

A Review on Electricity-hydrogen Coupling System: Methodologies, Applications, and Prospects

Jianlin Li, *Member, IEEE*, Zelin Shi, and Zhonghao Liang

Abstract—With the increasing integration of large-scale renewable energy (RE) sources into power systems, electricity-hydrogen coupling system has emerged as a transformative solution through flexible energy conversion and complementary utilization of electricity and hydrogen. It effectively addresses structural challenges in conventional energy systems regarding spatiotemporal regulation, environmental constraints, and supply security while creating significant opportunities in technological innovation and industrial transformation, accelerating the transition from traditional fossil fuels to clean energy. This paper reviews the strengths and limitations of the electricity-hydrogen coupling system in production, storage, and utilization in scenarios of high RE penetration. It examines the architectural frameworks and current development status of key technologies within the electricity-hydrogen coupling system, and builds on their operational characteristics across multiple timescales to analyze both short-term energy balance control and medium- and long-term optimal dispatch. This paper further investigates representative application scenarios, systematically evaluates demonstration projects deployed, and critically analyzes prevailing challenges alongside prospective research pathways.

Index Terms—Electricity-hydrogen coupling system, renewable energy, electrolytic hydrogen production, fuel cell power generation, hydrogen storage and transportation.

I. INTRODUCTION

AGAINST the backdrop of China's advancement toward a new energy system, it is crucial to develop a clean, efficient, and sustainable energy supply system for promoting high-quality energy development and ensuring national energy security [1]. Meeting deep decarbonization targets requires accelerated deployment of carbon-free power sources and long-duration energy storage technologies to replace

electricity generation based on fossil fuels. However, due to the stochastic nature of renewable energy (RE), new energy systems must integrate sufficient storage to ensure the stability of power systems with high RE penetration.

Hydrogen energy, as a green and low-carbon secondary energy carrier, offers high energy density, facilitates storage and transportation, and enables large-scale seasonal storage, demonstrating broad application prospects in the low-carbon development of power systems with high RE penetration [2]. Unlike pumped hydro storage and compressed air energy storage, which depend on specific geographical conditions, hydrogen can be flexibly stored as high-pressure gas, liquid, or solid, offering exceptional flexibility in site selection. Meanwhile, hydrogen storage equipment exhibits 20-30 years of service life without cyclic degradation issues inherent to electrochemical batteries, demonstrating significant full-life-cycle cost advantages. These provide innovative solutions to the current challenges in power system such as insufficient balancing support and inflexible regulation, making hydrogen a key energy vector for advancing energy structure transformation and achieving the carbon peaking and neutrality goals (also known as the dual carbon goals).

With breakthroughs in water electrolysis, fuel cell power generation, and hydrogen storage and transportation technologies, hydrogen has evolved from a mere energy storage medium to a more versatile energy carrier, along with the advancing commercialization. Through energy conversion and storage devices, the electricity-hydrogen coupling system now enables versatile applications across transportation, industrial, and building sectors [3]. This progression facilitates diversification and deep decarbonization of energy systems, thereby establishing the electricity-hydrogen coupling system as a distinct research domain [4]. The electricity-hydrogen coupling system achieves spatiotemporal resource optimization through deep integration of source-grid-load-storage components, addressing operational challenges posed by the intermittency and volatility of wind/photovoltaic (PV) power, as well as the limited support and low disturbance tolerance of renewable generation equipment. The integrated architectures provide critical solutions for maintaining power system stability by leveraging multi-timescale coordination and cross-sectoral energy complementarity [5]-[7].

Recently, countries worldwide have prioritized the development of hydrogen energy, strengthening support for hydro-

Manuscript received: July 3, 2025; revised: August 22, 2025; accepted: September 23, 2025. Date of CrossCheck: September 23, 2025. Date of online publication: October 1, 2025.

This work was supported in part by National Key Research and Development Program of China (No. 2024YFB4007400).

This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (<http://creativecommons.org/licenses/by/4.0/>).

J. Li and Z. Shi (corresponding author) are with National User-side Energy Storage Innovation Research and Development Center, North China University of Technology, Beijing, China (e-mail: dkyljl@163.com; szl835597416@126.com).

Z. Liang is with State Key Laboratory of High Density Electromagnetic Power and Systems, Institute of Electrical Engineering, Chinese Academy of Sciences, Beijing, China (e-mail: liangzhonghao@mail.iee.ac.cn).

DOI: 10.35833/MPCE.2025.000608



gen storage equipment and integrated hydrogen energy systems [8], [9]. Japan, the first nation to unveil a national hydrogen development strategy, published a revised Basic Hydrogen Strategy in 2023, providing financial support to the hydrogen industry through targeted projects and programs to sustain its leadership in the field [10]. Meanwhile, the U.S. Department of Energy released the Hydrogen Program Plan 2024, making concerted efforts to advance the research, development, demonstration, and deployment of hydrogen storage technologies to accelerate the realization of hydrogen applications across diverse sectors [11]. In December 2024, China issued the Implementation Plan for Accelerating the Application of Clean and Low-carbon Hydrogen in the Industrial Sector, mandating scaled adoption of green hydrogen in metallurgy and chemicals by 2027 while promoting hydrogen commercialization in transportation and energy storage [12]. Notably, the Energy Law of the People's Republic of China taking effect since January 2025, formally regards hydrogen as a strategic energy carrier at the national level for the first time, integrating it into the conventional energy management framework alongside petroleum, coal, and natural gas [13]. This milestone directs regional governments to foster the growth of hydrogen industry through strategic infrastructure development aligned with local comparative advantages [14]. Consequently, the development of the electricity-hydrogen coupling system that integrates production, storage, transportation, and utilization holds critical significance for optimizing energy structures, reducing carbon emissions, and driving the global transition towards a more sustainable energy system.

In existing studies on the electricity-hydrogen coupling system, notable gaps persist in exploring development pathways and application potential at scale, alongside a lack of comprehensive reviews and syntheses. The electricity-hydrogen coupling system confronts multidimensional challenges described as follows.

1) Gaps in technological maturity still persist, with unresolved disparities in the adaptability of electrolyzers to wide loads, dynamic response characteristics of fuel cells, and the efficiency and economic viability of hydrogen storage and transportation technologies [15], [16].

2) The decoupling of interactions among multiple energy flows may be inadequate, where differences in dynamic characteristics across time scales lead to delays in the coordinated control of source, grid, load, and storage components [17], [18].

3) Misalignments between policy and market may exist, such as institutional gaps in green hydrogen certification, cross-regional trading, and carbon-hydrogen synergy, which hinder the commercialization of the electricity-hydrogen coupling system [19], [20].

Resolving these critical bottlenecks is essential to advance the electricity-hydrogen coupling system from technological validation to large-scale implementation. This paper introduces key technologies and system architectures, including water electrolysis for hydrogen production, fuel cell power generation, and hydrogen storage and transportation. Based on this foundation, this paper organizes operational control strat-

egies across short-term and medium-to-long-term time scales from the perspective of coupling between electricity and hydrogen. Furthermore, it reviews four representative application scenarios: ancillary services, combined heat and power (CHP) supply, integration of hydrogen-based transportation sector, and power-to-fuel (PtF), supplemented by practical analyses of demonstration projects. This paper subsequently identifies persistent technical and systematic challenges in the development of the electricity-hydrogen coupling system, while proposing targeted research directions to address scalability limitations in core technologies, diversify application scenarios, and innovate market mechanisms.

II. DEVELOPMENT STATUS OF ELECTRICITY-HYDROGEN COUPLING SYSTEM

A. System Structure

With the high RE penetration into power systems, synchronous generators are being largely replaced by power electronic devices, leading to reduced system inertia and diminished frequency and voltage support capabilities. Furthermore, RE generation exhibits multiple inherent uncertainties, including randomness, intermittency, and seasonal variability, and the RE output profiles fail to fully match the load demand patterns. These characteristics collectively pose significant challenges to the power balance and the stable operation of power systems [21]. The electricity-hydrogen coupling system, characterized by its simple structure and operational flexibility, effectively bridges the critical demands of RE consumption and hydrogen utilization, offering an innovative solution for the low-carbon energy transition.

As illustrated in Fig. 1, the electricity-hydrogen coupling system encompasses hydrogen production, storage, transportation, and utilization [22]. It employs water electrolysis to convert primary RE sources such as wind turbine (WT) power and PV power into hydrogen for long-term storage, achieving green electricity-to-hydrogen conversion. During power supply shortages, fuel cells reconvert stored hydrogen into electricity to meet load demands, thereby enhancing reliability and operational stability of power systems. The hydrogen storage and transportation system, as a key intermediary, leverages the high density of hydrogen energy and low self-discharging characteristics, enabling large-scale storage and transportation over long distances via pipelines or specialized vehicles [23]. By fully utilizing the critical advantages of hydrogen in optimal allocation across regions and its capabilities of energy storage, the electricity-hydrogen coupling system not only meets the requirements for RE consumption on an ultra-large scale, but also significantly raises the security and stability levels of power systems.

B. Electrolytic Hydrogen Production

Currently, hydrogen production in China primarily includes industrial by-product hydrogen recovery, water electrolysis, chemical feedstock-based methods, and fossil fuel reforming. The production of different types of hydrogen is shown in Fig. 2.

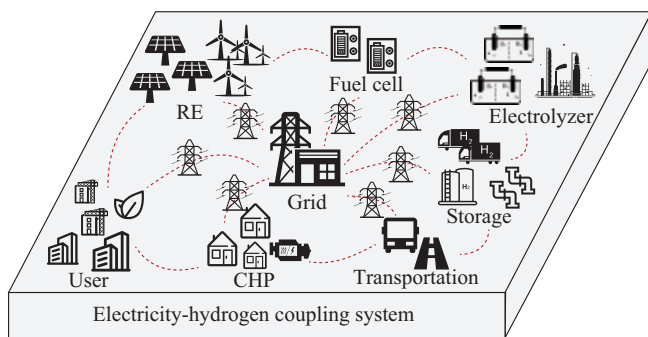


Fig. 1. Diagram of electricity-hydrogen coupling system.

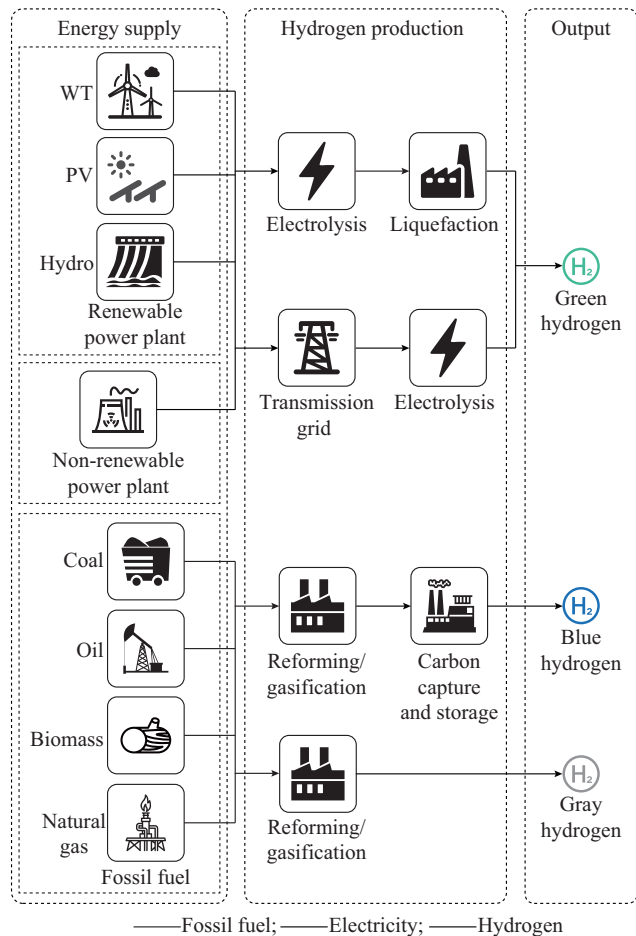


Fig. 2. Diagram representing production of different types of hydrogen.

Water electrolysis, which converts surplus RE into hydrogen energy for application or storage through electrolyzer, is the main method of producing green hydrogen in the electricity-hydrogen coupling system, and the hydrogen produced through this method accounts for about 4% of the global hydrogen production [24], [25].

