# Towards Renewable-dominated Energy Systems: Role of Green Hydrogen

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***Abstract*—Green hydrogen represents an important energy carrier for global decarbonization towards renewable-dominant energy systems. As a result, an escalating interdependency emerges between multi-energy vectors. Specifically, the coupling among power, natural gas, and hydrogen systems is strengthened as the injections of green hydrogen into natural gas pipelines. At the same time, the interaction between hydrogen and transportation systems would become indispensable with soaring penetrations of hydrogen fuel cell vehicles. This paper provides a comprehensive review for the modeling and coordination of hydrogen-integrated energy systems. In particular, we analyze the role of green hydrogen in decarbonizing power, natural gas, and transportation systems. Finally, pressing research needs are summarized.**

***Index Terms*—Renewable-dominant energy system, green hydrogen, gas-hydrogen blending, multi-energy coordination.**

## I. Introduction

CURRENT energy systems are heavily reliant on fossil fuels, and hence represent a major contributor to global carbon emissions [1]-[3]. Transition to a low-carbon or carbon-neutral energy system has become critical to cope with climate change issues. Although the energy transition pathways for different countries/regions might be diverse, high penetrations of renewable energy sources (RESs) are generally required for constructing a green and sustainable energy system [4]. Specifically, replacing fossil-fuel power generators with RESs would decarbonize the power sector [5]. Besides, the electrification of end-use energy consumption, e.g., electric vehicles (EVs), heat pumps, and power to gas, would contribute to the decarbonization of transportation, heat, and natural gas sectors [6].

However, the high penetrations of RESs pose significant operational challenges to power/energy systems. One major challenge is caused by intermittent and stochastic RES generation, which requires high operating flexibility at different time scales [7]. This flexibility is mainly provided by flexible power generators (e.g., natural gas turbines) and energy storages [8]. Although the power industry has designed a few flexibility market products [9], e.g., flexible ramping products in California Independent System Operator (CAISO) and performance-based regulation mechanism in Pennsylvania–New Jersey–Maryland (PJM), the cost to provide such flexibility is generally high at present due to the relatively high gas price and expensive investment cost of energy storages [10].

The emergence of hydrogen energy in recent years provides an alternative solution to the decarbonization of multi-energy sectors, particularly as the hydrogen is produced by RESs (i.e., green hydrogen) via power to hydrogen (P2H) technologies [11]-[13]. The P2H technologies can convert the surplus RES generation into hydrogen, which can be stored in hydrogen tanks and further utilized to generate electricity via fuel cell based generating units [14]. Alternatively, the green hydrogen can be injected into existing natural gas pipelines. As such, the P2H combined with fuel cell based generating units or natural gas pipelines represents an effective large-scale energy storage technology [15]. Another solution is to establish hydrogen transmission infrastructures. Converting existing natural gas pipelines into pure hydrogen pipelines represents a low-cost option to achieve this goal, while the investment in building new hydrogen pipelines might be required if large volumes of hydrogen need to be transported or stored [16].

The role of green hydrogen in decarbonizing future energy systems has been recognized by many countries/regions. For example, Europe Union (EU) has launched an ambitious hydrogen strategy, in which the priority is given to develop green hydrogen that functions as an energy carrier to achieve carbon-neutral economy [17]. China has planned to build a 400 km west-to-east green hydrogen transmission pipeline whose annual capacity is up to 100000 t [18].

As the green hydrogen acts an energy carrier towards the transition to a green energy future, the interdependency between multi-energy systems (including hydrogen, power, natural gas, and transportation networks) would be greatly strengthened [19]. Incorporating the hydrogen into an integrated energy system provides the following potential values.

1) Accommodation of high penetrations of RESs: the surplus RES generation (that otherwise would be curtailed)

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could be converted into hydrogen that functions as a green secondary energy source. Moreover, the coordination of multi-energy systems could provide the operating flexibility required to balance short-term fluctuation of RES generation [20].

2) Low-cost production and long-distance transmission of hydrogen: a high market share of RESs generally leads to relatively low power prices, which would decrease the production cost of green hydrogen. Besides, the existing expansive natural gas infrastructure could be used to transport hydrogen [21].

