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A Review of Electricity-Gas-Hydrogen Integrated Energy Systems for Low-Carbon Energy Transition: Planning, Operation and Market Optimization

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ABSTRACT

Electricity-gas-hydrogen integrated energy systems are becoming an important technical pathway for low-carbon energy transition, renewable energy accommodation and multi-energy coordination. With the increasing penetration of wind power and photovoltaic power, conventional energy systems face growing challenges related to intermittency, uncertainty, flexibility shortage and carbon emission reduction. Hydrogen, especially green hydrogen produced by renewable electricity through water electrolysis, can act as a flexible energy carrier, long-duration energy storage medium and cross-sector coupling resource. This paper provides a literature review of electricity-gas-hydrogen integrated energy systems from the perspectives of system architecture, hydrogen production, power-to-gas technology, hydrogen storage and transportation, coordinated planning, flexible operation, dynamic pricing and robust optimization. The review shows that power-to-gas, hydrogen storage and fuel cells can improve renewable energy utilization and enhance system flexibility. Meanwhile, market-oriented mechanisms such as dynamic pricing and Stackelberg game models can guide demand response and improve the economic performance of integrated energy systems. Robust optimization provides an effective tool for managing renewable generation uncertainty and load fluctuation. However, challenges remain in hydrogen infrastructure investment, multi-energy network modeling, hydrogen market design, carbon pricing coordination, safety standards and real-world demonstration. Finally, a technical route is proposed to summarize the future research framework for electricity-gas-hydrogen integrated energy systems.

KEYWORDS

Electricity-gas-hydrogen Integrated Energy System; Green Hydrogen; Power-to-gas; Fuel cell; Dynamic Pricing; Stackelberg Game; Robust Optimization; Renewable Energy Accommodation.

1. INTRODUCTION

The global energy system is undergoing a deep transition driven by carbon neutrality targets, renewable energy development and energy security concerns. Wind power and photovoltaic power have expanded rapidly in recent years, but their intermittent and uncertain characteristics bring new operational challenges to power systems. When renewable generation exceeds local demand or network transmission capability, renewable curtailment may occur. When renewable output is insufficient, conventional fossil energy units are still required to maintain system balance. Therefore, future low-carbon energy systems require more flexible resources and stronger coordination among different energy carriers.

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Hydrogen has been widely recognized as a key energy carrier in future low-carbon energy systems. Staffell et al. reviewed the role of hydrogen and fuel cells in the global energy system and pointed out that hydrogen can contribute to decarbonization in power generation, transport, industry, heating and long-duration energy storage [1]. The International Energy Agency also emphasized that low-emission hydrogen is important for achieving global net-zero emission targets, especially in hard-to-abate sectors [2]. From the perspective of policy and technology development, green hydrogen produced by renewable electricity is expected to become an important bridge between renewable energy systems and end-use sectors [3].

Electricity-gas-hydrogen integrated energy systems combine electricity networks, natural gas networks, hydrogen production, hydrogen storage, hydrogen transportation and hydrogen utilization. Through power-to-gas technology, surplus renewable electricity can be converted into hydrogen by electrolyzers. The produced hydrogen can be stored, transported, used by fuel cells, supplied to hydrogen refueling stations, consumed by industrial users, or blended into natural gas pipelines. In this way, hydrogen links electricity, gas, transport and industrial sectors.

The concept of integrated energy systems is closely related to the energy hub theory. Geidl and Andersson proposed a general modeling method for multiple energy carriers and energy hubs, which provides a theoretical foundation for the coordinated conversion, storage and utilization of different energy forms [4]. Mancarella further summarized the concept, modeling methods and evaluation frameworks of multi-energy systems, highlighting the importance of integrated planning and operation across electricity, gas, heat and other energy networks [5]. Based on these studies, electricity-gas-hydrogen integrated energy systems can be regarded as an extension of multi-energy systems under the background of hydrogen energy development and carbon neutrality.

However, the planning and operation of electricity-gas-hydrogen integrated energy systems are complex. First, different energy carriers have different physical laws and time scales. Electricity systems require real-time balance, gas systems involve pipeline pressure and line-pack effects, while hydrogen systems involve production, compression, storage, transportation, blending and utilization. Second, renewable energy generation and user demand are uncertain. Third, hydrogen infrastructure usually requires high investment, and its economic value depends on energy prices, carbon prices and market mechanisms. Fourth, different stakeholders, including integrated energy operators, renewable energy producers, gas suppliers, hydrogen station operators and load aggregators, may have different objectives.

