S.; Domakhin, E.A.; Anibroev, V.I.; Mosin, M.E. Increasing the energy efficiency of an electric vehicle powered by hydrogen fuel cells. *Int. J. Hydrogen Energy* **2024**, *85*, 406–415. [CrossRef]
17. Li, R.; Ren, H.; Wu, Q.; Li, Q.; Gao, W. Cooperative economic dispatch of EV-HV coupled electric-hydrogen integrated energy system considering V2G response and carbon trading. *Renew. Energy* **2024**, *227*, 120488. [CrossRef]
18. Du, Y.; Li, X.; Tan, C.; Tan, Z. Two-stage multi-objective distributionally robust operation optimization and benefits equalization of an off-grid type electric-hydrogen-ammonia-methanol coupling system. *Renew. Energy* **2024**, *236*, 121433. [CrossRef]
19. Bampaou, M.; Panopoulos, K.D. An overview of hydrogen valleys: Current status, challenges and their role in increased renewable energy penetration. *Renew. Sustain. Energy Rev.* **2025**, *207*, 114923. [CrossRef]
20. Li, L.; Zhang, Z.; Sethanan, K.; Tseng, M. Multi-energy synergistic planning of distributed energy supply system: Wind-solar-hydrogen coupling energy supply. *Renew. Energy* **2024**, *237*, 121769. [CrossRef]
21. Li, N.; Zhao, X.; Shi, X.; Pei, Z.; Mu, H.; Taghizadeh-Hesary, F. Integrated energy systems with CCHP and hydrogen supply: A new outlet for curtailed wind power. *Appl. Energy* **2021**, *303*, 117619. [CrossRef]
22. Liu, X.; Zu, L.; Wei, Z.; Wang, Y.; Pan, Z.; Xiao, G.; Jenkins, N. Two-layer optimal scheduling of integrated electric-hydrogen energy system with seasonal energy storage. *Int. J. Hydrogen Energy* **2024**, *82*, 1131–1145. [CrossRef]
23. Huo, S.; Li, Q.; Pu, Y.; Xie, S.; Chen, W. Low carbon dispatch method for hydrogen-containing integrated energy system considering seasonal carbon trading and energy sharing mechanism. *Energy* **2024**, *308*, 132794. [CrossRef]
24. Zhang, K.; Zhou, B.; Chung, C.Y.; Bu, S.; Wang, Q.; Voropai, N. A Coordinated Multi-Energy Trading Framework for Strategic Hydrogen Provider in Electricity and Hydrogen Markets. *IEEE Trans. Smart Grid* **2023**, *14*, 1403–1417. [CrossRef]
25. Götz, M.; Lefebvre, J.; Mörs, F.; McDaniel Koch, A.; Graf, F.; Bajohr, S.; Reimert, R.; Kolb, T. Renewable Power-to-Gas: A technological and economic review. *Renew. Energy* **2016**, *85*, 1371–1390. [CrossRef]
26. Raman, R.; Nair, V.K.; Prakash, V.; Patwardhan, A.; Nedungadi, P. Green-hydrogen research: What have we achieved, and where are we going? Bibliometrics analysis. *Energy Rep.* **2022**, *8*, 9242–9260. [CrossRef]
27. Wang, Z.; Zhang, X.; Rezazadeh, A. Hydrogen fuel and electricity generation from a new hybrid energy system based on wind and solar energies and alkaline fuel cell. *Energy Rep.* **2021**, *7*, 2594–2604. [CrossRef]
28. Cheng, S.; Hu, D.; Hao, D.; Yang, Q.; Wang, J.; Feng, L.; Li, J. Investigation and analysis of proton exchange membrane fuel cell dynamic response characteristics on hydrogen consumption of fuel cell vehicle. *Int. J. Hydrogen Energy* **2022**, *47*, 15845–15864. [CrossRef]

29. Emadi, M.A.; Chitgar, N.; Oyewunmi, O.A.; Markides, C.N. Working-fluid selection and thermoeconomic optimisation of a combined cycle cogeneration dual-loop organic Rankine cycle (ORC) system for solid oxide fuel cell (SOFC) waste-heat recovery. *Appl. Energy* **2020**, *261*, 114384. [CrossRef]