3) Decarbonization of energy consumption in industrial, commercial, and residential sectors: in the industrial sector, green hydrogen can replace carbon-intensive materials in steel manufacturing, chemical production, and refining processes. In the commercial and residential sectors, green hydrogen presents an opportunity to revolutionize building heating and cooling. Additionally, green hydrogen can be used as fuel for vehicles or as a component of synthetic fuels in the transportation section [22].

4) Provision of long-term energy storage: hydrogen has been considered as a promising long-term energy storage, which is much more cost-effective than battery storage systems. The long-term energy storage would be necessary for a renewable-dominant power system as the weather-dependent renewable power generation would lead to net demand fluctuation across different days, weeks, or even seasons [23].

The present work, therefore, provides a comprehensive review on the role of green hydrogen in decarbonizing energy sectors. In particular, we focus on two application scenarios of green hydrogen. The first one consists of integrated power−natural gas−hydrogen systems, which corresponds to the production and transportation of green hydrogen. The second one consists of integrated power−transportation−hydrogen systems, which corresponds to the consumption of green hydrogen.

The rest of this paper is organized as follows. Section II reviews the modeling and coordination of integrated power−natural gas−hydrogen systems. Section III reviews the modeling and coordination of integrated power−transportation−hydrogen systems. Both Sections II and III include a small example. Section IV presents future research directions. Section V concludes this paper.

## II. Modeling and Coordination of Integrated Power−Natural Gas−Hydrogen Systems

This section analyzes the role of green hydrogen in decarbonizing power and natural gas systems with high penetrations of RESs. Figure 1 depicts a typical structure of an integrated power−natural gas−hydrogen system. The coupling of power and natural gas systems consists of gas-fired power generators and P2H units. The following subsections review the modeling, planning, operation, and demonstration projects of integrated power−natural gas−hydrogen systems. Finally, an example is provided to detail the impact of green hydrogen injections on natural gas system operations.

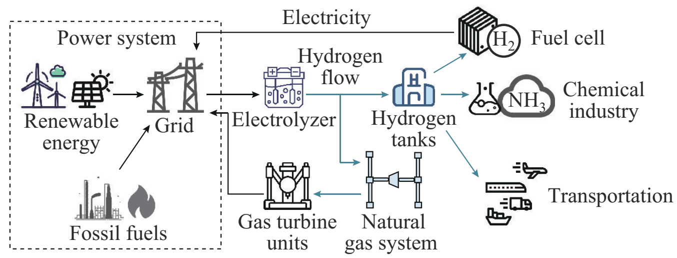


Fig. 1. Structure of an integrated power−natural gas−hydrogen system.

### A. Modeling of Power−Natural Gas−Hydrogen Systems

This subsection provides a review of modeling of hydrogen electrolyzers (i.e., P2H) and the natural gas system with hydrogen injections.

Reference [24] compares the techno-economic characteristics of three major hydrogen electrolyzers, i.e., solid oxide electrolyzer cell (SOEC), polymer electrolyte membrane (PEM), and alkaline electrolyzer. The alkaline electrolyzer represents a mature commercialized technology with low investment cost, but its exergy efficiency is relatively low. The PEM could provide very fast response that contributes to accommodating intermittent renewable power generation, but its hydrogen production cost is the most expensive. The SOEC provides the highest energy efficiency, but it needs to work at a high temperature, which might hinder its commercial application. Reference [25] proposes a real-time control model of electrolyzers that satisfy time-varying hydrogen demands, in which internal thermal dynamics are considered. Reference [26] proposes a three-state (i.e., on, off, and standby) operating model of alkaline electrolyzers, in which nonlinear P2H conversion efficiency is considered. This study shows that introducing the standby operating state saves cold-start cost of electrolyzers under intermittent RES generation. Reference [27] analyzes the flexibility of grid-scale alkaline electrolyzers that provide fast frequency support to a wind-dominated power system. Reference [28] develops a dynamic model of hydrogen electrolyzers that provide grid-forming services including voltage and frequency support. The impact of providing such service on the physical operation of electrolyzers is analyzed.