The system architecture of an electrolyzer primarily comprises an electrolyzer stack, power supply and conversion system, gas-water separation and treatment unit, thermal management module, control system, and auxiliary components, as schematically illustrated in Supplementary Material A Fig. A1 [26]. The electrolyzer stack, serving as the central functional unit, consists of multiple electrolyzer stacks ar-

ranged in series or parallel configurations, integrating critical elements including proton exchange membrane or alkaline electrolyte layers, bipolar plates, and electrodes coated with catalyst, whose structural design directly determines the efficiency and operational durability of hydrogen production [27].

Based on the type of electrolyte used, electrolyzers can be categorized into four types: alkaline water electrolyzer (AEL), proton exchange membrane electrolyzer (PEMEL), solid oxide electrolyzer (SOEL), and molten carbonate electrolyzer (MCEL). Among these, AEL is technologically mature, featuring low costs and high unit hydrogen production capacity, while PEMEL features fast response time and wide operating ranges. Both AEL and PEMEL systems have achieved MW-level integration and are widely applied in industrial green hydrogen production [28]. In contrast, SOEL and MCEL are constrained by their high costs and durability issues, remaining in the experimental validation stage without demonstration projects initiated in [29]. A comparison of the technical characteristics of the four water electrolysis hydrogen production technologies is shown in Supplementary Material A Table A1.

As power systems gradually evolve into integrated energy systems with complementary characteristics of multiple energy types including electricity, heat, and gas, along with an increasing RE penetration, the operating conditions of electrolyzers will become more complex, imposing higher demands on control strategies and hydrogen production technologies via electrolysis.

1) Optimizing the equipment design to enhance the capability of electrolyzer to operate across a wide power range can mitigate the impact of RE randomness and volatility on its long-term safe and stable operation. This improvement also strengthens the capability of electrolyzer to participate in ancillary services such as peak-shaving and frequency regulation within the power system.

2) Increasing the power rating and system scale of electrolyzers enables them to function as manageable loads for optimal dispatch. This scalability helps match the growing installed capacity of WT and PV, thereby enhancing the RE utilization.

3) Advancing manufacturing processes and leveraging economies of scale can reduce the investment cost of electrolytic hydrogen production systems, improve operational efficiency, extend system lifetime, and ultimately enhance the overall economic viability of the electricity-hydrogen coupling system.

C. Fuel Cell Technology

Fuel cells play a significant role in national energy strategies and demonstrate extensive potential in applications such as industrial, commercial, transportation, residential, on-site power generation and distribution, and portable power solutions. The structure of fuel cells is shown in Supplementary Material A Fig. A2 [30], [31]. Fuel cells are primarily categorized into low-temperature and high-temperature types. Low-temperature fuel cells typically operate below 200 °C, including alkaline fuel cell (AFC), proton exchange mem-

brane fuel cell (PEMFC), and direct methanol fuel cell (DMFC). In contrast, high-temperature fuel cells operate above 450 °C, including molten carbonate fuel cell (MCFC) and solid oxide fuel cell (SOFC) [32]. A comparison of the technical characteristics of various fuel cells is presented in Supplementary Material A Table AII. In China, the most widely adopted fuel cells are the PEMFC and SOFC.

PEMFC utilizes a perfluorosulfonic acid polymer electrolyte and operates at low temperatures. It relies on highly pure hydrogen as fuel, offering advantages such as rapid start-up, high power density, and compact design. However, its reliance on catalysts using platinum leads to elevated costs, and it shows sensitivity to impurities in the hydrogen supply. PEMFC is primarily applied in passenger vehicles and portable power sources. The deployment of PEMFC in the automotive sector is constrained by limitations in withstanding mechanical vibrations and dynamic movements. Existing studies have confirmed the impact of mechanical vibration on PEMFC performance and durability [33]. Therefore, vibration resistance constitutes a critical factor for PEMFCs in automotive applications. SOFC, typified by solid oxide electrolytes, is a high-temperature fuel cell that boasts advantages such as high energy conversion efficiency, broad fuel compatibility, and long service life. Its high operating temperature enhances tolerance to fuel impurities, enabling direct utilization of natural gas, biogas, or reformed synthesis gas as fuels. Waste heat can be directly harnessed for industrial steam, heating, or driving absorption chillers, forming combined cold, heat, and power (CCHP) generation systems. Currently, due to challenges in localization, thermal expansion matching, and sealing technology, the commercialization of SOFCs in China still needs further development. Furthermore, high-power fuel cell technologies remain largely in the theoretical research stage, with their power levels, service life, and economic viability failing to meet application requirements, thereby restricting large-scale adoption and commercial development. To address this, some studies have proposed to construct fuel cell systems with multiple stacks by connecting multiple individual fuel cells in series or parallel configurations for high-power demand scenarios [34].

The integration of fuel cell power supply into the multi-energy coordination framework of an electricity-hydrogen system is pivotal. It necessitates enhanced dynamic response capabilities to mitigate the strong variability of RE sources, enabling fast power adjustment during sudden WT/PV power output changes to address grid imbalances. Given the heavy reliance on green hydrogen as an energy carrier, fuel cells need to be compatible with hydrogen of varying purities and expand the flexibility of fuel, such as by coupling with biomass gasification or industrial byproduct hydrogen, to strengthen the resilience of the energy supply chain. In terms of energy efficiency, high-temperature fuel cells need further optimization of CHP efficiency, achieving cascaded energy utilization through waste heat recovery coupled with district heating networks and industrial processes, while low-temperature fuel cells must reduce parasitic power consumption to improve the net output efficiency. Regarding durability, it is essential to address catalyst degradation and material aging

caused by frequent startups, shutdowns, and load fluctuations, particularly in scenarios with high RE penetration, where the startup-shutdown cycles of the electricity-hydrogen coupling system may significantly shorten, necessitating the development of adaptive control strategies and resilient materials.

D. Hydrogen Storage and Transportation Technology

The geographical disparity between hydrogen production and consumption sites necessitates the implementation of efficient hydrogen storage technologies for energy retention coupled with advanced transportation systems to facilitate hydrogen distribution to users, as demonstrated in Supplementary Material A Figs. A3 and A4 [35]. Furthermore, considering the inherent low volumetric energy density of hydrogen and the challenges of storage across seasons, a critical prerequisite for integrating hydrogen into power systems lies in developing hydrogen storage technologies with high energy density [36]. Current hydrogen storage technologies are categorized into physical storage and chemical storage: physical storage includes high-pressure gaseous storage, liquid storage, and subsurface storage; while chemical storage includes solid hydrogen and liquid ammonia storage, with comparative technical characteristics of these hydrogen storage and transportation methods detailed in Supplementary Material A Table AIII [37].

High-pressure gaseous storage compresses hydrogen gas by increasing pressure and stores it in containers, characterized by its cost efficiency, high conversion efficiency, and low energy consumption. This method is predominantly utilized for hydrogen transportation via tube trailers, representing the most widely adopted hydrogen storage technology. However, its transport capacity is constrained by container volume limitations, posing challenges for large-scale centralized storage [38]. Hydrogen can be converted into a liquid form under cryogenic conditions and stored in cryogenically insulated containers, with its energy storage density approximately 845 times higher than that of high-pressure gaseous storage. The liquid storage provides substantial capacity, reduces transportation frequency, and enhances the supply efficiency of hydrogen refueling stations, making it especially advantageous for transportation scenarios involving long distances and large volumes [39]. However, the liquefaction process incurs high costs and significant energy losses, currently restricting its applications primarily to the aerospace sector, with civilian deployment limited by insufficient operational experience. Subsurface storage, leveraging salt caverns, abandoned mines, or aquifers as geological reservoirs, emerges as the optimal solution for large-scale long-term storage, which is recognized as a critical method for integrating hydrogen into power systems [40]. Reference [41] proposes an integrated energy system incorporating WT, PV, salt caverns, and hydrogen storage in Qianjiang, Hubei Province, China, verifying its economic viability and carbon reduction. Solid hydrogen storage involves the incorporation of hydrogen into solid materials through absorption or adsorption mechanisms, typically utilizing metal hydrides characterized by high hydrogen storage density, superior oxygen tolerance, and enhanced cycling stability, though current ap-

plications remain limited to research-phase development [42]. Liquid ammonia storage synthesizes hydrogen and nitrogen into ammonia via catalytic processes for transportation and storage, with subsequent catalytic decomposition into hydrogen and nitrogen during utilization [43]. While liquid ammonia storage achieves superior storage efficiency and enables the rapid release of substantial hydrogen quantities, inherent energy penalties during ammonia synthesis and decomposition processes significantly reduce the efficiency of power-to-ammonia conversion, rendering its application prospects contingent upon further technical validation and system optimization.

High-pressure gaseous storage currently dominates hydrogen storage and transportation, ensuring the supply of China’s hydrogen energy industry in its infancy. However, its low storage density and high costs in long-distance transportation make it inadequate for large-scale storage and transportation in the future. Breakthroughs are imperative in safety, economy, and scalability aspects, which are described as follows.

- 1) Develop high-capacity, economical solid-state or underground hydrogen storage technologies to match seasonal RE fluctuations and enable energy transfer over timescales from weeks to months.
- 2) Formulate civil standards for liquid hydrogen, accumulate operational experience through civilian demonstration projects, and promote the commercialization of liquid hydrogen applications.
- 3) Retrofit existing natural gas pipelines to reduce initial investment in hydrogen pipeline transportation and build technical reserves for large-scale pipeline networks.
- 4) Develop hydrogen embrittlement-resistant materials, lightweight high-pressure tanks, and components compatible with cryogenic conditions to enhance the density and safety of hydrogen storage and transportation.

III. OPERATIONAL CONTROL STRATEGIES OF ELECTRICITY-HYDROGEN COUPLING SYSTEM

Current studies on the operational control strategies of the electricity-hydrogen coupling system primarily encompasses two temporal scales: short-term energy balance control and medium-to-long-term optimal dispatch [44].

Short-term energy balance control aims to regulate equipment operating parameters in real time, rapidly respond to load fluctuations and RE output variations, maintain instantaneous power balance, and ensure the safe and efficient coordination of all units within their operational constraints. The involvement of multiple energy carriers and diverse equipment types with distinct dynamic characteristics results in significant challenges. These include formulating effective power allocation strategies, achieving coordinated control among multiple devices, and ensuring seamless mode transitions.

Medium-to-long-term optimal dispatch focuses on achieving the minimization of life cycle cost and maximization of energy efficiency through global resource allocation and scheduling strategies, while concurrently addressing the operational reliability of equipment and system sustainability. The seasonal fluctuations of RE outputs, capacity planning for hydrogen storage and conversion equipment, and the cou-

pling characteristics across temporal scales of multiple energy flows involving electricity, hydrogen, and thermal energy, must be integrated. Consequently, it involves optimizing the balance between energy supply and demand across timescales ahead of the day and month, alongside comprehensive investment and operational costs. The system life cycle cost, renewable generation capacity ratio, hydrogen storage scale, and degradation of equipment performance critically impact the economic indicators, carbon reduction benefits, and supply reliability. Key challenges thus involve constructing the scheduling models that simultaneously account for degradation of equipment performance and synergistic optimization of multiple energy flows, managing uncertainties in RE generation and errors in long-term load forecasting, and resolving the balance of multiple objectives between economic goals and equipment health management.

A. Short-term Energy Balance Control

To address the challenges of short-term energy balance control, current studies focus on optimizing dynamic power allocation strategies and coordination mechanisms. The goal is to reduce the frequency of equipment cycling and operational mode transitions while preserving power balance and stability throughout the system.

A widely adopted solution uses a hierarchical architecture for short-term energy balance control, consisting of a device layer and an energy management layer, as illustrated in Fig. 3.