This paper reviews the key literature on electricity-gas-hydrogen integrated energy systems, focusing on system architecture, hydrogen technologies, planning, operation, dynamic pricing and robust optimization. The main purpose is to provide a structured understanding of the current research progress and identify future research directions.

2. ARCHITECTURE AND KEY TECHNOLOGIES OF ELECTRICITY-GAS-HYDROGEN INTEGRATED ENERGY SYSTEMS

2.1. System Architecture

An electricity-gas-hydrogen integrated energy system generally consists of an electricity network, a natural gas network, a hydrogen network, renewable energy resources, energy conversion devices, storage facilities and multi-energy loads. The electricity network supplies conventional electrical loads and electrolyzers. Renewable energy sources such as wind power and photovoltaic power are connected to the electricity network. When renewable generation is higher than electricity demand, electrolyzers can consume surplus electricity to produce hydrogen.

The natural gas network supplies gas loads, gas turbines and combined heat and power units. It can also receive hydrogen through hydrogen blending within allowable safety limits. Hydrogen blending

provides a transitional pathway for using existing gas infrastructure, although the maximum blending ratio is limited by pipeline materials, gas quality standards, end-use equipment compatibility and safety requirements.

The hydrogen network includes hydrogen production, compression, storage, transportation and utilization. Hydrogen can be produced by electrolyzers, stored in tanks or underground storage facilities, transported by pipelines or tube trailers, and consumed by fuel cells, hydrogen refueling stations or industrial users. In a well-designed integrated energy system, hydrogen is not only a fuel but also a flexible storage and conversion medium.

Clegg and Mancarella investigated the operational impacts of power-to-gas on integrated electricity and gas transmission networks, showing that power-to-gas can provide additional flexibility and improve the interaction between electricity and gas systems [6]. This provides an important basis for the further development of electricity-gas-hydrogen coupling.

2.2. Power-to-Gas and Hydrogen Production

Power-to-gas is one of the core technologies in electricity-gas-hydrogen integrated energy systems. It converts electrical energy into gaseous energy carriers, mainly hydrogen or synthetic methane. The basic process includes water electrolysis and, in some cases, methanation. In the electrolysis process, electricity is used to split water into hydrogen and oxygen. In the methanation process, hydrogen reacts with carbon dioxide to produce methane, which can be injected into the natural gas network.

Götz et al. reviewed renewable power-to-gas technologies and discussed their technical and economic characteristics, including electrolysis, methanation and system integration [7]. Buttler and Spliethoff further reviewed water electrolysis technologies for energy storage, grid balancing and sector coupling, indicating that electrolysis is a key technology for converting renewable electricity into hydrogen [8]. Thema et al. summarized the status of electrolysis and methanation in power-to-gas systems and pointed out that power-to-gas can support large-scale renewable energy integration, although efficiency loss and investment cost remain important barriers [9].

The main electrolysis technologies include alkaline water electrolysis, proton exchange membrane electrolysis and solid oxide electrolysis. Alkaline electrolysis is relatively mature and suitable for large-scale hydrogen production. Proton exchange membrane electrolysis has fast dynamic response and is suitable for fluctuating renewable energy scenarios. Solid oxide electrolysis has high theoretical efficiency, especially when high-temperature heat is available, but it still faces commercialization challenges.

In integrated energy systems, electrolyzers can be regarded as controllable electrical loads. They can increase electricity consumption during periods of high renewable generation and reduce electricity consumption during peak-load periods. Therefore, electrolyzers can provide demand-side flexibility while producing green hydrogen.

2.3. Hydrogen Storage, Transportation and Utilization

Hydrogen storage is essential for improving the flexibility of electricity-gas-hydrogen systems. Compared with batteries, hydrogen storage is more suitable for long-duration and large-scale storage. It can store surplus renewable energy over hours, days, weeks or even seasons. Hydrogen storage technologies include compressed gaseous hydrogen storage, liquid hydrogen storage, metal hydride storage, chemical hydrogen storage and underground hydrogen storage.