Regarding the modeling of the natural gas system with hydrogen injections, it is noted that the gas−hydrogen blending results in gas composition variation at each node, which complicates the natural gas system modeling. Specifically, for traditional natural gas systems, the natural gas supply-demand balance is described by volumetric flows of the natural gas. However, for the natural gas system with hydrogen injections, two additional types of variables (i.e., gas energy flows and gross calorific values) are required [29]. Namely, an energy-based model rather than traditional volume-based models is required. Reference [30] proposes an energy-based approach to simulate gas flow dynamics with green hydrogen injections, in which variable gas-quality composition is included. Reference [31] compares the steady-state and transient energy flow models that are employed to simulate an integrated natural gas−hydrogen network. Reference [32] proposes a transient natural gas flow model to track gas compositions of a meshed natural gas network with multiple hydrogen injections, based on which the impact of hydrogen blending on natural gas system operations is analyzed. It should be noted that a transient/dynamic natural gas−hydrogen flow model (with line-pack) is required for short-term operations, while a steady-state natural gas−hydrogen flow could be used for long-term operation/planning problems.

We note that the hydrogen blending complicates the modeling of natural gas networks by introducing higher nonlinearity. Therefore, developing a sufficiently accurate linearized or convexified natural gas flow model with hydrogen blending is highly desirable. Interested readers can refer to [33] and [34] for the application of piecewise linearization and second-order cone relaxation to traditional natural gas flow models.

### *B. Planning of Power−Natural Gas−Hydrogen Systems*

The extant literature includes the studies on the investment in P2H units and coordinated expansion planning of integrated power−natural gas−hydrogen systems.

Reference [35] reviews the potential value of power-to-gas technology for the decarbonization in energy systems, in which the impact of hydrogen blending on natural gas pipeline operations and end users is analyzed. Reference [36] proposes an optimal investment model of electrolyzers and hydrogen storage, in which the operation of both electric networks and hydrogen supply chains is taken into account. Reference [37] develops an optimal allocation model of P2H units to satisfy growing hydrogen demands. The economic benefits of newly-built P2H units are investigated. Reference [38] analyzes the role of green hydrogen on decarbonizing power and gas systems based on a coordinated planning model of P2H units, showing that neglecting gas-hydrogen blending limits leads to misleading planning results.

Reference [39] provides a comprehensive review on the expansion planning of integrated power−natural gas−hydrogen systems, in which the value of detailed natural gas line-pack modeling on transporting hydrogen is quantified. Reference [40] proposes a bi-level planning model of integrated power−hydrogen systems that considers seasonal hydrogen storage and levelized cost of hydrogen. Reference [41] co-optimizes the planning of electricity and hydrogen infrastructure in diverse low-carbon scenarios. Results on a realistic case study of Texas show the impact of $CO_2$ price on hydrogen production. Reference [42] proposes a hydrogen supply chain planning model. The model includes hydrogen trucks and pipelines that function as flexible transmission and storage resources. Reference [43] proposes a coordinated planning model of integrated electricity−hydrogen networks, in which net demand uncertainties and $N-1$ contingencies are considered. Reference [44] proposes a robust coordinated planning model of power and hydrogen transmission networks, electrolyzers, and hydrogen storage. Reference [45] presents an expansion planning model of power and hydrogen systems that includes short-term unit commitment constraints, in which the short-term operating flexibility is considered at the planning stage. Reference [46] develops an investment equilibrium model of integrated power−natural gas−hydrogen systems that includes strategic decisions of different stakeholders. Reference [47] proposes a tri-level expansion planning model of integrated power−natural gas−hydrogen systems that considers the carbon emission flow model. The role of hydrogen as an energy carrier in carbon-emission reduction is analyzed.

We note that these studies provide quantitative results on the value of green hydrogen for energy transition at the planning stage. An open challenge in this area is that the green hydrogen blending limit has direct impact on planning results of hydrogen infrastructures. Specifically, a strict hydrogen blending limit could restrict the market share of green hydrogen. Conversely, a weak hydrogen blending limit could pose operational challenges to natural gas systems. The design of green hydrogen blending limit would be critical from the perspective of both planning and operation stages. Another interesting area is to develop a multi-stage transition pathway model for energy systems with retirement of coal-/gas-fired power generators and newly-built renewable power generator at each stage. At the same time, the traditional natural gas infrastructures would be gradually replaced by green hydrogen infrastructures to achieve the carbon-emission target at each stage.

### *C. Operation of Power−Natural Gas−Hydrogen Systems*

The coordination of coupled power, natural gas, and hydrogen systems is important due to the growing interdependence between multi-energy sectors. From the perspective of the power system operator, a sufficient coordination provides incremental operating flexibility that is required for power system operations. From the perspective of the natural gas system operator, this coordination could alleviate the impact of green hydrogen injections on natural gas system operations and hence contribute to the long-distance transportation of hydrogen energy.