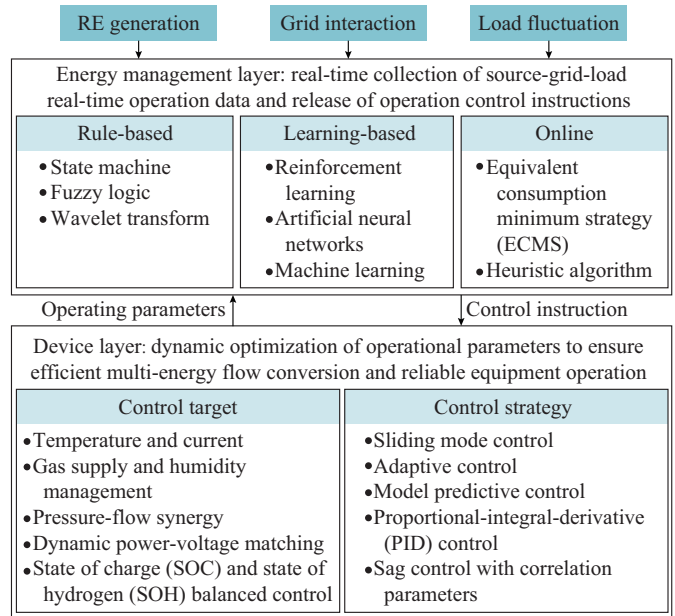


Fig. 3. Hierarchical architecture for short-term energy balance control.

The energy management system (EMS) facilitates bidirectional communication between these layers through advanced information technologies. Specifically, the energy management layer analyzes short-term operational data to determine the optimal control modes and power setpoints for each device [45], [46]. These optimized commands are subsequently dispatched to the corresponding device-level controllers via the EMS interface, forming a closed-loop control

structure. The subsequent texts will specifically focus on studies regarding control strategies for the device layer and the energy management layer. Key issues addressed include operational temperature regulation, hydrogen purity optimization, power allocation optimization, and state equalization of storage units.

1) Device Layer

Temperature control is critical for the economic and efficient operation of the electricity-hydrogen coupling system. During the operation of fuel cells and hydrogen production systems, high temperatures accelerate the degradation of equipment materials. As the life cycle extends, both the power generation and hydrogen production capacities of these systems decrease, with efficiency potentially decreasing by up to 10% compared with the initial state. This leads to a decline in the effective conversion rate throughout the life cycle, increasing the operation and maintenance (O&M) costs as well as equipment replacement expenses, thus affecting the system economy. In practical installations, PID control remains predominantly employed due to its simplicity of implementation, where thermal models integrated with PID-based temperature stabilization mechanisms modulate coolant flow rates or operational power consumption to maintain the temperature of device within prescribed ranges [47]. Moreover, model predictive control (MPC) has been increasingly adopted for thermal management, operating on principles similar to those of PID controllers in controlling coolant flow dynamics. Hydrogen purity management directly influences the performance of fuel cell and the efficiency of electrolyzer. Advanced MPC frameworks have demonstrated effectiveness in designing hydrogen purity enhancement strategies by dynamically optimizing the gas separation processes [48].

To address operational uncertainties caused by load fluctuations and RE intermittency in the electricity-hydrogen coupling system, adaptive control strategies demonstrate superior performance in maintaining optimal operating states of devices. These strategies autonomously adjust the power setpoints and control parameters in response to real-time variations of the process. Reference [49] proposes an adaptive voltage control strategy for alkaline electrolyzers based on DC bus voltage variations, which incorporates voltage constraints to maximize the efficiency of electrolyzer. This control strategy activates power curtailment of wind turbines through adaptive regulation when the DC bus voltage exceeds predefined thresholds, thereby maintaining operational parameters within safe limits while optimizing the performance of hydrogen production. To ensure continuous operation of the electrolyzer and prevent shutdowns caused by insufficient input power due to RE fluctuations, which would compromise the efficiency of hydrogen production and the life cycle of equipment, [50] employs sliding mode control to maintain the current of electrolyzer at the desired level. This enables the maximum hydrogen production even under fluctuating WT output and operating temperature conditions.

In the electricity-hydrogen coupling system, distributed energy storage units are typically connected directly in parallel with the DC bus. This configuration may lead to inconsisten-

cies between the SOC of battery and the SOH of hydrogen storage modules, which can adversely affect the lifespan of equipment and the system stability. To address this issue, a droop control strategy based on associated parameters can be employed. This strategy correlates the corresponding physical quantities according to different system control objectives, thereby achieving equilibrium in SOC or SOH across the storage units [51].

2) Energy Management Layer

State machine control (SMC) strategy establishes the foundational logic framework for operational mode transitions. During the transitions between grid-connected and islanding modes, the SMC strategy coordinates seamless transitions across predefined discrete states, including priority in hydrogen production, power generation, and storage charging, while incorporating triggering conditions informed by physics. These conditions include thresholds such as grid frequency deviations exceeding ± 0.5 Hz or SOC dropping below 20% [52], [53]. This structured strategy ensures systematic mode switching through verifiable state transitions and measurable physical parameters, maintaining operational continuity and system stability under dynamic conditions.

The ECMS achieves real-time energy balancing in the electricity-hydrogen coupling system by establishing equivalence relationships between electrical and hydrogen energy conversions, dynamically optimizing the coordinated dispatch of carriers of multiple energy sources. The ECMS unifies the power consumption of electrolyzer, generation of fuel cell, and charging/discharging behaviors of energy storage into equivalent fuel consumption metrics, thereby enabling globally optimal energy flow allocation. Grounded in principles of instantaneous optimization, the ECMS introduces equivalence factors to formulate a multi-objective optimization function. This function is solved online to determine the operating point that minimizes equivalent consumption while satisfying all system constraints [54].

Fuzzy control strategies are widely applied in power allocation of the electricity-hydrogen coupling system due to their strong adaptability to nonlinear dynamics. The hydrogen production efficiency of electrolyzers exhibits nonlinear variations with load ratios, prompting fuzzy controllers to define linguistic variables such as “low load”, “medium load”, and “high load” states, thereby linking power regulation strategies to distinct efficiency regions for enhanced yield optimization of hydrogen. Given that fuel cells exhibit slow response yet high energy density, while lithium batteries offer fast response but limited capacity, fuzzy control coordinates their complementary operation through multiple priority rules that leverage dynamic response characteristics, effectively reducing the frequency recovery time and mitigating the degradation of lithium battery [55], [56]. However, the performance of fuzzy control critically depends on the completeness of the rule base and expertise in parameter tuning. Initial rule bases are typically developed based on subjective expert knowledge, which may fail to account for optimal strategies under edge-case operating conditions. To address this limitation, the evolution frameworks of fuzzy rules based on reinforcement learning are increasingly adopted.

These frameworks autonomously explore and expand rule libraries within simulation environments, accelerating the iterative optimization of fuzzy controllers [57].

B. Medium- and Long-term Optimal Dispatch

RE sources and loads characterized by wide power fluctuations exert a substantial impact on the operational efficiency and lifespans of electrolyzers and fuel cells. In the medium-to-long-term operational timescales of the electricity-hydrogen coupling system, control strategies prioritize the economic efficiency, flexibility, and reliability as the objectives of optimization, while incorporating constraints such as energy supply-demand balance, grid integration limits, and equipment operational boundaries [58], [59]. These control strate-

gies aim to leverage the flexibility of system components, fully exploit their potential for multi-dimensional complementarity, and strike a balance between environmental sustainability and economic viability. In this way, they achieve optimal resource allocation benefits by coordinating the dynamics of energy conversion and storage [60].

Currently, regarding the multi-timescale optimal scheduling problem of the electricity-hydrogen coupling system, studies have been carried out from day-ahead economic dispatch to month-ahead resource planning, where significant advancements have been achieved in model formulation and optimization methodologies. The medium-to-long-term optimal dispatch issues for the electricity-hydrogen coupling system are summarized in Table I.

TABLE I
SUMMARY OF MEDIUM-TO-LONG-TERM OPTIMAL DISPATCH ISSUES FOR ELECTRICITY-HYDROGEN COUPLING SYSTEM

Type	Classification	Example
Optimization objective [61]-[63]	Economic optimization	Life cycle cost, system integrated operation revenue, carbon trading cost
	Stability assurance	Hydrogen supply-demand balance, fluctuation rates of WT and PV power outputs
	Efficiency enhancement	Multi-energy conversion efficiency
	Environmental sustainability	Life-cycle carbon emission, RE penetration rate
Decision variable	Equipment operational variable	On/off status of electrolyzer and power output of fuel cell, charging/discharging rate and capacity status of hydrogen storage tank, operating mode of hydrogen compressor
	Energy interaction variable	Electricity-to-hydrogen conversion power, hydrogen purchasing/selling volume, demand response capacity, multi-energy allocation ratio in CCHP system
	Market transaction variable	Electricity spot market bidding, ancillary service (frequency regulation, reserve) capacity, carbon quota trading
Constraint	Physical constraint	Equipment operational limit, hydrogen pipeline network flow rate, power flow constraint
	Supply-demand balance constraint	Multi-energy supply-demand balance, tie-line capacity
	Market rule constraint	Electricity market settlement rule
Optimization method [64]-[69]	Mathematical programming	Linear programming (LP), second-order cone programming (SOCP), mixed-integer linear programming (MILP), multi-stage dynamic programming
	Stochastic optimization	Two-stage stochastic programming, chance-constrained programming
	Robust optimization	Adaptive robust optimization, distributionally robust optimization
	Reinforcement learning	Deep Q-network (DQN), deep deterministic policy gradient (DDPG), multi-agent reinforcement learning (MARL)
	Game theory method	Stackelberg game, Nash equilibrium, cooperative game
	Distributed algorithm	Alternating direction method of multipliers (ADMM), consensus algorithm
Heuristic algorithm	Genetic algorithm (GA), particle swarm optimization (PSO), simulated annealing (SA)	

The day-ahead dispatch operates on a 24-hour cycle. Compared with conventional power systems, the electricity-hydrogen coupling system exhibits significantly expanded optimization dimensions such as the coordinated management of multiple variables including hydrogen production rates of electrolyzer, hydrogen storage tank pressures, generation outputs of fuel cell, and charging/discharging states of electrical energy storage, while satisfying complex constraints such as the transmission limits of hydrogen pipelines, the minimum start-stop intervals of electrolyzer, and ramping rate limits of fuel cell [70]. The primary objective lies in formulating hourly operational schedules for next-day equipment dispatch to minimize operational costs and maximize RE utilization [71]. However, the inherent low prediction accuracy of supply-demand dynamics and intense intraday energy fluctuations often render day-ahead schedules infeasible. This leads to equipment operation outside permissible limits, frequent

start-stop cycles, accelerated lifetime degradation, and hydrogen waste. Addressing these challenges requires studies on coordinated scheduling planned a day ahead and within the day, to achieve seamless transitions across temporal scales and enhance the scheduling accuracy. Furthermore, recognizing the high capital costs of PEMEL and the limitations of AEL in dynamic response and compatibility with fluctuating RE sources, researchers have proposed to synergistically integrate both technologies into hybrid electrolyzer systems. These efforts capitalize on their complementary operational characteristics to enhance the production flexibility and economic viability of electrolytic hydrogen [72], while enabling subsequent development of rotating strategy and optimization frameworks for day-ahead dispatch.

Month-ahead dispatch typically covers a time frame of 1 to 6 months, focusing on strategic decisions such as equipment capacity planning, hydrogen procurement strategies,

and seasonal energy storage configuration. In the electricity-hydrogen coupling system, hydrogen showcases its unique value through storage capabilities across seasons [73]. Surplus RE from wind and PV sources in summer is converted into hydrogen via electrolyzers for storage, while the gaps between supply and demand in winter for heating and power generation are offset by deploying fuel cells or operating gas turbines (GTs) fired by hydrogen. Such scheduling models typically adopt stochastic programming frameworks with two or three stages: the first stage determines long-term investment variables such as the capacities of electrolyzer and fuel cell, hydrogen storage volumes, and RE installation ratios, while subsequent stages optimize monthly hydrogen production and consumption plans considering uncertainties such as seasonal RE generation patterns and demand fluctuations in the hydrogen market [74]. Additionally, modeling the degradation of equipment constitutes a critical research focus, particularly addressing accelerated reduction of the lifespan of electrolyzer membrane electrodes under frequent start-stop operations, necessitating integrated optimization of maintenance cycles and production schedules in month-ahead planning.