Hydrogen transportation can be realized by tube trailers, liquid hydrogen tankers, dedicated hydrogen pipelines or blending into natural gas pipelines. In the early stage of hydrogen market development, tube trailers may be more flexible and suitable for distributed hydrogen demand. In large-scale hydrogen systems, pipeline transportation and underground storage may become more economical.

Hydrogen blending in natural gas pipelines can reduce the carbon intensity of gas supply and make use of existing infrastructure, but it requires strict safety and compatibility assessment.

Hydrogen utilization covers power, transport, industry and heating sectors. In the power sector, fuel cells can convert hydrogen into electricity with high efficiency and low local emissions. In the transport sector, hydrogen fuel cell vehicles are suitable for heavy-duty, long-distance and high-utilization applications. In the industrial sector, green hydrogen can replace fossil-based hydrogen in ammonia production, refining, methanol production and steelmaking. Therefore, hydrogen provides an important route for deep decarbonization of hard-to-electrify sectors.

3. PLANNING AND OPERATION OF ELECTRICITY-GAS-HYDROGEN INTEGRATED ENERGY SYSTEMS

3.1. Coordinated Planning

Coordinated planning determines the location, capacity and investment timing of key energy facilities. In electricity-gas-hydrogen integrated energy systems, planning objects include renewable energy plants, electrolyzers, hydrogen storage tanks, fuel cells, power-to-gas units, gas turbines, hydrogen refueling stations, gas pipelines and hydrogen pipelines. The planning objective is usually to minimize the total investment and operation cost while satisfying energy demand, carbon constraints and reliability requirements.

Power-to-gas equipment is a key planning object because it connects electricity, gas and hydrogen networks. Appropriate capacity allocation of power-to-gas facilities can reduce renewable curtailment, improve renewable energy accommodation and enhance system flexibility. Hydrogen storage planning is also important. If hydrogen storage capacity is too small, the system cannot fully absorb renewable fluctuations. If it is too large, investment cost will increase. Therefore, optimal hydrogen storage sizing should balance flexibility value and investment cost.

Gabrielli et al. studied the optimal design of multi-energy systems with seasonal storage and showed that long-duration storage can play an important role in highly renewable energy systems [10]. This conclusion is closely related to the value of hydrogen storage in electricity-gas-hydrogen integrated systems. Hydrogen can provide seasonal storage capability and support energy supply during periods of low renewable output.

In addition, the planning of hydrogen refueling stations links energy systems with transportation systems. Its location and capacity are affected by hydrogen demand, traffic flow, distribution network constraints, hydrogen supply chain and refueling service characteristics. Coordinated planning of hydrogen production, storage and refueling infrastructure is necessary for the large-scale application of hydrogen fuel cell vehicles.

3.2. Flexible Operation

The operation of electricity-gas-hydrogen integrated energy systems aims to coordinate renewable generation, electrolyzers, hydrogen storage, gas turbines, fuel cells and multi-energy loads. The main operational objective is to improve economic performance, reduce carbon emissions, increase renewable energy utilization and maintain system security.

When renewable generation is abundant, electrolyzers can produce green hydrogen. The hydrogen can be stored or supplied to hydrogen users. When electricity demand is high or renewable output is low, stored hydrogen can be used by fuel cells to generate electricity. This process provides a bidirectional energy conversion path between electricity and hydrogen.

The natural gas network also contributes to system flexibility. Gas pipelines have line-pack characteristics, which means that gas can be temporarily stored in pipelines through pressure variation.

When hydrogen is blended into natural gas pipelines, the gas network can indirectly participate in hydrogen utilization. However, hydrogen blending must satisfy constraints related to safety, pipeline materials and terminal equipment.

Flexible operation requires coordinated modeling of electricity balance, gas flow, hydrogen production, hydrogen storage, hydrogen consumption and equipment operating limits. The resulting optimization problem may be nonlinear, mixed-integer and multi-objective. Therefore, advanced optimization methods are needed to support practical operation.

4. DYNAMIC PRICING, STACKELBERG GAME AND DEMAND RESPONSE

4.1. Dynamic Pricing in Integrated Energy Systems

Dynamic pricing is an important market mechanism for improving the operational efficiency of integrated energy systems. By adjusting electricity, gas or hydrogen prices over time, energy operators can guide users to change consumption behavior. For example, when renewable generation is high and electricity price is low, users may increase flexible electricity consumption or hydrogen production. When electricity demand is high, higher prices can encourage users to reduce or shift load.