Reference [26] proposes a day-ahead optimization model of hybrid power plants that consist of renewable power sources and electrolyzers, in which the standby operating states and a detailed linearized operating model of electrolyzers are included. Reference [48] proposes a joint scheduling model of integrated power−hydrogen systems. A convex-concave approach is proposed to convexify the nonlinearity of hydrogen-flow fluid dynamics. Reference [49] designs an energy sharing mechanism of power and gas systems with high penetrations of hybrid electric and hydrogen vehicles. The economic benefits provided by coordinated power and hydrogen sharing are investigated. Reference [50] investigates the impact of the integration of hydrogen in integrated energy systems based on a sequential Monte Carlo simulation model. Numerical results show that increasing hydrogen integration reduces the total operating cost, but poses reliability issues to the natural gas system. Reference [51] analyzes the acceptability of natural gas infrastructures to hydrogen integration. It shows that the distribution network allows a higher penetration level of hydrogen if the gas quality requirement can be satisfied. Reference [52] investigates the impact of enforcing a renewable hydrogen quota on power and natural gas markets in Europe, indicating that increasing the hydrogen share of the end consumers will lead to an increase in power prices and slightly lower gas prices. Reference [53] investigates the feasibility of injecting hydrogen into natural gas networks based on a natural gas fluid simulation model, in which physical and chemical operating characteristics are considered. Reference [54] quantifies the operating flexibility provided by P2H units in integrated power−natural gas−hydrogen systems. It shows that the gas quality limit with hydrogen blending could restrict the aggregated flexibility of multiple P2H units. Reference [55] designs a coordinated control model for coupling power and natural gas systems with hydrogen blending, in which a cell segmentation approach is proposed to capture the spatial and temporal dynamics of natural gas−hydrogen blending flows. Reference [56] coordinates the operation of integrated power−natural gas−hydrogen systems that includes the tracking of hydrogen concentration. A sequential linear programming approach is adopted to tackle the energy flows that are highly nonlinear. Reference [57] proposes a day-ahead operation framework of integrated power−natural gas−hydrogen systems that considers diverse security indices of gas mixtures, in which a sequential conic programming model is adopted. Reference [58] develops a moment-based distributionally robust optimization approach to coordinate power and natural gas systems with hydrogen injections. The flexibility of P2H facilities is exploited to participate in the voltage regulation.

An open challenge on this area lies in the fact that the multi-energy sectors are actually operated by different entities, which may hinder the information sharing of the coordination framework. Moreover, under a market environment, the strategic behaviors of different market agents (e.g., the owner of P2H facilities that participate in different energy markets) may complicate the clearing of coupled energy markets and the resulting market equilibria. Readers can refer to [59]-[61] for the coordination of traditional power and natural gas markets. Another challenge pertains to the flexibility operating quantification of hydrogen-integrated energy systems. One feasible approach is to create time-varing operating envelopes that aggregate flexibility provided by multiple flexible energy resources. Note that the concept of operating envelopes has been widely applied to quantify the flexibility from distributed energy sources at power distribution networks, e.g., the studies in [62] and [63].

### D. Demonstration Projects

Typical hydrogen blending demonstration projects worldwide are summarized as follows.

1) EU NaturalHy project [64]: the European Gas Research Group (GERG) Institution conducted this project, which analyzed the impact of hydrogen blending concentration ranging from 20% to 50% on pipeline fracture toughness and safety risk. GERG has also conducted a project that aims to analyze the transmission capacity for 100% hydrogen in existing natural gas pipelines.

2) UK HyDeploy project [65]: this project investigated the impact of 20% hydrogen blending on natural gas consumers and distribution pipelines. The engineering demonstration in 100 households and 30 school buildings showed that all kinds of household appliances operated safely even with a hydrogen blending concentration up to 28.4%.

3) The New York Power Authority (NYPA) green hydrogen project [66]: this project experimented the usage of mixed green hydrogen with natural gas as fuel to generate electricity. Experiment result showed that 35% hydrogen blending contributed to 14% reduction of carbon emissions.