The selection of optimization methodologies must be rigorously aligned with system characteristics and operational en-

vironments. The states of current studies on medium- and long-term optimal dispatch are shown in Table II. In deterministic scenarios characterized by low prediction errors in RE generation and clearly defined load patterns, traditional mathematical programming methods such as LP, SOCP, and MILP prove to be effective for developing the optimization model. These programming methods construct deterministic models by linearizing the efficiency curves of electrolyzer and using piecewise approximations for relationships between hydrogen storage pressure and capacity, while leveraging commercial solvers like Gurobi and Yalmip to rapidly identify the optimal combinations of equipment starting and stopping and power allocation schemes. Their principal advantages lie in computational efficiency and guaranteed solution optimality through rigorous verification, albeit at the expense of reduced model fidelity due to inherent linearization and approximation trade-offs [75]. In scenarios where system operational models are highly complex and conventional optimization frameworks are intractable, heuristic algorithms such as GA and PSO are effective in addressing multiple-scale characteristics involving multiple agents and strong nonlinearity inherent to the electricity-hydrogen coupling system [76].

TABLE II
STATES OF CURRENT STUDIES ON MEDIUM-TO-LONG-TERM OPTIMAL DISPATCH

Component	Application	Objective	Method	Highlight	Reference
GT, PV, WT, grid, hydrogen energy storage system (HESS)	Cross-seasonal storage	Minimize economic cost, carbon emission, and operating cost	MOPSO and MILP	Synergistically optimize upper-tier capacity planning and lower-tier economic dispatch to achieve dynamic balance between annual-scale investment and daily-scale operation, and use of cross-seasonal hydrogen storage to address long-term supply-demand imbalances in RE sources	[77]
GT, PV, WT, HESS, battery	Low-carbon transportation system	Minimize operating cost	Deep deterministic policy (DRL)	The security and imitation mechanism ensures constraint satisfaction through security layer, and imitation learning accelerates the convergence of the policy while reducing the cost of DRL by 40.1% compared with traditional DRL	[78]
PV, WT, HESS, gas boiler (GB), electric boiler (EB)	Vessel transportation	Minimize economic cost	MILP and MPC	The hydrogen-electricity-heat system is deeply coupled to realize cross-form complementarity of ship energy and increase the total energy utilization rate to 85.53%-91.83%	[79]
PV, WT, HESS	Island renewable system	Maximize annual return	FC and GA	FC-GA dynamically adjusts the optimization step by fuzzy rules and proposes a hybrid electrolyzer system to enhance the system adaptability to fluctuating energy sources with improvement of annual revenue by 6.6%	[80]
PV, WT, HESS, GB, EB	Integrated energy management	Minimize economic cost	Deep deterministic policy (DRO) and column-and-constraint generation (C&CG)	Dealing with multi-source uncertainty via DRO balances conservatism and robustness more than traditional methods	[81]
WT, grid, HESS	On-grid hydrogen production system	Maximize RE utilization and electrolyzer life	staged control strategy	"Fast start + equal distribution" dual-phase control is proposed, which improves energy utilization to 98.75% and extends the lifespan of the electrolyzer	[82]
PV, WT, grid, HESS, HFCV, GT, battery	Distributed energy system	Maximize interests of multiple subjects	Leader-follower game and DRO	A distributional robust model is constructed to realize the balance between robustness and economy of the system under the worst distribution, significantly improving the economy of the system through a multi-actor game	[83]
FC, BAT, HFCV	Low-carbon transportation system	Maximize energy efficiency and extend system lifespan	Siberian tiger optimization (STO) and enhanced Wasserstein generative adversarial network (IWGAN)	System performance is optimized over the entire life cycle considering fuel consumption and fuel cell health status	[84]

For operational environments characterized by uncertainty, stochastic or robust optimization methodologies are commonly employed. Stochastic optimization frequently employs

Monte Carlo simulations based on historical data to generate RE output sequences, coupled with autoregressive integrated moving average (ARIMA) models for hydrogen demand

trend forecasting, thereby facilitating the solution process by transforming the stochastic optimization problem into deterministic formulations through scenario reduction techniques. Robust optimization addresses uncertainty by constructing data-driven uncertainty sets and employs C&CG algorithms combined with heuristic methods to identify feasible solutions in the worst scenarios [85]. Its strengths lie in eliminating the need for probability distribution assumptions and exhibiting strong disturbance resistance, though excessive conservatism may compromise economic efficiency. Some studies integrate conditional value-at-risk (CVaR) to develop risk-averse optimization models, balancing economic performance with robustness through adjustable risk preference coefficients.

In highly dynamic environments characterized by intense RE fluctuations and game-theoretic interactions involving multiple agents, where the complexity of optimization models hinders dispatch in real time, DRL offers unique advantages. DRL constructs scheduling policy networks within a framework involving the state, action, and reward, leveraging Q-learning or policy gradient algorithms to autonomously learn coordination rules among multiple devices and derive optimal dispatch strategies.

Academic studies on control strategies for the electricity-hydrogen coupling system encompasses a range of methodologies. In terms of short-term energy balance control, efforts span from the improvement of traditional control strategies to the exploration of advanced innovative ones. Traditional control strategies such as PID control and SMC have been extensively validated in practical applications. Having undergone rigorous technical verification, current studies often focus on optimizing these strategies to further enhance the control performance. Concurrently, there is a growing emphasis on developing more sophisticated control strategies including MPC and adaptive control. These strategies are characterized by their ability to handle complex nonlinear dynamics, pre-

cisely regulate multivariable systems, and adapt to evolving operational conditions. Although still in the early stages of practical implementation, the performance improvements demonstrated by these advanced control strategies in theoretical and simulation studies render them a highly compelling area of research.

In the context of medium-to-long-term optimal dispatch, existing studies operate within a multi-timescale framework ranging from day-ahead to month-ahead scheduling. By matching different scenarios such as deterministic, complex nonlinear, uncertain, and highly dynamic multi-agent scenarios, corresponding methodologies are employed: traditional mathematical programming, heuristic algorithms, stochastic/robust optimization, and deep reinforcement learning. With economic efficiency, flexibility, and reliability as core objectives, the medium- and long-term optimal dispatch incorporates multiple constraints to achieve multi-energy complementarity and optimal resource allocation. Furthermore, progress has been made in addressing key challenges such as equipment degradation modeling and multi-timescale coordination, demonstrating strong scenario adaptability and technical relevance. However, limitations persist, including inadequate integration across timescales, conflicts between model fidelity and solution efficiency, and constraints in handling uncertainties. Future studies should leverage data-driven technologies to characterize model parameters of key operational links in the electricity-hydrogen coupling system, thereby enhancing the rationality of optimized operation and scheduling models and improving the feasibility of related decisions.

IV. TYPICAL APPLICATION SCENARIOS

As depicted in Fig. 4, this section systematically investigates innovative deployment of the electricity-hydrogen coupling system across four representative scenarios, while elucidating their catalytic effects in advancing the energy system transformation.

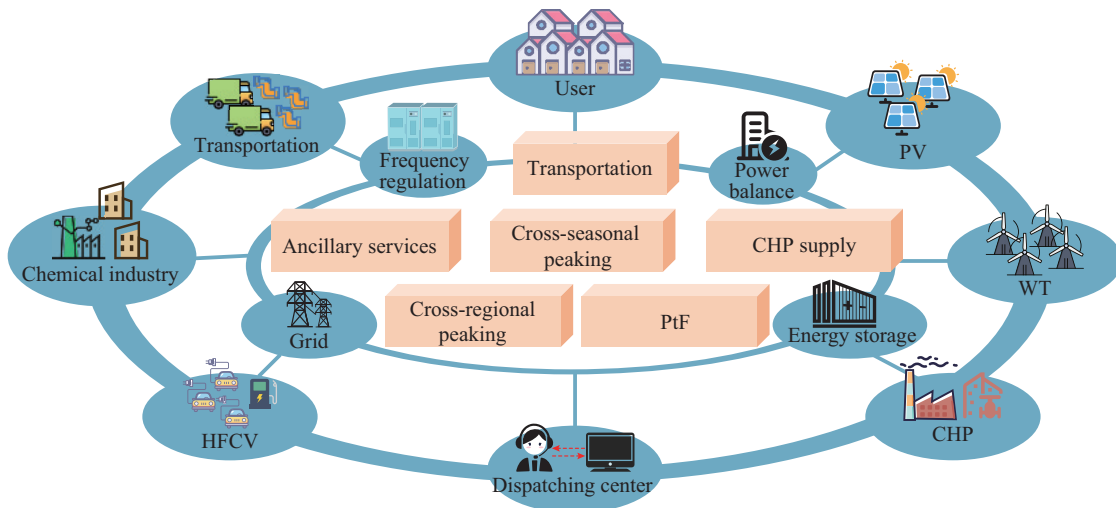


Fig. 4. Innovative deployment of electricity-hydrogen coupling system.

A. Ancillary Services

The high penetration of power electronic devices has led

to reduced system inertia, which in turn results in significant frequency fluctuations and deviations subsequent to distur-

bances. Conventional stability control measures such as reserve capacity provisioning and load shedding are increasingly inadequate to meet the operational requirements of modern power systems. Fuel cells and electrolyzers emerge as critical enablers of ancillary services, enhancing system stability and flexibility while addressing the imperative for integrating the RE. The ancillary services primarily involved are shown in Fig. 5.

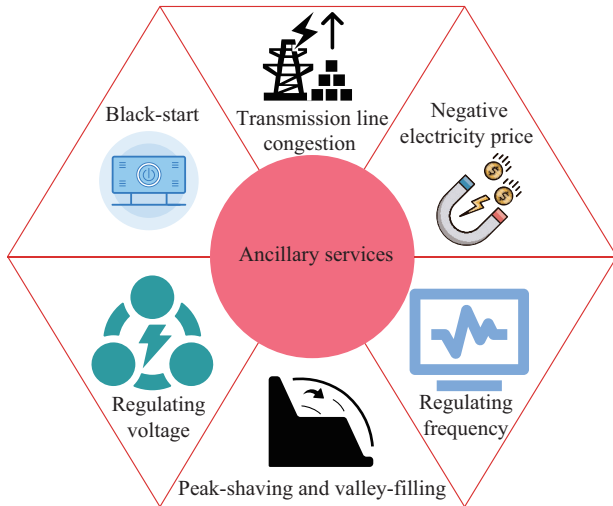


Fig. 5. Illustration of ancillary services.

HES provides a viable solution to mitigate the congestion in transmission and distribution lines stemming from inadequate line capacity [86]. For instance, when WT and PV power outputs exceed the capacity of transmission line, this operational constraint gives rise to electricity market price surges, increased power dispatch costs, and RE curtailment. The electricity-hydrogen coupling system further demonstrates the potential to reduce capital investments in costly new transmission and distribution infrastructure. The negative pricing phenomenon, characterized by market clearing prices falling below zero, primarily stems from imbalances between supply and demand induced by inflexible generation assets. This operational challenge can be mitigated by dynamically adjusting hydrogen production rates of electrolyzers to rapidly elevate the power demand, while complementary reductions in the power output of fuel cell achieve analogous stabilization effects [87].

Frequency regulation, aimed at maintaining the power system frequency near nominal values through coordinated power injection or absorption, benefits from the dynamic energy conversion mechanisms inherent in the electricity-hydrogen coupling system. These mechanisms provide agile and sustained frequency response solutions critical for power systems with high RE penetration, effectively bridging the flexibility gap in modern electricity markets. Reference [88] develops a data-driven model for hydrogen storage system based on dynamic mode decomposition and control theory, establishing a framework for coordinated optimization control at multiple levels to achieve synergistic operation between hydrogen storage units and distributed generation. This model validates the efficacy of fuel cells in mitigating frequency deviations within microgrids through experimental

verification. In Laiwu, Shandong Province, China, a 3.6 MW PEMFC peaking power station has been constructed, which is capable of achieving 0-100% load regulation within 5 min. This milestone has validated the feasibility of PEMFC for application in power system frequency regulation.

The large-scale energy storage capacity, extended duration capabilities, and operational flexibility of hydrogen position it as a transformative solution for voltage regulation, peak-shaving, and valley-filling in RE-dominated power systems. Electricity with low cost during periods of low demand can be stored as hydrogen and dispatched during periods of high demand via fuel cells, enhancing system profitability through peak-valley price arbitrage while addressing renewable intermittency and storage challenges [89]. This dual functionality improves the system stability and facilitates RE integration.