30. Sorrenti, I.; Harild Rasmussen, T.B.; You, S.; Wu, Q. The role of power-to-X in hybrid renewable energy systems: A comprehensive review. *Renew. Sustain. Energy Rev.* **2022**, *165*, 112380. [CrossRef]
31. Bokde, N.; Tranberg, B.; Andresen, G.B. A graphical approach to carbon-efficient spot market scheduling for Power-to-X applications. *Energy Convers. Manag.* **2020**, *224*, 113461. [CrossRef]
32. Yue, M.; Lambert, H.; Pahon, E.; Roche, R.; Jemei, S.; Hissel, D. Hydrogen energy systems: A critical review of technologies, applications, trends and challenges. *Renew. Sustain. Energy Rev.* **2021**, *146*, 111180. [CrossRef]
33. Wu, Y.; Gu, W.; Huang, S.; Wei, X.; Safaraliev, M. A four-layer business model for integration of electric vehicle charging stations and hydrogen fuelling stations into modern power systems. *Appl. Energy* **2025**, *377*, 124630. [CrossRef]
34. Sahin, H. Hydrogen refueling of a fuel cell electric vehicle. *Int. J. Hydrogen Energy* **2024**, *75*, 604–612. [CrossRef]
35. François, A.; Roche, R.; Grondin, D.; Winckel, N.; Benne, M. Investigating the use of hydrogen and battery electric vehicles for public transport: A technical, economical and environmental assessment. *Appl. Energy* **2024**, *375*, 124143. [CrossRef]
36. Lee, S.; Al-Ghussain, L.; Alrbai, M.; Al-Dahidi, S. Integrating hybrid PV/wind-based electric vehicles charging stations with green hydrogen production in Kentucky through techno-economic assessment. *Int. J. Hydrogen Energy* **2024**, *71*, 345–356. [CrossRef]
37. Wu, X.; Li, H.; Wang, X.; Zhao, W. Cooperative Operation for Wind Turbines and Hydrogen Fueling Stations With On-Site Hydrogen Production. *IEEE Trans. Sustain. Energy* **2020**, *11*, 2775–2789. [CrossRef]
38. Sulaiman, N.; Hannan, M.A.; Mohamed, A.; Ker, P.J.; Majlan, E.H.; Wan Daud, W.R. Optimization of energy management system for fuel-cell hybrid electric vehicles: Issues and recommendations. *Appl. Energy* **2018**, *228*, 2061–2079. [CrossRef]
39. Soomro, A.M.; Rathi, M.K.; Shaikh, A.; Kumar, L.; El Haj Assad, M.; Ehyaei, M.A. Techno-economic analysis of stand-alone hybrid PV-hydrogen-based plug-in electric vehicle charging station. *Energy Rep.* **2024**, *12*, 3279–3290. [CrossRef]
40. Rozzi, E.; Giglio, E.; Moscoloni, C.; Novo, R.; Mattiazzo, G.; Lanzini, A. Comparative study of electric and hydrogen mobility infrastructures for sustainable public transport: A PyPSA optimization for a remote island context. *Int. J. Hydrogen Energy* **2024**, *80*, 516–527. [CrossRef]
41. Zhang, Q.; Qin, T.; Wu, J.; Hao, R.; Su, X.; Li, C. Synergistic operation strategy of electric-hydrogen charging station alliance based on differentiated characteristics. *Energy* **2024**, *304*, 132132. [CrossRef]
42. Grüger, F.; Dylewski, L.; Robinius, M.; Stolten, D. Carsharing with fuel cell vehicles: Sizing hydrogen refueling stations based on refueling behavior. *Appl. Energy* **2018**, *228*, 1540–1549. [CrossRef]
43. He, Y.; Li, N.; Lu, J.; Li, N.; Yan, J. Meeting thermal needs of occupants in shared space with an adjustable thermostat and local heating in winter: An experimental study. *Energy Build.* **2021**, *236*, 110776. [CrossRef]
44. Wang, D.; Meng, W.; Zhou, H.; Li, G.; Yang, Y.; Li, H. Green hydrogen coupling with CO_2 utilization of coal-to-methanol for high methanol productivity and low CO_2 emission. *Energy* **2021**, *231*, 120970.