4) PetroChina hydrogen project [67]: PetroChina has completed a 100-day test that injected 24% hydrogen into a 400 km gas pipeline in Ningxia, China.

### E. Example

We use a simple example shown in Fig. 2 to illustrate the impact of hydrogen injections (produced from intermittent RESs) on natural gas system operations. This natural gas system consists of two gas suppliers at nodes 1 and 2, three gas consumers at nodes 2-4, and one hydrogen supplier at node 3. The two gas suppliers S1 and S2 have a capacity of 50 MW and 60 MW, and their marginal production costs are 10 \$/MWh and 15 \$/MWh, respectively. The three gas consumers C1-C3 at nodes 2-4 have a fixed demand of 20 MW, 30 MW, and 40 MW, respectively. The P2H unit at node 3 has a capacity of 4 MW, and its energy conversion efficiency is $0.7p$, where $p$ is the amount of power injected into the P2H unit at node 3. For simplicity, we consider a single-period operation without considering natural gas-pipeline line-pack. It should be clarified that a steady-state gas flow model might result in conservative results since the gas dynamics (line-pack) are not taken into account. Nevertheless, this subsection focuses on analyzing the impact of green hydrogen injections, not on providing a detailed power−natural gas−hydrogen simulation model.

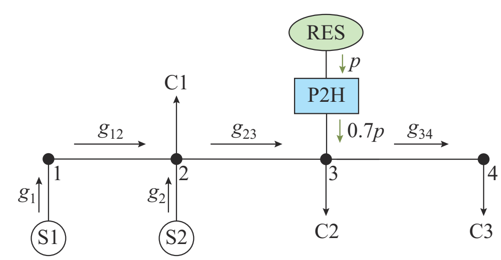

Fig. 2. Topology of a four-node natural gas system with green hydrogen injection.

The single-period operating problem of the four-node natural gas system is provided as:

$$\min_{g_1, g_2, p} (10g_1 + 15g_2) \tag{1}$$

s.t.

$$g_1 = g_{12} \tag{2}$$

$$g_{12} + g_2 = 20 + g_{23} \tag{3}$$

$$g_{23} + 0.7p = 30 + g_{34} \tag{4}$$

$$g_{34} = 40 \tag{5}$$

$$\begin{cases} 0 \le g_1 \le 50 \\ 0 \le g_2 \le 60 \end{cases} \tag{6}$$

$$0 \le p \le \bar{p} \tag{7}$$

$$\begin{cases} g_{12} = f_{12} h_1 \\ g_{23} = f_{23} h_2 \\ g_{34} = f_{34} h_3 \end{cases} \tag{8}$$

$$h_1 = h_2 = h_{gas} \tag{9}$$

$$f_{23} + 0.7p/h_{H_2} = f_{34} + 30/h_3 \tag{10}$$

$$f_{12} = 0.000668\sqrt{\pi_1^2 - \pi_2^2} \tag{11}$$

$$f_{23} = 0.000128\sqrt{\pi_2^2 - \pi_3^2} \tag{12}$$

$$f_{34} = 0.000320\sqrt{\pi_3^2 - \pi_4^2} \tag{13}$$

$$\pi_1, \pi_2, \pi_3, \pi_4 \le 60 \tag{14}$$

where $g_1$ and $g_2$ denote the natural gas productions of S1 and S2, respectively; $g_{12}$, $g_{23}$, and $g_{34}$ denote the energy flow rates of pipelines 1-2, 2-3, and 3-4, respectively; $f_{12}$, $f_{23}$, and $f_{34}$ denote the volumetric flow rates of pipelines 1-2, 2-3, and 3-4, respectively; $h_1$, $h_2$, and $h_3$ denote the gross calorific values at nodes 1, 2, and 3, respectively; $\pi_1$, $\pi_2$, $\pi_3$, and $\pi_4$ denote the pressures of nodes 1, 2, 3, and 4, respectively; $\bar{p}$ is the available power generation from RESs; and $h_{gas}$ and $h_{H_2}$ denote the gross calorific values of natural gas and hydrogen, respectively, and their values are 10636 MWh/Mm$^3$ (i.e., 38.29 MJ/m$^3$) and 3542 MWh/Mm$^3$ (i.e., 12.75 MJ/m$^3$) [29], respectively.