Fuel cells exhibit superior black-start potential compared with conventional diesel generators, primarily due to their rapid power ramping, environmental friendliness, and low noise emissions. Though large-scale implementations remain limited, validations at the laboratory scale and demonstration projects have shown stable power restoration performance during outages. Achieving reliable black-start operations requires optimized capacity allocation between fuel cells and complementary power sources, alongside stringent safety protocols, to ensure the system resilience under extreme contingencies [90]. Fuel cells exhibit rapid start-up characteristics to achieve rated power output within seconds, and demonstrate significant advantages over conventional diesel generators in black-start applications through superior environmental benefits and low noise emissions. Although practical implementations of hydrogen fuel cells in black-start scenarios remain limited, laboratory-scale validations and demonstrations in small-scale power system have yielded promising results [91]. In the demonstration projects, hydrogen fuel cells have been successfully deployed as backup power sources, providing prompt initiation and stable power supply during outages. Given considerations of operational costs and safety requirements, black-start operations using fuel cells enhance the system stability, necessitating strategic capacity coordination between hydrogen fuel cells and complementary power sources to optimize the system restoration efficiency.

In the context of ancillary services, current ancillary service revenues often fail to offset the high capital costs of hydrogen equipment and O&M such as compression and storage, which weakens the motivation of operators to integrate hydrogen systems. Additionally, frequent starting/stopping cycles or large-scale load adjustments of electrolyzers and fuel cells are required to respond to power system frequency or voltage fluctuations, leading to accelerated aging of membrane electrodes and shortened lifespan of equipment.

B. CHP Supply

Fuel cells serve as a primary power source in CHP and CCHP systems to enhance efficiency and cost-effectiveness. Figure 6 shows the structure of the CCHP system [92]. Featuring zero- or low-carbon emissions, such systems substantially reduce reliance on fossil energy, thereby aligning with clean energy supply requirements under China's goals of "carbon emission peak and carbon neutrality". Owing to

their exceptional adaptability, they are particularly suitable for distributed energy scenarios, including industrial parks, commercial complexes, and residential communities. In these scenarios, the flexible adjustment of thermo-electric ratios enables the optimal dynamic load matching and enhances the resilience of energy systems [93]. The advantages in modular design and noise-free operation could minimize the transmission losses while facilitating user-side deployment, synergizing with RE-based hydrogen production to establish a sustainable “electricity-hydrogen-thermal-cooling” circular configuration. This configuration not only eases pressures from peak-shaving on the power system, but also promotes complementarity among multiple forms of energy, providing critical technical support for building power systems with high RE penetration.

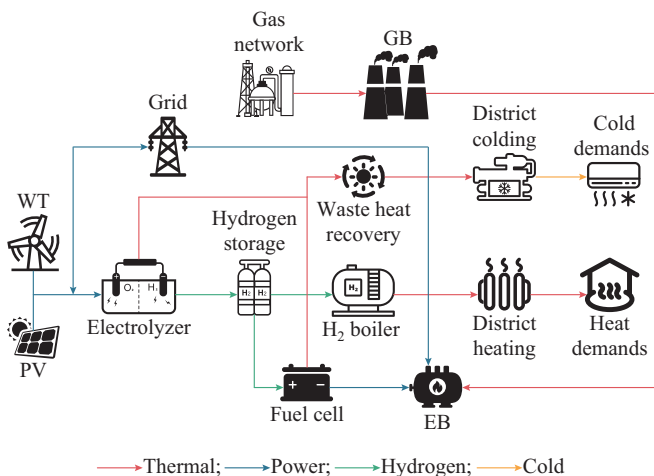


Fig. 6. Structure of CCHP system.

Currently advancing applications in fuel cell cogeneration include numerous demonstration projects globally. Japan leads in small-scale cogeneration units, primarily attributed to its residential distributed hydrogen fuel cell initiative launched in 2001. This program deployed 0.3-1 kW PEMFCs integrated with reformers converting domestic liquefied petroleum gas into hydrogen while utilizing recovered waste heat for water heating. The PEMFCs electrochemically combine hydrogen with ambient oxygen to generate water, simultaneously producing electricity and thermal energy to power households and providing space/water heating, thereby optimizing the energy utilization efficiency [94].

Within the European Union, residential micro-CCHP systems have entered into the stage of commercialization, with over 2500 units installed across 11 member states from 2012 to 2022, demonstrating 60% electrical efficiency and 95% total system efficiency. The Magnum CHP project in the Netherlands first demonstrated that existing GTs can safely operate with 30% hydrogen blending, featuring improved low-load performance and thereby enhancing grid flexibility [95]. These advancements not only enhance the energy efficiency, but also achieve substantial emission reductions.

The development of fuel cell cogeneration in China remains in the research phase, with a primary focus on PEMFC and SOFC technologies [96]. Current limitations stem

primarily from high hydrogen production costs and underdeveloped hydrogen infrastructure. Future progress could capitalize on China’s extensive natural gas pipeline network to develop diversified fuel strategies incorporating hydrogen blending and alternative fuels, thereby accelerating the domestic deployment of fuel cell cogeneration.

C. Transportation

With ongoing technological advancements and cost reductions, HFCVs are anticipated to achieve large-scale commercialization. Currently, HFCVs dominate the commercial vehicle market, including buses, logistics trucks, and heavy-duty trucks. The passenger vehicle sector remains in the validation and pilot demonstration phases. However, multiple provinces in China have implemented policies exempting hydrogen-powered vehicles from expressway tolls, aiming to reduce life cycle costs and enhance market competitiveness. The sales of hydrogen fuel cell vehicles in China reached 5805 units in 2023, with projected annual production exceeding 100000 units by 2025, positioning HFCVs as a vital component of the new energy vehicle market [97], [98].

The electricity-hydrogen coupling system serves as a critical intermediary, facilitating RE absorption while meeting the hydrogen refueling demands for HFCVs. When public grid capacity proves insufficient to meet the load demands of hydrogen fuel cell vehicles, the electricity-hydrogen coupling system enables on-site power generation through hydrogen fuel cells [99]. Conversely, during peak-demand periods of hydrogen, water electrolysis systems are activated for hydrogen production. Continuous advancements in urban infrastructure, particularly hydrogen refueling station deployment, have significantly strengthened the operational synergy between the electricity-hydrogen coupling system and transportation networks. Singapore and Toyota collaborated to launch the first commercial case of hydrogen fuel cell vehicles in Southeast Asia, featuring 70 MPa high-pressure hydrogen refueling stations that enable a single refueling range exceeding 600 km, thereby validating hydrogen storage and transportation safety standards in dense urban environments.

The application of fuel cells in unmanned aerial vehicles (UAVs) represents an emerging research frontier. At the same volume, fuel cells demonstrate superior energy density and are approximately 3.5 times lighter than lithium-ion batteries, thereby enabling a significant extension of UAV flight durations [100]. China has achieved remarkable progress in marine hydrogen fuel cell propulsion systems, exemplified by the successful maiden voyage of the national first demonstration vessel powered by hydrogen, the Three Gorges Hydrogen Vessel 1 in Yichang, Hubei Province, China in 2023. Subsequent demonstration projects including the advanced tourism vessel Xihai Xinyuan 1 and the ferry Lihu Future powered by hydrogen, have further accelerated the adoption of maritime hydrogen technology. The marine market for hydrogen fuel cells is poised for rapid expansion, progressively replacing ships powered by conventional fuel to establish paradigms for green shipping.

Technical challenges in the transportation sector are manifested as follows. Underdeveloped infrastructure such as dedicated pipelines and hydrogen refueling stations results in

high costs of hydrogen storage and transportation. Furthermore, limitations in low-temperature performance, including the proneness of fuel cell stacks to freezing, reduced reaction kinetics, and prolonged start-up times in harsh cold environments, lower the reliability in high-latitude regions and hinder the market penetration.

D. PtF

In terms of hydrogen consumption, ammonia synthesis and methanol synthesis represent the primary downstream hydrogen utilization scenarios, accounting for 32% and 27% of total consumption, respectively [101]. Thus, among chemical sectors dependent on hydrogen, carbon emissions from ammonia and methanol synthesis are most pronounced. Renewable PtF converts electricity into synthetic fuels by leveraging hydrogen produced via renewable-powered water electrolysis and carbon dioxide directly captured from flue gases of power plants, industries, and transportation, as well as biogas from anaerobic digestion. The technical route of PtF is shown in Fig. 7. These synthetic fuels serve as efficient energy carriers, enabling storage, transportation, and application in diverse energy sectors, thereby facilitating large-scale decarbonization in the chemical industry. Moreover, both ammonia and methanol can be stored and transported in liquid phase, which significantly reduces logistics costs while enhancing safety and reliability. This drives the electricity-hydrogen coupling system projects to evolve from green hydrogen toward hydrogen-based derivatives, with ammonia synthesis demonstrating the most rapid growth momentum.

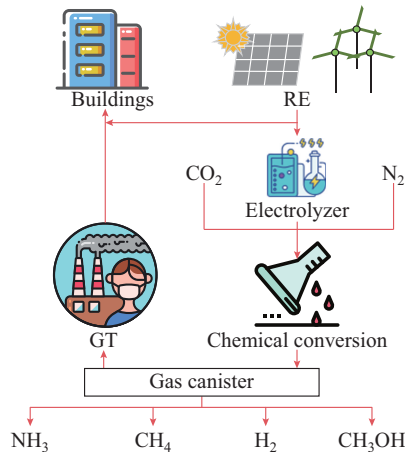


Fig. 7. Technical route of PtF.

Green ammonia and methanol show great potential for decarbonization in the shipping, aviation, and other industries hard for electrification. According to International RE Agency projections, under the 2050 net-zero target, green ammonia is anticipated to constitute 43% of shipping fuel demand, amounting to 183 million tons, which is comparable to the current scale of ammonia synthesis in the chemical industry. Leveraging the mature methanol-to-gasoline technology chain, the methanol can be converted into sustainable aviation fuel that meets aviation standards, thereby facilitating carbon neutrality in the aviation sector.

As an energy conversion paradigm, PtF enables grid bal-

ancing through its adjustable operational flexibility and long-term storage capacity for surplus RE, thus contributing to the potential decarbonization of the energy sector by reducing carbon footprints and greenhouse gas emissions. The ammonia co-firing demonstration project led by Japanese company JERA in coal-fired power plants, which represents the world's first systematic commercial validation of ammonia co-firing technology in thermal power generation, has completed 20% ammonia co-firing trials and plans to achieve 50% co-firing by 2030. This enables green ammonia co-firing to be a primary retrofitting method for coal-fired units. With projected cost reductions in renewable electricity, electrolyzers, and direct air capture of CO₂, the production of synthetic e-fuels demonstrates significant potential for the scaling of PtF.

The key technical bottlenecks of PtF include low synergistic efficiency between carbon capture and hydrogen conversion. The unstable quality and large concentration fluctuations of CO₂ captured from industrial flue gases or direct air capture lead to fluctuations in reaction rates during ammonia/methanol synthesis. Additionally, high energy consumption and costs persist, with the cost of green ammonia/methanol remaining 2-3 times higher than that of fossil-based alternatives, making the commercialization difficult without subsidies.

V. OUTLOOKS

This section summarizes comprehensive outlooks of the electricity-hydrogen coupling system regarding future performance evolution trends, based on analysis of the current status across various domains, as illustrated in Fig. 8.

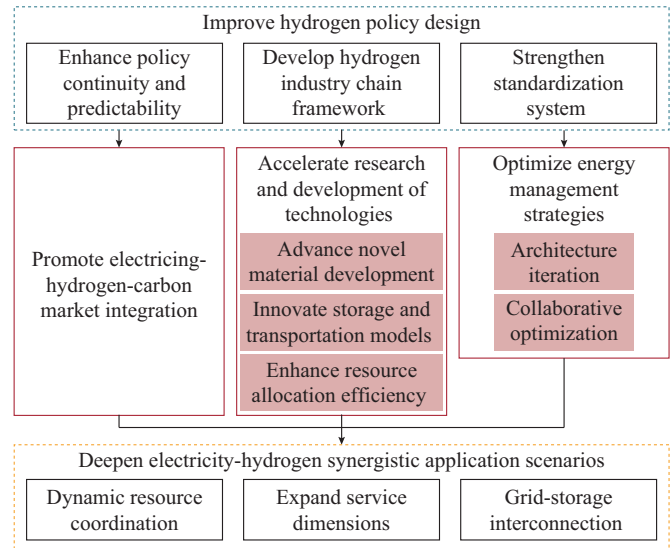


Fig. 8. Outlooks of electricity-hydrogen coupling system.