45. Zhang, Y.; Yue, Q.; Chai, X.; Wang, Q.; Lu, Y.; Ji, W. Analysis of process parameters on energy utilization and environmental impact of hydrogen metallurgy. *J. Clean. Prod.* **2022**, *361*, 132289. [CrossRef]
46. Han, X.; Feng, J.; Zhao, Y.; Bai, W. Economic analysis of hydrogen production from electrolyzed water technology by provinces in China. *Glob. Energy Interconnect.* **2024**, *7*, 629–641. [CrossRef]
47. Li, Q.; Li, R.; Pu, Y.; Li, S.; Sun, C.; Chen, W. Coordinated control of electric-hydrogen hybrid energy storage for multi-microgrid with fuel cell/electrolyzer/PV/battery. *J. Energy Storage* **2021**, *42*, 103110. [CrossRef]
48. Samani, A.E.; D'Amicis, A.; De Kooning, J.D.; Bozalakov, D.; Silva, P.; Vandevelde, L. Grid balancing with a large-scale electrolyser providing primary reserve. In *8th Renewable Power Generation Conference (RPG 2019)*; Institution of Engineering and Technology: Edison, NJ, USA, 2019; pp. 1–7.
49. Xu, X.; Hu, W.; Cao, D.; Huang, Q.; Chen, Z. Optimal operational strategy for an offgrid hybrid hydrogen/electricity refueling station powered by solar PVs. *J. Power Sources* **2020**, *451*, 227810. [CrossRef]
50. Xu, Q.; Xia, L.; He, Q.; Guo, Z.; Ni, M. Thermo-electrochemical modelling of high temperature methanol-fuelled solid oxide fuel cells. *Appl. Energy* **2021**, *291*, 116832.
51. Gargari, S.G.; Rahimi, M.; Ghaebi, H. Thermodynamic analysis of a novel power-hydrogen cogeneration system. *Energy Convers. Manag.* **2018**, *171*, 1093–1105. [CrossRef]
52. Ge, L.; Zhang, B.; Huang, W.; Li, Y.; Hou, L.; Xiao, J.; Mao, Z.; Li, X. A review of hydrogen generation, storage, and applications in power system. *J. Energy Storage* **2024**, *75*, 109307. [CrossRef]
53. Li, Y.; Hu, W.; Zhang, F.; Li, Y. Collaborative operational model for shared hydrogen energy storage and park cluster: A multiple values assessment. *J. Energy Storage* **2024**, *82*, 110507. [CrossRef]
54. Deng, H.; Wang, J.; Shao, Y.; Zhou, Y.; Cao, Y.; Zhang, X.; Li, W. Optimization of configurations and scheduling of shared hybrid electric-hydrogen energy storages supporting to multi-microgrid system. *J. Energy Storage* **2023**, *74*, 109420. [CrossRef]

55. Yamamoto, H.; Fujioka, H.; Okano, K. Cost analysis of stable electric and hydrogen energy supplies derived from 100% variable renewable resources systems. *Renew. Energy* **2021**, *178*, 1165–1173. [CrossRef]
56. Zhang, X.; Pei, W.; Mei, C.; Deng, W.; Tan, J.; Zhang, Q. Transform from gasoline stations to electric-hydrogen hybrid refueling stations: An islanding DC microgrid with electric-hydrogen hybrid energy storage system and its control strategy. *Int. J. Electr. Power Energy Syst.* **2022**, *136*, 107684. [CrossRef]
57. Li, J.; Xiao, Y.; Lu, S. Optimal configuration of multi microgrid electric hydrogen hybrid energy storage capacity based on distributed robustness. *J. Energy Storage* **2024**, *76*, 109762. [CrossRef]