The objective function (1) is the total cost of gas supply. Constraints (2)-(5) pertain to energy flow balance at nodes 1-4, respectively. Constraint (6) represents the capacity of S1 and S2. Constraint (7) limits the amount of power injected into the P2H unit at node 3. Constraint (8) calculates the energy flow rate through each pipeline by multiplying the volumetric flow rate and the gross calorific value of this pipeline. Constraint (9) specifies the gross calorific value at nodes 1 and 2 as there is no hydrogen blending at both nodes. Constraint (10) corresponds to the gas flow balance at node 3 with hydrogen injections. Constraints (11)-(13) relate the volumetric flow rates with nodal pressures for pipelines 1-2, 2-3, and 3-4, respectively. Constraint (14) limits the operating pressure of each node. It should be clarified that the hydrogen blending limit and the lower bound of nodal pressures are omitted here to analyze the impact of hydrogen injections on gas system operations.

We consider three comparative cases (Cases I-III), in which the available power generation from RESs (i. e., the value of $\bar{p}$) is set to be 2, 3, and 4 MW, respectively. Case II represents a reference case, while Cases I and III correspond to the scenario of intermittent RES generation. Table I summarizes the operating results of gas system obtained under the three cases.

TABLE I
OPERATING RESULTS OF GAS SYSTEM OBTAINED UNDER CASES I-III

| Case | Hydrogen blending of node 3 (%) | Gross calorific value of node 3 (MWh/Mm$^3$) | Pressure of node 3 (bar) | Pressure of node 4 (bar) | Gas flow rate through pipeline 3-4 (Mm$^3$/h) |
|---|---|---|---|---|---|
| Case I | 5.8 | 10226 | 31.8 | 29.4 | 0.0039 |
| Case II | 8.5 | 10033 | 32.6 | 30.1 | 0.0040 |
| Case III | 11.1 | 9847 | 33.4 | 30.9 | 0.0041 |

The comparison of the operating results obtained in Cases I and III with those obtained from Case II indicates that:

1) A relatively high penetration level of green hydrogen might result in insecure gas-hydrogen blending, e.g., the hydrogen blending at node 3 of Case III is up to 11.1%, which exceeds the allowed limit of 10%.

2) A relatively low penetration level of green hydrogen might result in insecure nodal pressures, e.g., the pressure at node 4 of Case I (27.7 bar) is lower than its lower operating bound (30 bar).

These results quantitatively show how the stochastic hydrogen injection affect the secure operation of the gas system. This calls for accurate simulation of gas−hydrogen systems and sufficient coordination of gas and power in short-term operations.

## III. MODELING AND COORDINATION OF INTEGRATED POWER−TRANSPORTATION−HYDROGEN SYSTEMS

This section analyzes the coordination of integrated power−transportation−hydrogen systems. The coupling of the three systems includes EV charging stations and hydrogen refueling stations, as shown in Fig. 3. Specifically, the multi-energy interdependency includes the following two aspects.

1) The spatial-temporal traffic flows are impacted by the charging demands of EVs or refueling demands of hydrogen fuel cell vehicles (HFCVs).

2) The delivery of hydrogen between hydrogen refueling stations using tube trailers is impacted by traffic flows.

Note that both EVs and HFCVs contribute to the decarbonization of transportation networks. At present, the market share of HFCVs is much lower than that of EVs due to the high hydrogen cost. However, the growth of hydrogen supply chain in the near future might increase the market competitiveness of HFCVs.

The following two subsections summarize the planning and operation of integrated power−transportation−hydrogen systems. Then, a simplified example is used to illustrate the flexibility provided by the transportation network to accommodate the fluctuation of RES generation.