A. Hydrogen Energy Policy

China's hydrogen energy policies have been progressively advancing since 2002, though early policies have primarily focused on technological research and development. In recent years, with the rapid development of the hydrogen energy industry, policy orientations and industrial positioning

have gradually clarified, yet policy fluctuations remain frequent. As the market scale of hydrogen fuel cell vehicles expands, the industry is constrained by the absence of specialized hydrogen energy policies and the strictness of hazardous chemical regulations in China. This is compounded by insufficient infrastructure such as hydrogen refueling stations, most of which are located in remote suburban areas failing to meet the current development requirements of the industry. Currently, almost all segments of the hydrogen energy industry face the dilemma of “inadequate demand and oversupply”. The uncertainty and variability of policies have influenced decision-making by enterprises and investors, hindering the sustainable and stable development of the hydrogen energy industry.

The hydrogen energy industry suffers from uncoordinated policy guidance and insufficient resource support for hydrogen production. The lack of systematic and synergistic methods in promoting industry development has led to uneven resource allocation and waste. Current hotspots in hydrogen energy development are mostly in the stage of exploration led by the government, with severe homogenization in industrial planning across regions. Additionally, the industrial chain for hydrogen energy is long and has multiple levels, with poor coordination between regions and among links in the industrial chain, making it difficult to form a cohesive driving force.

Furthermore, the lagging standardization system exacerbates uncertainties in technological pathways. The absence of unified specifications for voltage and power ratings at the interface between electrolyzers and fuel cells forces the design of power electronic converters to reserve redundant functional modules, increasing the equipment costs.

In the future, it is necessary to continue exploration based on realities in China. The common challenges faced by the hydrogen energy industry development in pioneer cities should be sorted out to improve institutional design at the national level, provide effective policy guidance, and comprehensively promote the implementation of the national hydrogen energy strategy.

B. Accelerating Research and Development of Key Technologies

Due to the late start in China’s hydrogen energy development and insufficient advancement in key technologies, equipment, and materials, the comprehensive cost of hydrogen energy storage remains high. Specifically, the production cost of green hydrogen is approximately 32.03 ¥/kg, which is higher than that of gray and blue hydrogen (both blue hydrogen and gray hydrogen are derived from fossil fuels, but blue hydrogen production incorporates carbon capture and storage, resulting in significantly reduced carbon emissions compared with the conventional gray hydrogen production process). In contrast, the costs of hydrogen production via coal combustion and natural gas combustion, which are technologies with large-scale application, are only 9.73 ¥/kg and 14.61 ¥/kg, respectively. Thus, it is essential to enhance the innovation in efficient hydrogen production, utilization, storage, and transportation to reduce green hydrogen costs and foster the hydrogen energy market.

Enhancing energy conversion efficiency in electrolyzers

and fuel cells remains the critical technological frontier. While current PEMELs have achieved single-stack power outputs exceeding 5 MW, they still retain an efficiency improvement potential of over 20% relative to theoretical limits. Breakthroughs in novel electrode materials and innovative membrane electrode assembly fabrication techniques are expected to drive the reduction of specific electricity consumption from the current 4.5 kWh/(N·m³) to 3.8 kWh/(N·m³) for hydrogen production. Concurrently, advancements in material stability for solid oxide electrolyzers under high-temperature operation could enable thermo-electrochemical synergistic conversion efficiencies surpassing 90% through optimized heat-electricity-hydrogen integration mechanisms.

The development of power electronic converters must move towards adaptability to a broad range of voltages and high-frequency operations. Energy routers with multiple ports based on silicon carbide (SiC) will enable dynamic matching between fluctuating power sources from WT/PV and electrolyzers through advanced topologies for power regulation.

The technological pathways for hydrogen storage and transportation are projected to achieve diversified milestones: cryogenic liquid hydrogen storage density exceeding 70 g/L, cost reduction reaching 40% for Type IV 70 MPa composite hydrogen storage vessels, and hydrogen blending ratios surpassing 20% in natural gas pipeline networks. These coordinated advancements in material science and system integration will fundamentally reconfigure the spatial distribution patterns and economic models of hydrogen supply chains through synergistic optimization of energy density, infrastructure compatibility, and transmission efficiency.

C. Deepening Electricity-hydrogen Synergistic Application Scenarios

The coupling of electricity and hydrogen is poised to transcend the spatiotemporal constraints of conventional energy systems, establishing new architectures for complementarity among multiple forms of energy. With ongoing validation of hydrogen production, storage, and power generation systems on a scale of hundreds of megawatts, the inherent advantages of hydrogen as an energy storage medium across seasons will be fully realized. This particularly holds true in regions with seasonal mismatches in RE resources, where storing hydrogen could raise annual utilization rates of RE by 15%-25%, as shown in Supplementary Material A Figs. A8 and A9.

In ancillary services, by leveraging the rapid frequency regulation capabilities of hydrogen storage and load modulation characteristics of electrolyzers, the electricity-hydrogen coupling system is anticipated to deliver diversified services including inertia support and peak-shaving, achieving millisecond-level response speeds with 3-5 times larger regulation capacity compared with pumped hydro storage. Intelligent upgrades of CCHP systems promise to elevate cascading energy utilization efficiency beyond 75%, while the integration of hydrogen fuel cell based distributed energy systems with critical infrastructure such as data centers and 5G base stations will give rise to novel forms of energy microgrid.

The integration of cyber and physical systems for hydrogen transportation infrastructure with power networks will generate synergistic optimization effects through the mechanisms coordinating bidirectional energy flows. Hydrogen refueling stations, functioning as distributed energy storage nodes, are currently undergoing pilot validation of technical pathways for participating in electricity spot market transactions via advanced power electronic interface systems. The extension of vehicle-to-grid (V2G) interaction paradigms to hydrogen energy carriers will create innovative mobile energy storage scenarios, where onboard hydrogen storage systems and characteristics of fuel cell vehicles enable the dynamic provisioning of services.

D. Promoting Development of Electricity-hydrogen-carbon Market Trading

Institutional innovation and development of market mechanism will emerge as pivotal determinants for scaling the electricity-hydrogen coupling system. This necessitates establishment of a comprehensive regulatory framework spanning the entire hydrogen value chain, encompassing the integration of green hydrogen into RE quota compliance system, formulating concessions across regions for hydrogen pipeline networks, and refining future trading protocols for hydrogen commodities.

Deep coupling between electricity and hydrogen markets requires overcoming institutional barriers through innovative mechanisms such as premium transmission frameworks for RE-powered hydrogen production, enabling hydrogen producers to obtain environmental attribute certificates via green power purchasing agreements. Critical focus must be directed towards mechanism design linking the carbon and hydrogen markets, particularly establishing life cycle assessment based hydrogen certification systems to facilitate value migration from gray to blue/green hydrogen through carbon intensity differentiation.

The price formation mechanism should establish hydrogen pricing models that capture spatiotemporal value differentials, enabling cross-regional value transfer between production hubs and consumption centers through locational marginal pricing frameworks. To achieve this, it is required to develop a coordinated trading platform for electricity, hydrogen, and carbon, equipped with derivative instruments such as capacity leasing and ancillary service contracts, to create a market architecture with multiple tiers. Such institutional innovations demand technological empowerment through digital twins and blockchain infrastructures, where smart contracts automate green hydrogen traceability, carbon footprint tracking, and settlement processes.

E. Breaking Through Limitations of Operational Control Strategies

The development of collaborative architectures featuring coupling in both directions and dynamic iteration requires models for mapping information across scales. These models continuously integrate real-time operational data into planning cycles for each month through interfaces connecting the cyber and physical systems. Game theory methods could be implemented by conceptualizing multi-timescale optimization

challenges as interactive participants with heterogeneous information sets, achieving objective coordination through Nash equilibrium solutions or cooperative bargaining mechanisms. Advanced multi-objective optimization methodologies should incorporate Pareto frontier exploration algorithms within the integrated month-ahead, day-ahead, and real-time decision spaces to identify non-dominated solution sets.

Modular hardware platforms developed through collaboration between industry and academia could leverage the technology for power hardware-in-the-loop to create testing environments that can be reconfigured. This architecture enables seamless integration of physical components for electricity and hydrogen with virtual power systems, supporting emulation of scenarios across multiple scales that range from simulations of fluctuations in RE generation to validation of strategies for controlling electrolyzer arrays.

VI. CONCLUSION

The electricity-hydrogen coupling system, as a critical technological pathway for achieving China's goals of "carbon emission peak and carbon neutrality", enables synergistic energy conversion and complementary utilization between electricity and hydrogen. The electricity-hydrogen coupling system effectively addresses critical challenges, including high RE penetration, spatiotemporal energy distribution, and cross-sectoral deep decarbonization, providing strategic solutions for constructing clean, low-carbon, secure, and efficient modern energy systems. Within this context, this paper conducts a comprehensive analysis of current research progress in system architectures and core technologies. Technological breakthroughs in water electrolysis systems and fuel cell power generation technologies have significantly enhanced the system efficiency, while diversified developments in technologies for storing and transporting hydrogen establish physical foundations for the energy storage between seasons and mutual energy support across regions. This paper further summarizes operational control strategies across multiple temporal scales, spanning from short-term energy balance control to medium-to-long-term optimal dispatch. Based on these analyses, this paper explores and summarizes various application scenarios of the electricity-hydrogen coupling system, revealing new developmental opportunities for advancement and demonstration projects. This paper identifies current challenges and proposes future research directions focusing on core technologies, application scenarios, and market transaction mechanisms, aiming to provide valuable insights for the large-scale deployment of the electricity-hydrogen coupling system.

REFERENCES

- [1] M. Markovic, A. Sajadi, A. Florita *et al.*, "Voltage estimation in low voltage distribution grids with distributed energy resources," *IEEE Transactions on Sustainable Energy*, vol. 12, no. 3, pp. 1640-1650, Jul. 2021.
- [2] C. Kang and L. Yao, "Key scientific issues and theoretical research framework for power systems with high proportion of renewable energy," *Automation of Electric Power Systems*, vol. 41, no. 9, pp. 1-11, May 2017.
- [3] D. Song, W. Meng, M. Dong *et al.*, "A critical survey of integrated energy system: Summaries, methodologies and analysis," *Energy Conver-*