58. Rubio, F.; Llopis-Albert, C.; Besa, A.J. Optimal allocation of energy sources in hydrogen production for sustainable deployment of electric vehicles. *Technol. Forecast. Soc. Change* **2023**, *188*, 122290. [CrossRef]
59. Peng, Y.; Li, G.; Xu, M.; Chen, A. Mixed-fleet operation of battery electric bus and hydrogen bus: Considering limited depot size with flexible refueling processes. *Transp. Res. Part E Logist. Transp. Rev.* **2024**, *188*, 103630. [CrossRef]
60. Baker, J.; Guler, M.; Medonna, A.; Li, Z.; Ghosh, A. Analysis of large-scale (1GW) off-grid agrivoltaic solar farm for hydrogen-powered fuel cell electric vehicle (HFCEV) charging station. *Energy Convers. Manag.* **2025**, *323*, 119184. [CrossRef]
61. Rezaee Jordehi, A.; Mansouri, S.A.; Tostado-Véliz, M.; Hossain, M.J.; Nasir, M.; Jurado, F. Optimal placement of hydrogen fuel stations in power systems with high PV penetration and responsive electric demands in presence of local hydrogen markets. *Int. J. Hydrogen Energy* **2024**, *50*, 62–76. [CrossRef]
62. Shi, M.; Huang, Y. Dynamic planning and energy management strategy of integrated charging and hydrogen refueling at highway energy supply stations considering on-site green hydrogen production. *Int. J. Hydrogen Energy* **2023**, *48*, 29835–29851. [CrossRef]
63. Wei, X.; Chan, K.W.; Wu, T.; Wang, G.; Zhang, X.; Liu, J. Wasserstein distance-based expansion planning for integrated energy system considering hydrogen fuel cell vehicles. *Energy* **2023**, *272*, 127011. [CrossRef]
64. Lin, R.; Ye, Z.; Guo, Z.; Wu, B. Hydrogen station location optimization based on multiple data sources. *Int. J. Hydrogen Energy* **2020**, *45*, 10270–10279. [CrossRef]
65. El-Sayed, W.T.; Awad, A.S.A.; Al-Abri, R.; Alawasa, K.; Onen, A.; Ahshan, R. Integrated planning of hydrogen supply chain and reinforcement of power distribution network for accommodating fuel cell electric vehicles. *Int. J. Hydrogen Energy* **2024**, *81*, 865–877. [CrossRef]
66. Zhou, Y.; Qin, X.; Mei, W.; Yang, W.; Ni, M. Multi-period urban hydrogen refueling stations site selection and capacity planning with many-objective optimization for hydrogen supply chain. *Int. J. Hydrogen Energy* **2024**, *79*, 1427–1441. [CrossRef]
67. Zhang, J.; Li, C.; Chen, G.; Dong, Z. Planning of Hydrogen Refueling Stations in Urban Setting While Considering Hydrogen Redistribution. *IEEE Trans. Ind. Appl.* **2022**, *58*, 2898–2908. [CrossRef]
68. Li, L.; Manier, H.; Manier, M. Integrated optimization model for hydrogen supply chain network design and hydrogen fueling station planning. *Comput. Chem. Eng.* **2020**, *134*, 106683. [CrossRef]
69. Mehrjerdi, H. Off-grid solar powered charging station for electric and hydrogen vehicles including fuel cell and hydrogen storage. *Int. J. Hydrogen Energy* **2019**, *44*, 11574–11583. [CrossRef]
70. Wang, Y.; Kazemi, M.; Nojavan, S.; Jermsittiparsert, K. Robust design of off-grid solar-powered charging station for hydrogen and electric vehicles via robust optimization approach. *Int. J. Hydrogen Energy* **2020**, *45*, 18995–19006. [CrossRef]