In electricity-gas-hydrogen integrated energy systems, dynamic pricing can be extended from electricity pricing to multi-energy pricing. The integrated energy operator may determine electricity price, gas price and hydrogen price simultaneously. Users or load aggregators can respond by shifting electricity demand, adjusting gas consumption or changing hydrogen refueling behavior. This multi-energy demand response can improve renewable energy accommodation and reduce peak-load pressure.

Dynamic pricing also affects the economic value of hydrogen. If electricity prices are low during renewable surplus periods, green hydrogen production becomes more attractive. If carbon prices are high, green hydrogen can obtain additional low-carbon value. Therefore, the coordination of electricity price, hydrogen price and carbon price is important for hydrogen market development.

4.2. Stackelberg Game-Based Energy Management

Stackelberg game theory is widely used to describe hierarchical decision-making between energy operators and users. In a typical Stackelberg game, one participant acts as the leader and makes decisions first, while other participants act as followers and respond to the leader's strategy.

Maharjan et al. applied a Stackelberg game approach to demand response management in smart grids, showing that hierarchical interaction can effectively coordinate utility companies and consumers [11]. Yu and Hong proposed a real-time demand response algorithm based on Stackelberg game theory, demonstrating that price-based interaction can improve both system operation and user-side response [12]. These studies provide methodological support for dynamic pricing in integrated energy systems.

In electricity-gas-hydrogen integrated energy systems, the integrated energy operator can be modeled as the leader. It determines electricity, gas and hydrogen prices according to renewable generation, energy purchase cost, hydrogen production cost and system operation constraints. Load aggregators or users are modeled as followers. They adjust flexible loads according to price signals in order to minimize energy costs while satisfying comfort or production requirements.

The Stackelberg game framework is suitable for multi-energy systems because it can reflect the interaction between operators and users. However, several challenges remain. First, users may have heterogeneous preferences and different flexibility levels. Second, energy prices are affected by renewable uncertainty and market volatility. Third, the leader's pricing strategy must satisfy

regulatory constraints and fairness requirements. Therefore, Stackelberg game models should be combined with uncertainty modeling and robust optimization.

5. ROBUST OPTIMIZATION UNDER UNCERTAINTY

5.1. Uncertainty Sources

Uncertainty is one of the most important challenges in electricity-gas-hydrogen integrated energy systems. The main sources of uncertainty include wind power output, photovoltaic output, electricity load, gas load, hydrogen demand, electricity market price, gas price, hydrogen price and carbon price. If these uncertainties are ignored, the system may face infeasible operation, insufficient energy supply, excessive renewable curtailment or high operation cost.

Renewable generation uncertainty directly affects hydrogen production. When actual renewable output is lower than forecasted, electrolyzers may not receive enough electricity for planned hydrogen production. When actual renewable output is higher than forecasted, insufficient electrolyzer or storage capacity may lead to curtailment. Similarly, hydrogen demand uncertainty affects storage scheduling and hydrogen supply reliability.

In long-term planning, uncertainty is even more significant. Technology cost, hydrogen demand growth, carbon policy and infrastructure development are difficult to predict accurately. Therefore, planning models should not only optimize expected cost but also consider system robustness under unfavorable scenarios.

5.2. Robust Optimization Methods

Robust optimization is an effective method for decision-making under uncertainty. It seeks solutions that remain feasible under all possible realizations within a predefined uncertainty set. Bertsimas and Sim proposed a widely used robust optimization framework and discussed the relationship between robustness and conservatism [13]. Ben-Tal et al. systematically developed the theory and applications of robust optimization, providing a theoretical foundation for energy system uncertainty management [14].

In electricity-gas-hydrogen integrated energy systems, robust optimization can be applied to capacity planning, unit commitment, economic dispatch, hydrogen production scheduling, storage management and dynamic pricing. For example, a robust dispatch model can ensure that electricity demand, gas demand and hydrogen demand are satisfied even under low renewable generation and high load conditions. A robust planning model can determine electrolyzer and hydrogen storage capacity that remains cost-effective under different future scenarios.

However, robust optimization may produce conservative results. If the uncertainty set is too large, the system may over-invest in storage or reserve capacity. If the uncertainty set is too small, the system may not be sufficiently secure. Therefore, data-driven uncertainty sets, adjustable robust optimization and distributionally robust optimization are important future research directions.