- sion and Management*, vol. 266, p. 115863, Aug. 2022.
- [4] B. Pan, X. Yin, Y. Ju *et al.*, "Underground hydrogen storage: influencing parameters and future outlook," *Advances in Colloid and Interface Science*, vol. 294, p. 102473, Aug. 2017.
 - [5] W. Kong, K. Sun, and J. Zhao, "Two-stage optimal scheduling of community integrated energy system considering operation sequences of hydrogen energy storage systems," *Journal of Modern Power Systems and Clean Energy*, vol. 13, no. 1, pp. 276-288, Jan. 2024.
 - [6] J. O. Abe, A. P. I. Popoola, E. Ajenifuja *et al.*, "Hydrogen energy, economy and storage: review and recommendation," *International Journal of Hydrogen Energy*, vol. 44, no. 29, pp. 15072-15086, Jun. 2019.
 - [7] Y. Li, Y. Wang, R. Zhou *et al.*, "Energy transition roadmap towards net-zero communities: a case study in Japan," *Sustainable Cities and Society*, vol. 100, p. 105045, Jun. 2024.
 - [8] Z. Chen, Z. H. Li, D. Lin *et al.*, "Multi-time-scale optimal scheduling of integrated energy system with electric-thermal-hydrogen hybrid energy storage under wind and solar uncertainties," *Journal of Modern Power Systems and Clean Energy*, vol. 13, no. 1, pp. 276-288, Jan. 2025.
 - [9] F. Yang, X. Yang, and X. Li, "China's diverse energy transition pathways toward carbon neutrality by 2060," *Sustainable Production and Consumption*, vol. 47, pp. 236-250, Jun. 2024.
 - [10] B. Bergougui, S. M. Murshed, M. Shahbaz *et al.*, "Towards secure energy systems: examining asymmetric impact of energy transition," *Environmental Technology and Digitalization on Chinese City-level Energy Security*, vol. 238, p. 121883, Jun. 2025.
 - [11] Y. Sun, R. Du, and H. Chen, "Energy transition and policy perception acuity: an analysis of 335 high-energy-consuming enterprises in China," *Applied Energy*, vol. 377, p. 124627, Jun. 2025.
 - [12] H. Ishaq, I. Dincer, and C. Crawford, "A review on hydrogen production and utilization: challenges and opportunities," *International Journal of Hydrogen Energy*, vol. 47, no. 62, pp. 26238-26264, Jul. 2019.
 - [13] F. Dawood, M. Anda, and G. M. Shafiqullah, "Hydrogen production for energy: an overview," *International Journal of Hydrogen Energy*, vol. 45, no. 7, pp. 3847-3869, Feb. 2020.
 - [14] M. G. Rasul, M. A. Hazrat, M. A. Sattar *et al.*, "The future of hydrogen: challenges on production, storage and applications," *Energy Conversion and Management*, vol. 272, p. 116326, Nov. 2022.
 - [15] Z. Abidin, A. Zafaranloo, A. Rafiee *et al.*, "Hydrogen as an energy vector," *Renewable and Sustainable Energy Reviews*, vol. 120, p. 109620, Mar. 2020.
 - [16] G. Pan, W. Gu, H. Zhang *et al.*, "Electricity and hydrogen energy system towards accommodation of high proportion of renewable energy," *Automation of Electric Power Systems*, vol. 44, no. 23, pp. 1-10, Dec. 2020.
 - [17] T. S. Babu, K. R. Vasudevan, V. K. Ramachandramurthy *et al.*, "A comprehensive review of hybrid energy storage systems: converter topologies, control strategies and future prospects," *IEEE Access*, vol. 8, pp. 148702-148721, Aug. 2020.
 - [18] A. Mohammadi and M. Mehrpooya, "A comprehensive review on coupling different types of electrolyzer to renewable energy sources," *Energy*, vol. 158, pp. 632-655, Sept. 2018.
 - [19] X. Zhang, W. Pei, C. Mei *et al.*, "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," *International Journal of Electrical Power & Energy Systems*, vol. 136, p. 107684, Mar. 2022.
 - [20] S. A. Grigoriev, V. N. Fateev, D. G. Bessarabov *et al.*, "Current status, research trends, and challenges in water electrolysis science and technology," *International Journal of Hydrogen Energy*, vol. 45, no. 49, pp. 26036-26058, Oct. 2020.
 - [21] J. Shair, H. Li, J. Hu *et al.*, "Power system stability issues, classifications and research prospects in the context of high-penetration of renewables and power electronics," *Renewable and Sustainable Energy Reviews*, vol. 145, p. 111111, Jul. 2021.
 - [22] P. Liu and X. Han, "Comparative analysis on similarities and differences of hydrogen energy development in the world's top 4 largest economies: a novel framework," *International Journal of Hydrogen Energy*, vol. 47, no. 16, p. 9485-9503, Feb. 2022.
 - [23] T. Egeland-Eriksen, A. Hajizadeh, and S. Sartori, "Hydrogen-based systems for integration of renewable energy in power systems: Achievements and perspectives," *International Journal of Hydrogen Energy*, vol. 46, no. 63, pp. 31963-31983, Sept. 2021.
 - [24] C. Gunathilake, I. Soliman, D. Panthi *et al.*, "A comprehensive review on hydrogen production, storage, and applications," *Chemical Society Reviews*, vol. 53, no. 22, pp. 10900-10969, Oct. 2024.
 - [25] Y. Li, X. Shi, and H. Phoumin, "A strategic roadmap for large-scale green hydrogen demonstration and commercialisation in China: a review and survey analysis," *International Journal of Hydrogen Energy*, vol. 47, no. 58, pp. 24592-24609, Jul. 2022.
 - [26] S. A. Grigoriev, V. N. Fateev, D. G. Bessarabov *et al.*, "Current status, research trends, and challenges in water electrolysis science and technology," *International Journal of Hydrogen Energy*, vol. 45, no. 49, pp. 26036-26058, Oct. 2020.
 - [27] J. Chi and H. Yu, "Water electrolysis based on renewable energy for hydrogen production," *Chinese Journal of Catalysis*, vol. 39, no. 3, pp. 390-394, Mar. 2018.
 - [28] H. Zhao and Z. Yuan, "Progress and perspectives for solar-driven water electrolysis to produce green hydrogen," *Advanced Energy Materials*, vol. 13, no. 16, p. 2300254, Apr. 2023.
 - [29] H. Lange, A. Klose, W. Lippmann *et al.*, "Technical evaluation of the flexibility of water electrolysis systems to increase energy flexibility: a review," *International Journal of Hydrogen Energy*, vol. 48, no. 42, pp. 15771-15783, May 2023.
 - [30] M. K. Singla, P. Nijhawan, and A. S. Oberoi, "Hydrogen fuel and fuel cell technology for cleaner future: a review," *Environmental Science and Pollution Research*, vol. 28, no. 13, pp. 15607-15626, Feb. 2021.
 - [31] L. Fan, Z. Tu, and S. Chan, "Recent development of hydrogen and fuel cell technologies: a review," *Energy Reports*, vol. 7, pp. 8421-8446, Nov. 2021.
 - [32] V. Cigolotti, M. Genovese, and P. Fragiaco, "Comprehensive review on fuel cell technology for stationary applications as sustainable and efficient poly-generation energy systems," *Energies*, vol. 14, no. 16, p. 4963, Aug. 2021.
 - [33] X. Xu, M. Zhu, S. Wu *et al.*, "Investigation of mechanical vibration effect on proton exchange membrane fuel cell cold start," *International Journal of Hydrogen Energy*, vol. 45, pp. 14528-14538, May 2020.
 - [34] M. Liu, Q. Li, T. Wang *et al.*, "Power adaptive allocation method for multi-stack fuel cell power generation system considering the stacks operation performance," *Proceedings of the CSEE*, vol. 39, no. 22, pp. 6666-6677, Nov. 2019.
 - [35] S. Bosu and N. Rajamohan, "Recent advancements in hydrogen storage – comparative review on methods, operating conditions and challenges," *International Journal of Hydrogen Energy*, vol. 52, pp. 352-370, Jan. 2024.
 - [36] P. Muthukumar, A. Kumar, M. Afzal *et al.*, "Review on large-scale hydrogen storage systems for better sustainability," *International Journal of Hydrogen Energy*, vol. 48, no. 85, pp. 33223-33259, Oct. 2023.
 - [37] I. A. Hassan, H. S. Ramadan, M. A. Saleh *et al.*, "Hydrogen storage technologies for stationary and mobile applications: review, analysis and perspectives," *Renewable and Sustainable Energy Reviews*, vol. 149, p. 111311, Oct. 2021.
 - [38] G. Rohit, M. S. Santosh, M. N. Kumar *et al.*, "Numerical investigation on structural stability and explicit performance of high-pressure hydrogen storage cylinders," *International Journal of Hydrogen Energy*, vol. 48, no. 14, pp. 5565-5575, Feb. 2023.
 - [39] I. Rossetti, A. Tripodi, M. Tommasi *et al.*, "Conceptual design of a process for hydrogen production from waste biomass and its storage in form of liquid ammonia," *International Journal of Hydrogen Energy*, vol. 48, no. 96, pp. 37443-37460, Dec. 2023.
 - [40] A. Raza, M. Arif, G. Glatz *et al.*, "A holistic overview of underground hydrogen storage: influencing factors, current understanding, and outlook," *Fuel*, vol. 330, p. 125636, Dec. 2022.
 - [41] F. Wu, R. Gao, C. Li *et al.*, "A comprehensive evaluation of wind-PV-salt cavern-hydrogen energy storage and utilization system: a case study in Qianjiang salt cavern, China," *Energy Conversion and Management*, vol. 277, p. 116633, Feb. 2023.
 - [42] Y. Wang, H. Dai, Z. Chen *et al.*, "Simulation study on a novel solid-gas coupling hydrogen storage method for photovoltaic hydrogen production systems," *Energy Conversion and Management*, vol. 299, p. 117866, Jan. 2024.
 - [43] Z. Abidin, C. Tang, Y. Liu *et al.*, "Large-scale stationary hydrogen storage via liquid organic hydrogen carriers," *iScience*, vol. 24, no. 9, p. 102966, Sept. 2021.
 - [44] N. Yu, W. Duan, and X. Fan, "Hydrogen-fueled microgrid energy management: nvel EMS approach for efficiency and reliability," *International Journal of Hydrogen Energy*, vol. 80, pp. 1466-1476, Aug. 2024.
 - [45] S. Klyapovskiy, Y. Zheng, S. You *et al.*, "Optimal operation of the hydrogen-based energy management system with P2X demand response and ammonia plant," *Applied Energy*, vol. 304, p. 117559, Dec. 2021.
 - [46] A. M. Abomazid, N. A. El-Taweel, and H. E. Z. Farag, "Optimal energy management of hydrogen energy facility using integrated battery energy storage and solar photovoltaic systems," *IEEE Transactions on*