71. Zhang, G.; Ge, Y.; Ye, Z.; Al-Bahrani, M. Multi-objective planning of energy hub on economic aspects and resources with heat and power sources, energizable, electric vehicle and hydrogen storage system due to uncertainties and demand response. *J. Energy Storage* **2023**, *57*, 106160. [CrossRef]
72. Tao, Y.; Qiu, J.; Lai, S.; Sun, X. Coordinated Planning of Electricity and Hydrogen Networks with Hydrogen Supply Chain for Fuel Cell Electric Vehicles. *IEEE Trans. Sustain. Energy* **2023**, *14*, 1010–1023. [CrossRef]
73. Gan, W.; Yan, M.; Yao, W.; Guo, J.; Fang, J.; Ai, X.; Wen, J. Multi-Network Coordinated Hydrogen Supply Infrastructure Planning for the Integration of Hydrogen Vehicles and Renewable Energy. *IEEE Trans. Ind. Appl.* **2022**, *58*, 2875–2886. [CrossRef]
74. Lei, Y.; Wang, D.; Jia, H.; Li, J.; Chen, J.; Li, J.; Yang, Z. Multi-stage stochastic planning of regional integrated energy system based on scenario tree path optimization under long-term multiple uncertainties. *Appl. Energy* **2021**, *300*, 117224. [CrossRef]
75. Xiong, Z.; Shen, X.; Wu, Q.; Guo, Q.; Sun, H. Stochastic planning for low-carbon building integrated energy system considering electric-heat-V2G coupling. *Int. J. Electr. Power Energy Syst.* **2023**, *151*, 109148. [CrossRef]
76. Zeng, B.; Wang, W.; Zhang, W.; Wang, Y.; Tang, C.; Wang, J. Optimal configuration planning of vehicle sharing station-based electro-hydrogen micro-energy systems for transportation decarbonization. *J. Clean. Prod.* **2023**, *387*, 135906. [CrossRef]
77. Tao, Y.; Qiu, J.; Lai, S.; Zhang, X.; Wang, G. Collaborative Planning for Electricity Distribution Network and Transportation System Considering Hydrogen Fuel Cell Vehicles. *IEEE Trans. Transp. Electrif.* **2020**, *6*, 1211–1225. [CrossRef]
78. Tabar, V.S.; Tohidi, S.; Ghassemzadeh, S. Risk-constrained day-ahead planning of an energy hub integrated with the on-site hydrogen fueling station and active battery swapping infrastructure considering high level of renewable energies and load redistribution. *J. Energy Storage* **2023**, *72*, 108700. [CrossRef]
79. Wang, Y.; Liu, J.; Qu, Z. Multi-stage collaborative planning of electricity-hydrogen-transportation coupling network considering carbon emission reduction. *Electr. Power Syst. Res.* **2024**, *228*, 110071. [CrossRef]

80. Shoja, Z.M.; Mirzaei, M.A.; Seyedi, H.; Zare, K. Sustainable energy supply of electric vehicle charging parks and hydrogen refueling stations integrated in local energy systems under a risk-averse optimization strategy. *J. Energy Storage* **2022**, *55*, 105633. [CrossRef]
81. Dong, W.; Shao, C.; Li, X.; Zhu, D.; Zhou, Q.; Wang, X. Integrated planning method of green hydrogen supply chain for hydrogen fuel cell vehicles. *Int. J. Hydrogen Energy* **2023**, *48*, 18385–18397. [CrossRef]
82. Kuvvetli, Y. Multi-objective and multi-period hydrogen refueling station location problem. *Int. J. Hydrogen Energy* **2020**, *45*, 30845–30858.