6. ARCHITECTURE AND KEY TECHNOLOGIES OF ELECTRICITY-GAS-HYDROGEN INTEGRATED ENERGY SYSTEMS

6.1. Technical Route

The technical route of electricity-gas-hydrogen integrated energy system research is shown in Fig. 1. The route starts from low-carbon energy transition and renewable energy integration. Then, the architecture and key technologies of the integrated system are analyzed. Based on this, planning,

operation, market optimization and uncertainty management are studied. Finally, the performance of the system is evaluated from economic, environmental and reliability perspectives.

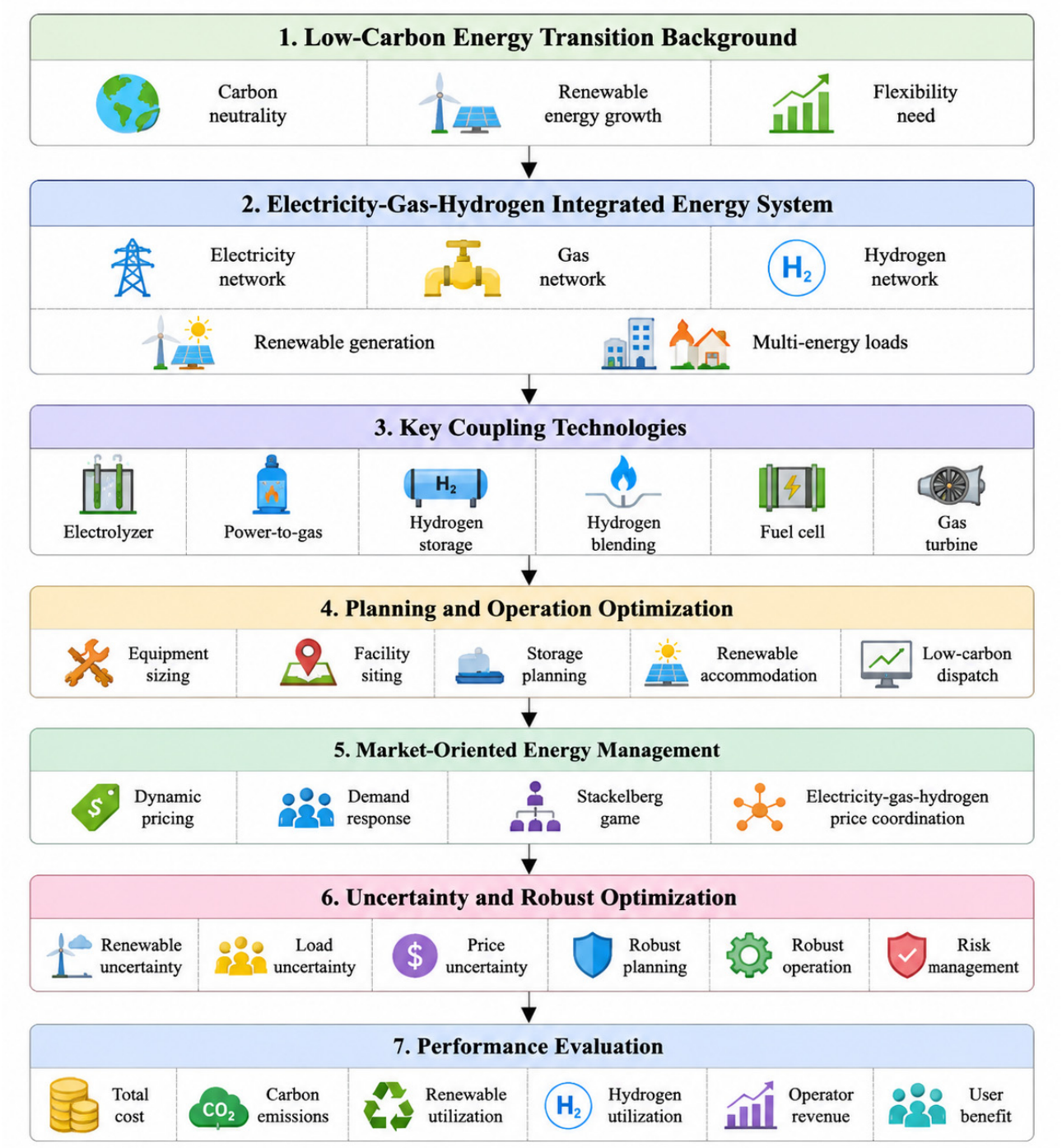


Figure 1. Technical route of electricity-gas-hydrogen integrated energy system research

The technical route shows that electricity-gas-hydrogen integrated energy systems require coordinated research on technology, planning, operation and market mechanisms. Hydrogen technologies provide physical flexibility, while dynamic pricing and robust optimization provide economic and decision-making flexibility.