- Sustainable Energy*, vol. 13, no. 3, pp. 1457-1468, Mar. 2022.
- [47] R. Qi, J. Li, J. Lin *et al.*, "Thermal modeling and controller design of an alkaline electrolysis system under dynamic operating conditions," *Applied Energy*, vol. 332, p. 120551, Feb. 2023.
- [48] V. Khaligh, A. Ghezalbashi, M. Zarei *et al.*, "Efficient integration of alkaline water electrolyzer – a model predictive control approach for a sustainable low-carbon district heating system," *Energy conversion and management*, vol. 292, p. 117404, Sept. 2023.
- [49] C. Zhu, H. Xu, L. Gu *et al.*, "Adaptive coordination control based on alkaline water electrolyzers and battery driven by wind power," *Journal of Physics: Conference Series*, vol. 2567, no. 1, p. 012006, Aug. 2023.
- [50] J. G. G. Clúa, H. de Battista, and R. J. Mantz, "Control of a grid-assisted wind-powered hydrogen production system," *International Journal of Hydrogen Energy*, vol. 35, no. 11, pp. 5786-5792, Jun. 2010.
- [51] W. Han, C. Zou, C. Zhou *et al.*, "Estimation of cell SOC evolution and system performance in module-based battery charge equalization systems," *IEEE Transactions on Smart Grid*, vol. 10, no. 5, pp. 4717-4728, Aug. 2019.
- [52] A. Behzadi and S. Sadrizadeh, "A rule-based energy management strategy for a low-temperature solar/wind-driven heating system optimized by the machine learning-assisted grey wolf approach," *Energy Conversion and Management*, vol. 277, p. 116590, Feb. 2023.
- [53] X. Zhao, L. Wang, Y. Zhou *et al.*, "Energy management strategies for fuel cell hybrid electric vehicles: classification, comparison, and outlook," *Energy Conversion and Management*, vol. 270, p. 116179, Oct. 2022.
- [54] Y. Han, W. Chen, Q. Li *et al.*, "Two-level energy management strategy for PV-Fuel cell-battery-based DC microgrid," *International Journal of Hydrogen Energy*, vol. 44, no. 35, pp. 19395-19404, Jul. 2019.
- [55] R. Zahedi and M. M. Ardehali, "Power management for storage mechanisms including battery, supercapacitor, and hydrogen of autonomous hybrid green power system utilizing multiple optimally-designed fuzzy logic controllers," *Energy*, vol. 204, p. 117935, Aug. 2020.
- [56] F. Ramadhani, M. A. Hussain, H. Mokhlis *et al.*, "Two-stage fuzzy-logic-based for optimal energy management strategy for SOFC/PV/TEG hybrid polygeneration system with electric charging and hydrogen fueling stations," *Journal of Renewable and Sustainable Energy*, vol. 13, p. 024301, Mar. 2021.
- [57] L. Bo, L. Han, C. Xiang *et al.*, "A Q-learning fuzzy inference system based online energy management strategy for off-road hybrid electric vehicles," *Energy*, vol. 252, p. 123976, Aug. 2022.
- [58] L. Valverde, F. Rosa, and C. Bordons, "Design, planning and management of a hydrogen-based microgrid," *IEEE Transactions on Industrial Informatics*, vol. 9, no. 3, pp. 1398-1404, Feb. 2013.
- [59] A. Maroufmashat, M. Fowler, S. S. Khavas *et al.*, "Mixed integer linear programming based approach for optimal planning and operation of a smart urban energy network to support the hydrogen economy," *International Journal of Hydrogen Energy*, vol. 41, no. 19, pp. 7700-7716, May 2016.
- [60] J. Zhang, C. Li, G. Chen *et al.*, "Planning of hydrogen refueling stations in urban setting while considering hydrogen redistribution," *IEEE Transactions on Industry Applications*, vol. 58, no. 2, pp. 2898-2908, Oct. 2021.
- [61] M. Arfan, O. Eriksson, Z. Wang *et al.*, "Life cycle assessment and life cycle costing of hydrogen production from biowaste and biomass in Sweden," *Energy Conversion and Management*, vol. 291, p. 117262, Sept. 2023.
- [62] X. Shi, Y. Qian, and S. Yang, "Fluctuation analysis of a complementary wind-solar energy system and integration for large scale hydrogen production," *ACS Sustainable Chemistry & Engineering*, vol. 8, no. 18, pp. 7097-7110, Apr. 2020.
- [63] F. Suleman, I. Dincer, and M. Agelin-Chaab, "Comparative impact assessment study of various hydrogen production methods in terms of emissions," *International Journal of Hydrogen Energy*, vol. 41, no. 19, pp. 8364-8375, May 2016.
- [64] Y. Zhao, J. Lin, Y. Song *et al.*, "A hierarchical strategy for restorative self-healing of hydrogen-penetrated distribution systems considering energy sharing via mobile resources," *IEEE Transactions on Power Systems*, vol. 38, no. 2, pp. 1388-1404, May 2022.
- [65] Y. Yang, X. Xu, Y. Luo *et al.*, "Distributionally robust planning method for expressway hydrogen refueling station powered by a wind-PV system," *Renewable Energy*, vol. 225, p. 120210, May 2024.
- [66] H. Li, C. Wang, S. Yuan *et al.*, "Energy scheduling of hydrogen hybrid UAV based on model predictive control and deep deterministic policy gradient algorithm," *Algorithms*, vol. 18, no. 2, p. 80, Feb. 2025.
- [67] H. Guo, D. Gong, L. Zhang *et al.*, "Hierarchical game for low-carbon energy and transportation systems under dynamic hydrogen pricing," *IEEE Transactions on Industrial Informatics*, vol. 19, no. 2, pp. 2008-2018, Jul. 2022.
- [68] Y. Yuan, T. Ding, X. Chang *et al.*, "A distributed multi-objective optimization method for scheduling of integrated electricity and hydrogen systems," *Applied Energy*, vol. 355, p. 122287, Feb. 2024.
- [69] X. Guo, A. M. Abed, M. A. Alghassab *et al.*, "Development of a geo-thermal-driven multi-output scheme for electricity, cooling, and hydrogen production: techno-economic assessment and genetic algorithm-based optimization," *Case Studies in Thermal Engineering*, vol. 63, p. 105228, Nov. 2024.
- [70] J. Wang, J. Wen, J. Wang *et al.*, "Water electrolyzer operation scheduling for green hydrogen production: a review," *Renewable and Sustainable Energy Reviews*, vol. 203, p. 114779, Oct. 2024.
- [71] S. Wang, S. Wang, Q. Zhao *et al.*, "Optimal dispatch of integrated energy station considering carbon capture and hydrogen demand," *Energy*, vol. 269, p. 126981, Apr. 2023.
- [72] S. W. Sharshir, A. Joseph, M. M. Elsayad *et al.*, "A review of recent advances in alkaline electrolyzer for green hydrogen production: performance improvement and applications," *International Journal of Hydrogen Energy*, vol. 49, pp. 458-488, Jan. 2024.
- [73] Y. Zhou, S. Chen, and J. Chen, "A comprehensive survey of low-carbon planning and operation of electricity, hydrogen fuel, and transportation networks," *IET Energy Systems Integration*, vol. 6, no. 2, pp. 89-103, Jun. 2024.
- [74] F. A. Sarwar, I. Hernando-Gil, and I. Vechiu, "Review of energy management systems and optimization methods for hydrogen-based hybrid building microgrids," *Energy Conversion and Economics*, vol. 5, no. 4, pp. 259-279, Aug. 2024.
- [75] B. Modu, M. P. Abdullah, A. L. Bukar *et al.*, "A systematic review of hybrid renewable energy systems with hydrogen storage: sizing, optimization, and energy management strategy," *International Journal of Hydrogen Energy*, vol. 48, no. 97, pp. 38354-38373, Dec. 2023.
- [76] N. Thakkar and P. Paliwal, "Hydrogen storage based micro-grid: a comprehensive review on technology, energy management and planning techniques," *International Journal of Green Energy*, vol. 20, no. 4, pp. 445-463, Mar. 2022.
- [77] X. Liu, L. Zu, Z. Wei *et al.*, "Two-layer optimal scheduling of integrated electric-hydrogen energy system with seasonal energy storage," *International Journal of Hydrogen Energy*, vol. 82, pp. 1131-1145, Sept. 2024.
- [78] J. Liu, X. Meng, and J. Wu, "Data-driven optimal scheduling for integrated electricity-heat-gas-hydrogen energy system considering demand-side management: a deep reinforcement learning approach," *International Journal of Hydrogen Energy*, vol. 103, pp. 147-165, Feb. 2025.
- [79] Z. Wang, P. Liao, S. Liu *et al.*, "Scenario-based energy management optimization of hydrogen-electric-thermal systems in sustainable ship," *International Journal of Hydrogen Energy*, vol. 99, pp. 566-578, Jan. 2025.
- [80] B. Yu, G. Fan, K. Sun *et al.*, "Adaptive energy optimization strategy of island renewable power-to-hydrogen system with hybrid electrolyzers structure," *Energy*, vol. 301, pp. 131508, Aug. 2024.
- [81] Y. Qiu, Y. Li, W. Ai *et al.*, "Two-stage distributionally robust optimization-based coordinated scheduling of integrated energy system with electricity-hydrogen hybrid energy storage," *Protection and Control of Modern Power Systems*, vol. 8, no. 2, pp. 1-14, Apr. 2023.
- [82] X. Wang, X. Meng, G. Nie *et al.*, "Optimization of hydrogen production in multi-Electrolyzer systems: a novel control strategy for enhanced renewable energy utilization and electrolyzer lifespan," *Applied Energy*, vol. 376, no. 2, p. 124299, Dec. 2024.
- [83] Z. Tong, Z. Ren, J. Wu *et al.*, "Multi-agent game operation of electricity-hydrogen-transportation system considering hydrogen refueling uncertainty of hydrogen fuel cell vehicles," *Automation of Electric Power Systems*, vol. 49, no. 2, pp. 154-164, Jan. 2025.
- [84] D. Viji, S. J. Dhanka, M. B. Thomas *et al.*, "Hybrid STO-IWGAN method based energy optimization in fuel cell electric vehicles," *Energy Conversion and Management*, vol. 305, p. 118249, Apr. 2024.
- [85] F. Marzbani and A. Abdelfatah, "Economic dispatch optimization strategies and problem formulation: a comprehensive review," *Energies*, vol. 17, no. 3, pp. 550, Jan. 2024.
- [86] L. Bird, D. Lew, M. Milligan *et al.*, "Wind and solar energy curtailment: a review of international experience," *Renewable and Sustainable Energy Reviews*, vol. 65, pp. 577-586, Nov. 2016.
- [87] J. Alpizar-Castillo, L. Ramirez-Elizondo, and P. Bauer, "Assessing the role of energy storage in multiple energy carriers toward providing an-

- cillary services: a review,” *Energies*, vol. 16, no. 1, p. 379, Dec. 2022.
- [88] G. H. Lee, J. Y. Park, J. Ban *et al.*, “Data-driven modeling and optimal control of hydrogen energy storage for frequency regulation,” *IEEE Transactions on Energy Conversion*, vol. 38, no. 2, pp. 1231-1245, Nov. 2022.
- [89] P. M. Falcone, M. Hiete, and A. Sapio, “Hydrogen economy and sustainable development goals: review and policy insights,” *Current Opinion in Green and Sustainable Chemistry*, vol. 31, p. 100506, Oct. 2021.
- [90] I. Staffell, D. Scamman, A. V. Abad *et al.*, “The role of hydrogen and fuel cells in the global energy system,” *Energy & Environmental Science*, vol. 12, no. 2, pp. 463-491, Dec. 2019.
- [91] P. D. Lund, J. Lindgren, J. Mikkola *et al.*, “Review of energy system flexibility measures to enable high levels of variable renewable electricity,” *Renewable and Sustainable Energy Reviews*, vol. 45, pp. 785-807, May 2015.
- [92] O. Erixno, N. A. Rahim, F. Ramadhani *et al.*, “Energy management of renewable energy-based combined heat and power systems: a review,” *Sustainable Energy Technologies and Assessments*, vol. 51, p. 101944, Jun. 2022.
- [93] H. Zhou, J. Xue, H. Gao *et al.*, “Hydrogen-fueled gas turbines in future energy system,” *International Journal of Hydrogen Energy*, vol. 64, pp. 569-582, Apr. 2024.
- [94] D. Parra, L. Valverde, F. J. Pino *et al.*, “A review on the role, cost and value of hydrogen energy systems for deep decarbonization,” *Renewable and Sustainable Energy Reviews*, vol. 101, pp. 279-294, Mar. 2019.
- [95] Y. Zhou, “Low-carbon transition in smart city with sustainable airport energy ecosystems and hydrogen-based renewable-grid-storage-flexibility,” *Energy Reviews*, vol. 1, no. 1, p. 100001, Sept. 2022.
- [96] N. S. Ganesh and M. Omprakash, “Comprehensive review on cogeneration systems for low and medium temperature heat recoveries,” *Energy Sources Part A: Recovery, Utilization, and Environmental Effects*, vol. 44, no. 3, pp. 6404-6432, Jul. 2022.
- [97] Y. Tao, J. Qiu, S. Lai *et al.*, “Collaborative planning for electricity distribution network and transportation system considering hydrogen fuel cell vehicles,” *IEEE Transactions on Transportation Electrification*, vol. 6, no. 3, pp. 1211-1225, May 2020.
- [98] G. Sun, G. Li, P. Li *et al.*, “Coordinated operation of hydrogen-integrated urban transportation and power distribution networks considering fuel cell electric vehicles,” *IEEE Transactions on Industry Applications*, vol. 58, no. 2, pp. 2652-2665, Sept. 2021.
- [99] S. Lü, Z. Wei, G. Sun *et al.*, “Optimal power and semi dynamic traffic flow in urban electrified transportation networks,” *IEEE Transactions Smart Grid*, vol. 11, no. 3, pp. 1854-1865, May 2020.
- [100] W. Wei, S. Mei, L. Wu *et al.*, “Optimal traffic power flow in urban electrified transportation networks,” *IEEE Transactions Smart Grid*, vol. 8, no. 1, pp. 84-95, Jan. 2017.
- [101] J. Kurtz, S. Sprik, and T. H. Bradley, “Review of transportation hydrogen infrastructure performance and reliability,” *International Journal of Hydrogen Energy*, vol. 44, no. 23, pp. 12010-12023, May 2019.

Jianlin Li received the Ph.D. degree in electrical engineering from Zhejiang University, Hangzhou, China, in 2005. He is currently the Responsible Professor with the Department of Electrical Engineering, North China University of Technology, Beijing, China. He is also the Secretary General of the Energy Storage Committee of the Chinese Renewable Energy Society, Secretary General of the Energy Storage Standard Committee of the Chinese Electrotechnical Society, and Vice Chairman of the Operation and Control Committee of IEEE PES Energy Storage Technology. His main research interests include large-scale energy storage application and energy storage technology in power system.

Zelin Shi received the B.S. degree in electrical engineering from Taiyuan Institute of Technology, Taiyuan, China, in 2023. He is currently working toward the master’s degree in energy storage technology with North China University of Technology, Beijing, China. His research interests include optimal planning of electricity-hydrogen coupling system.

Zhonghao Liang received the B.S. degree in electrical engineering from North China University of Water Resources and Hydropower, Zhengzhou, China, in 2013. She currently working toward the Ph.D. degree with Chinese Academy of Sciences, Beijing, China. Her research interests include hydrogen energy and control technology.