83. Wang, Y.; Liu, C.; Qin, Y.; Wang, Y.; Dong, H.; Ma, Z.; Lin, Y. Synergistic planning of an integrated energy system containing hydrogen storage with the coupled use of electric-thermal energy. *Int. J. Hydrogen Energy* **2023**, *48*, 15154–15178. [CrossRef]
84. Shaillan, H.M.; Tohidi, S.; Hagh, M.T.; Tabar, V.S. Risk-aware two-stage stochastic short-term planning of a hybrid multi-microgrid integrated with an all-in-one vehicle station and end-user cooperation. *J. Energy Storage* **2024**, *78*, 110083. [CrossRef]
85. Yu, K.; Cen, Z.; Chen, X.; Bu, L.; Gan, L.; Huang, Z.; Shen, J.; Hua, H. Coordinated planning and operation of inter seasonal heat storage and P2G devices integrated to urban multi-energy system. *Energy Rep.* **2023**, *9*, 4617–4634. [CrossRef]
86. Mehrjerdi, H.; Iqbal, A.; Rakhshani, E.; Torres, J.R. Daily-seasonal operation in net-zero energy building powered by hybrid renewable energies and hydrogen storage systems. *Energy Convers. Manag.* **2019**, *201*, 112156. [CrossRef]
87. Wang, J.; Xue, K.; Guo, Y.; Ma, J.; Zhou, X.; Liu, M.; Yan, J. Multi-objective capacity programming and operation optimization of an integrated energy system considering hydrogen energy storage for collective energy communities. *Energy Convers. Manag.* **2022**, *268*, 116057. [CrossRef]
88. Liu, J.; Cao, S.; Chen, X.; Yang, H.; Peng, J. Energy planning of renewable applications in high-rise residential buildings integrating battery and hydrogen vehicle storage. *Appl. Energy* **2021**, *281*, 116038. [CrossRef]
89. Cao, S.; Klein, K.; Herkel, S.; Sirén, K. Approaches to enhance the energy performance of a zero-energy building integrated with a commercial-scale hydrogen fueled zero-energy vehicle under Finnish and German conditions. *Energy Convers. Manag.* **2017**, *142*, 153–175.
90. He, J.; Wu, Y.; Wu, M.; Xu, M.; Liu, F. Two-stage configuration optimization of a novel standalone renewable integrated energy system coupled with hydrogen refueling. *Energy Convers. Manag.* **2022**, *251*, 114953. [CrossRef]
91. Jung, Y.; Heo, Y.; Cho, H.; Kang, Y.T.; Kim, Y.; Lee, H. A plan to build a net zero energy building in hydrogen and electricity-based energy scenario in South Korea. *J. Clean. Prod.* **2023**, *397*, 136537. [CrossRef]
92. Endo, N.; Shimoda, E.; Goshome, K.; Yamane, T.; Nozu, T.; Maeda, T. Simulation of design and operation of hydrogen energy utilization system for a zero emission building. *Int. J. Hydrogen Energy* **2019**, *44*, 7118–7124. [CrossRef]
93. Farahani, S.S.; Bleeker, C.; van Wijk, A.; Lukszo, Z. Hydrogen-based integrated energy and mobility system for a real-life office environment. *Appl. Energy* **2020**, *264*, 114695. [CrossRef]
94. Chamout, M.W.; Perl, A.; Hengeveld, E.J.; Aué, J. Simulation and analysis of hybrid hydrogen-battery renewable energy storage for off-electric-grid Dutch household system. *Int. J. Hydrogen Energy* **2024**, *70*, 170–182. [CrossRef]
95. Islam, M.S. A techno-economic feasibility analysis of hybrid renewable energy supply options for a grid-connected large office building in southeastern part of France. *Sustain. Cities Soc.* **2018**, *38*, 492–508. [CrossRef]
96. Huo, Q.; Liu, Q.; Deng, H.; Wang, W.; Shi, C.; Wei, T. Research on dual-layer optimization strategy of PV-storage-hydrogen system in coal chemical industry park. *Renew. Energy* **2024**, *230*, 120813. [CrossRef]
97. Niknam, T.; Bornapour, M.; Ostadi, A.; Gheisari, A. Optimal planning of Molten Carbonate Fuel Cell Power Plants at distribution networks considering Combined Heat, Power and Hydrogen production. *J. Power Sources* **2013**, *239*, 513–526. [CrossRef]
98. Wang, Y.; Song, M.; Jia, M.; Li, B.; Fei, H.; Zhang, Y.; Wang, X. Multi-objective distributionally robust optimization for hydrogen-involved total renewable energy CCHP planning under source-load uncertainties. *Appl. Energy* **2023**, *42*, 121212. [CrossRef]
99. Liu, J.; Xu, Z.; Wu, J.; Liu, K.; Guan, X. Optimal planning of distributed hydrogen-based multi-energy systems. *Appl. Energy* **2021**, *281*, 116107. [CrossRef]
100. Lin, J.; Cai, R. Optimal planning for industrial park-integrated energy system with hydrogen energy industry chain. *Int. J. Hydrogen Energy* **2023**, *48*, 19046–19059. [CrossRef]
101. Luo, W.; Wu, J.; Cai, J.; Mao, Y.; Chen, S. Capacity Allocation Optimization Framework for Hydrogen Integrated Energy System Considering Hydrogen Trading and Long-Term Hydrogen Storage. *IEEE Access* **2023**, *11*, 15772–15787.