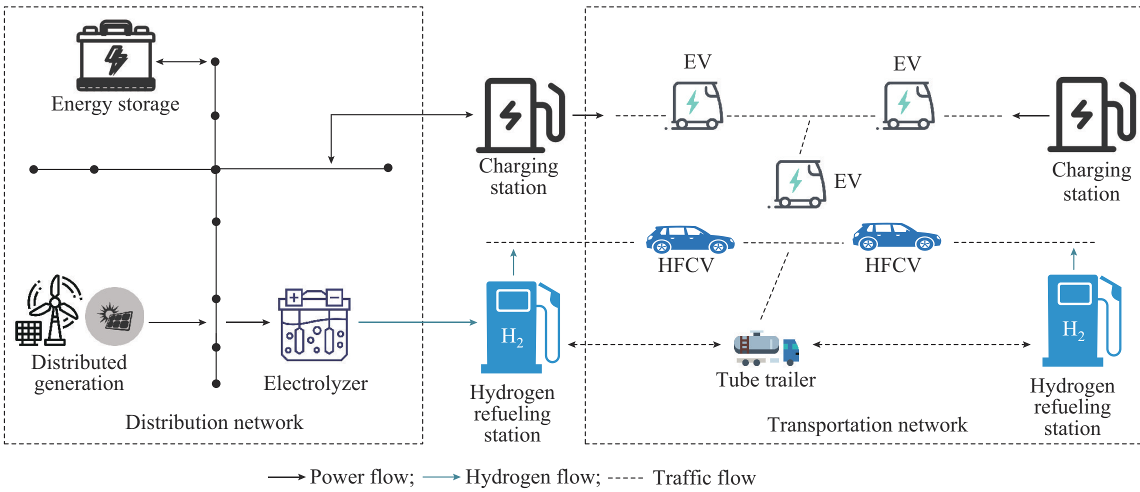


Fig. 3. Structure of an integrated power–transporation–hydrogen system.

### *A. Planning of Integrated Power–Transportation–Hydrogen Systems*

The current literature examines a few approaches to build new hydrogen supply chains that coordinate with the expansion planning strategies of power distribution networks.

Reference [68] provides a comprehensive review on the major challenges faced by the planning of hydrogen refueling infrastructures. It concludes that the green hydrogen could become a competitive transportation fuel as the progress in RES generation and P2H technology. Reference [69] proposes a coordinated planning model of power distribution and transportation networks, in which the planning of both EV charging and hydrogen refueling stations is considered. It shows that hydrogen refueling stations function as energy storages that contribute to accommodating RES generation. Reference [70] analyzes the interaction of planning hydrogen refueling stations and the national power system. The interdependency between marginal power prices and levelized cost of hydrogen is quantified. Reference [71] develops a bi-level planning model of hybrid EV charging facilities and hydrogen refueling stations that considers interdependent power, hydrogen, and traffic flows. It shows that neglecting network constraints at the planning stage might result in insecure operating results in practical operations. Reference [72] provides a comprehensive economic comparison between centralized and decentralized hydrogen supply facilities for heavy road transportation. Comparison results demonstrate that decentralized electrolysis-based hydrogen supply generally provides lower hydrogen delivery cost. Reference [73] investigates the role of P2H on the decarbonization of power distribution and transportation networks based on a long-term planning model. Results from Texas show that the deployment of P2H contributes to 93% reduction of renewable energy curtailment in zero-emission scenario. Reference [74] proposes a multi-objective planning model of hydrogen refueling stations, in which both operating cost and operational risk are taken into account. Reference [75] considers the integrated investment of power and hydrogen supply infrastructures including hydrogen pipelines and refueling stations, P2H facilities, and RESs. The economic benefit provided by power – transportation – hydrogen coordination is analyzed. Reference [76] develops a coordinated planning model for gas refueling stations, in which the expansion planning strategies of power and gas distribution networks are co-optimized. Reference [77] presents a centralized planning model for hydrogen supply chain that consists of hydrogen production stations, refueling stations, storages, and delivery network. Both truck logistics and gas pipelines are considered for hydrogen delivery. Reference [78] proposes an integrated planning model of hydrogen production stations, refueling stations, and pipelines, in which the simulation of refueling demands of HFCVs is included.

An open challenge on this research topic is that the investment decisions of transportation infrastructures need to take spatial-temporal traffic flows into account to produce realistic planning results. This, however, might result in significant computational challenge. Additionally, the entity that operates charging or refueling stations need to consider the approaches to satisfying demands from EVs or HFCVs (e.g., from energy storage or demand response) in case of energy supply shortage due to RES generation fluctuation.

### *B. Operation of Integrated Power–Transportation–Hydrogen Systems*

The extant literature examines a few approaches to coordinate the operation of power, transportation, and hydrogen systems, including the coordination between green hydrogen production and transportation, the coordination between charging/refueling stations (powered by RESs) with charging/refueling demands from EVs and HFCVs, and the coordination of multi-energy resources to provide flexibility operating service for the power grid.