6.2. Comparison of Key Technologies

Table 1 summarizes the main technologies in electricity-gas-hydrogen integrated energy systems. Each technology has its own function, advantage and limitation. Therefore, future system design

should not rely on a single technology but should coordinate multiple technologies according to local renewable resources, infrastructure conditions, market rules and carbon policies.

Table 1. Comparison of key technologies in electricity-gas-hydrogen integrated energy systems

Technology	Main Function	Advantages	Limitations
Alkaline electrolysis	Hydrogen production	Mature and relatively low cost	Slower dynamic response
PEM electrolysis	Hydrogen production	Fast response and suitable for renewable fluctuation	High investment cost
Solid oxide electrolysis	High-efficiency hydrogen production	High efficiency and heat utilization potential	Commercial maturity is limited
Power-to-gas	Electricity-gas-hydrogen coupling	Improves renewable energy accommodation	Efficiency loss and high cost
Hydrogen storage	Long-duration energy storage	Supports seasonal flexibility	Infrastructure and safety requirements
Hydrogen blending	Gas-hydrogen coupling	Uses existing gas infrastructure	Limited blending ratio
Fuel cell	Hydrogen-to-electricity conversion	High efficiency and low local emissions	Cost and durability challenges
Dynamic pricing	Demand response	Guides flexible consumption	Requires market participation
Stackelberg game	Operator-user interaction	Models hierarchical decisions	User behavior uncertainty
Robust optimization	Uncertainty management	Improves security under uncertainty	May be conservative

7. CHALLENGES AND FUTURE RESEARCH DIRECTIONS

Although electricity-gas-hydrogen integrated energy systems have significant potential, several challenges still restrict their large-scale application. The first challenge is the high cost of hydrogen technologies. Electrolyzers, fuel cells, hydrogen storage tanks and hydrogen pipelines still require significant investment. Cost reduction depends on technological innovation, manufacturing scale-up and policy support.

The second challenge is infrastructure development. Hydrogen production sites, storage facilities, refueling stations and pipelines should be planned in coordination with renewable energy bases, power grids, gas networks and industrial clusters. Without coordinated infrastructure planning, hydrogen supply chains may face high cost and low utilization.

The third challenge is multi-energy modeling. Electricity, gas and hydrogen systems have different physical characteristics. Electricity systems have fast dynamic response, gas systems involve pressure and line-pack constraints, and hydrogen systems include compression, storage and blending constraints. A unified and computationally efficient modeling framework is still needed.

The fourth challenge is market mechanism design. Electricity, gas, hydrogen and carbon markets are closely related, but their coordination is still insufficient. Green hydrogen certification, carbon accounting, dynamic pricing and ancillary service compensation should be improved to reflect the flexibility and low-carbon value of hydrogen.

The fifth challenge is uncertainty management. Renewable generation, load demand, hydrogen consumption and market prices are uncertain. Future research should combine robust optimization, stochastic programming, machine learning and real-time control to improve system adaptability.

Future studies should focus on several directions. First, digital twin technology can be used to build real-time simulation and monitoring platforms for electricity-gas-hydrogen systems. Second, data-driven robust optimization can reduce conservatism while maintaining system security. Third, Stackelberg game models can be extended to multi-agent and multi-market environments. Fourth, hydrogen infrastructure planning should be integrated with transport and industrial decarbonization. Fifth, more demonstration projects are needed to verify the technical feasibility and economic performance of electricity-gas-hydrogen integrated energy systems.

8. SUMMARY

This paper reviews the research progress of electricity-gas-hydrogen integrated energy systems under the background of low-carbon energy transition. Hydrogen can act as an energy carrier, storage medium and cross-sector coupling resource. Through power-to-gas technology, surplus renewable electricity can be converted into green hydrogen, thereby improving renewable energy accommodation and reducing carbon emissions.