102. Rizk-Allah, R.M.; Hassan, I.A.; Snasel, V.; Hassanien, A.E. An optimal standalone wind-PV power plant system for green hydrogen generation: Case study for hydrogen refueling station. *Results Eng.* **2024**, *22*, 102234. [CrossRef]
103. Deng, Z.; Jiang, Y. Optimal sizing of wind-hydrogen system considering hydrogen demand and trading modes. *Int. J. Hydrogen Energy* **2020**, *45*, 11527–11537. [CrossRef]
104. Song, Y.; Mu, H.; Li, N.; Wang, H. Multi-objective optimization of large-scale grid-connected PV-hydrogen-natural gas integrated energy power station based on carbon emission priority. *Int. J. Hydrogen Energy* **2023**, *48*, 4087–4103. [CrossRef]
105. Fu, C.; Lin, J.; Song, Y.; Li, J.; Song, J. Optimal Operation of an Integrated Energy System Incorporated With HCNG Distribution Networks. *IEEE Trans. Sustain. Energy* **2020**, *11*, 2141–2151. [CrossRef]

106. Qiu, Y.; Zhou, S.; Wang, J.; Chou, J.; Fang, Y.; Pan, G.; Gua, W. Feasibility analysis of utilising underground hydrogen storage facilities in integrated energy system: Case studies in China. *Appl. Energy* **2020**, *269*, 115–140. [CrossRef]
107. Rezaee Jordehi, A.; Mansouri, S.A.; Tostado-Véliz, M.; Iqbal, A.; Marzband, M.; Jurado, F. Industrial energy hubs with electric, thermal and hydrogen demands for resilience enhancement of mobile storage-integrated power systems. *Int. J. Hydrogen Energy* **2024**, *50*, 77–91. [CrossRef]
108. Liu, J.; Cao, X.; Xu, Z.; Guan, X.; Dong, X.; Wang, C. Resilient operation of multi-energy industrial park based on integrated hydrogen-electricity-heat microgrids. *Int. J. Hydrogen Energy* **2021**, *46*, 28855–28869. [CrossRef]
109. Gao, X.; Chu, H.; Yang, Z.; Luo, T.; Zhang, S.; Zhang, X. Impacts of the scenario temporal structure and data variability on the planning and reliability of integrated energy system coupling electricity–thermal–hydrogen. *Electr. Power Syst. Res.* **2026**, *258*, 113168. [CrossRef]
110. Li, Z.; Xia, Y.; Bo, Y.; Wei, W. Optimal planning for electricity-hydrogen integrated energy system considering multiple timescale operations and representative time-period selection. *Appl. Energy* **2024**, *362*, 122965. [CrossRef]
111. Ren, P.; Dong, Y.; Zhang, H.; Wang, C.; Fan, X. Collaborative planning of multi-park electricity hydrogen integrated energy systems based on refined categorized demand response: A bi-level stochastic optimization framework considering flexibility enhancement and uncertainty mitigation. *Reliab. Eng. Syst. Saf.* **2026**, *275*, 112748. [CrossRef]
112. Yang, D.; Zhan, T.; Liu, X.; Jiang, C.; Huang, G.; Wang, H. Scenario information gap planning for electricity-gas-hydrogen integrated energy systems considering the impact of grid interaction locations. *Energy* **2025**, *335*, 137869. [CrossRef]
113. Zeng, G.; Liu, M.; Lei, Z.; Huang, X. Bi-level robust planning of hydrogen energy system for integrated electricity–heat–hydrogen energy system considering multimode utilization of hydrogen. *Energy* **2024**, *303*, 132029. [CrossRef]