The review shows that coordinated planning and flexible operation are essential for electricity-gas-hydrogen integrated energy systems. Electrolyzers, hydrogen storage, fuel cells and hydrogen blending facilities provide important flexibility. Dynamic pricing and Stackelberg game models can guide demand response and improve market-oriented operation. Robust optimization can enhance system reliability under renewable generation and load uncertainty.

However, challenges remain in hydrogen cost, infrastructure construction, multi-energy modeling, market mechanism design, uncertainty management and safety standards. Future research should further integrate hydrogen technologies, digital modeling, robust decision-making and multi-energy market coordination. Overall, electricity-gas-hydrogen integrated energy systems are expected to become an important pathway for renewable energy accommodation, energy system flexibility and deep decarbonization.

CONFLICTS OF INTEREST

The authors declare that they have no conflict of interest.

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REFERENCES

[1] Staffell, I., Scamman, D., Velazquez Abad, A., Balcombe, P., Dodds, P. E., Ekins, P., Shah, N., & Ward, K. R. (2019). The role of hydrogen and fuel cells in the global energy system. *Energy & Environmental Science*, *12*(2), 463–491. https://doi.org/10.1039/C8EE01157E.

[2] International Energy Agency. (2023). *Global hydrogen review 2023*. IEA. https://www.iea.org/reports/global-hydrogen-review-2023.

[3] International Renewable Energy Agency. (2020). *Green hydrogen: A guide to policy making*. IRENA. https://www.irena.org/publications/2020/Nov/Green-hydrogen.

[4] Geidl, M., & Andersson, G. (2007). Optimal power flow of multiple energy carriers. *IEEE Transactions on Power Systems*, *22*(1), 145–155. https://doi.org/10.1109/TPWRS.2006.888988.

[5] Mancarella, P. (2014). MES: Multi-energy systems: An overview of concepts and evaluation models. *Energy*, *65*, 1–17. https://doi.org/10.1016/j.energy.2013.10.041.

[6] Clegg, S., & Mancarella, P. (2015). Integrated modeling and assessment of the operational impact of power-to-gas on electrical and gas transmission networks. *IEEE Transactions on Sustainable Energy*, *6*(4), 1234–1244. https:// doi. org/10.1109/TSTE.2015.2424885.

[7] Götz, M., Lefebvre, J., Mörs, F., Koch, A. M., Graf, F., Bajohr, S., Reimert, R., & Kolb, T. (2016). Renewable power-to-gas: A technological and economic review. *Renewable Energy*, *85*, 1371–1390. https://doi.org/ 10. 1016/ j. renene.2015.07.066.

[8] Buttler, A., & Spliethoff, H. (2018). Current status of water electrolysis for energy storage, grid balancing and sector coupling via power-to-gas and power-to-liquids: A review. *Renewable and Sustainable Energy Reviews*, *82*, 2440–2454. https://doi.org/10.1016/j.rser.2017.09.003.

[9] Thema, M., Bauer, F., & Sterner, M. (2019). Power-to-Gas: Electrolysis and methanation status review. *Renewable and Sustainable Energy Reviews*, *112*, 775–787. https://doi.org/10.1016/j.rser.2019.06.030.

[10] Gabrielli, P., Gazzani, M., Martelli, E., & Mazzotti, M. (2018). Optimal design of multi-energy systems with seasonal storage. *Applied Energy*, *219*, 408–424. https://doi.org/10.1016/j.apenergy.2017.07.142.

[11] Maharjan, S., Zhu, Q., Zhang, Y., Gjessing, S., & Başar, T. (2013). Dependable demand response management in the smart grid: A Stackelberg game approach. *IEEE Transactions on Smart Grid*, *4*(1), 120–132. https:// doi. org/ 10. 1109/TSG.2012.2223766.

[12] Yu, M., & Hong, S. H. (2016). A real-time demand-response algorithm for smart grids: A Stackelberg game approach. *IEEE Transactions on Smart Grid*, *7*(2), 879–888. https://doi.org/10.1109/TSG.2015.2413813.

[13] Bertsimas, D., & Sim, M. (2004). The price of robustness. *Operations Research*, *52*(1), 35–53. https://doi.org/ 10. 1287/ opre.1030.0065.

[14] Ben-Tal, A., El Ghaoui, L., & Nemirovski, A. (2009). *Robust optimization*. Princeton University Press.