Reference [79] presents a transportation system with 100% renewable power, in which hydrogen acts as a core energy carrier. The technical feasibility of designing such a carbon-neutral energy system is analyzed. Reference [80] proposes a coordinated operating model of urban power and transportation systems. The model considers the delivery of hydrogen using tube trailers, in which an improved optimal vehicle routing model is adopted. Reference [81] designs a off-grid charging station powered by solar panels and P2H facilities. Diesel generators are included in the charging station to provide stable energy supply for EVs and HFCVs. Reference [82] develops a stochastic operation model of coupled power, hydrogen, and transportation networks. The alternating direction method of multipliers (ADMM) algorithm is adopted to provide a decentralized operating strategy that preserves the information privacy of different energy sectors. Reference [83] coordinates the multi-period operation of solar power, EV charging, and hydrogen refueling stations. The model preventive control approach is employed to smooth the fluctuation of solar power generation. Reference [84] designs a decentralized local energy market mechanism for integrated power and hydrogen microgrid with EVs and HFCVs. A fast ADMM algorithm combined with mobile edge computing is employed to produce decentralized market clearing results. Reference [85] proposes a joint scheduling model of integrated power and hydrogen transportation networks, which considers the emission cost from both power and hydrogen production. The transportation of hydrogen using tube trailers is represented as vehicle routing problem with time-delay penalization. Reference [86] develops a coordinated control model of multiple hydrogen refueling stations. The green hydrogen demands are estimated based on a capsule network that captures spatial-temporal traffic flows. Reference [87] models the cooperation between hydrogen and transportation systems as a Stackelberg game, which incorporates a dynamic hydrogen pricing model that depends on the market share of green hydrogen. Reference [88] proposes a bi-level optimization model of profit-maximization hydrogen service providers that decide the production and transportation of hydrogen and the strategic bidding strategy in power markets. It shows that the information interchange among power, hydrogen, and transportation systems contributes to lower operating cost of hydrogen service providers. Reference [89] presents a resilient operating strategy for hydrogen-integrated power distribution networks, in which the flexibility of mobile HFCVs is exploited to provide restorative strategies. An energy sharing strategy is proposed to coordinate the flexible operation of hydrogen refueling stations, HFCVs, and distributed generators. Reference [90] presents a coordinated operation model of power and hydrogen systems that integrates the price-based demand response from HFCVs. The impact of traffic flows on hydrogen delivery and refueling demands is analyzed in detail. Reference [91] develops a low-carbon operation model of integrated power, transportation, and hydrogen systems that considers nodal carbon intensity limits. A specific hydrogen refueling service fee (HRSF) is designed to allocate the refueling demands of HFCVs.

We note that these related studies generally assume that all EVs/HFCVs have identical routing and charging/refueling preferences, which might not be realistic in practice. Besides, one or more agents are generally required to exploit the flexibility of decentralized EVs/HFCVs. Hence, analyzing the market equilibria that model the interactions among power/hydrogen suppliers, market agents, and EVs/HFCVs is of practical relevance.

### C. Demonstration Projects

The typical demonstration projects of hydrogen-integrated transportation are summarized as follows.

1) EU H2Haul project [92]: this five-year project started in 2019, and aims to deploy 16 heavy-duty hydrogen trucks in four European countries combined with building a new network of refueling stations.

2) The Hydrogen Energy Supply Chain (HESC) liquefied hydrogen carrier project [93]: as the worldwide first liquefied hydrogen carrier, the ship Suiso Frontier transported 1250 $m^3$ liquefied hydrogen with the distance of over 9000 km. This project showed that the large-scale transportation of liquefied hydrogen can be achieved like traditional natural gas.

3) The Alberta Motor Transport Association (AMTA) hydrogen commercial vehicle demonstration program [94]: this project was launched in Feb. 2023, and was the first demonstration program of hydrogen-fueled trucks in Canada. The performance information of hydrogen trucks, including fuel reliability, vehicle cost, and maintenance, will be gathered and analyzed.

4) Hydrogen-powered buses in Beijing Winter Olympics [95]: in 2022 Beijing Winter Olympics, the public transport in Zhangjiakou was provided by 710 hydrogen-powered buses, whose fuels were provided by ten hydrogen production plants and refueling stations.

### D. Example

We illustrate the flexibility of traffic network scheduling using a straightforward example, as shown in Fig. 4.

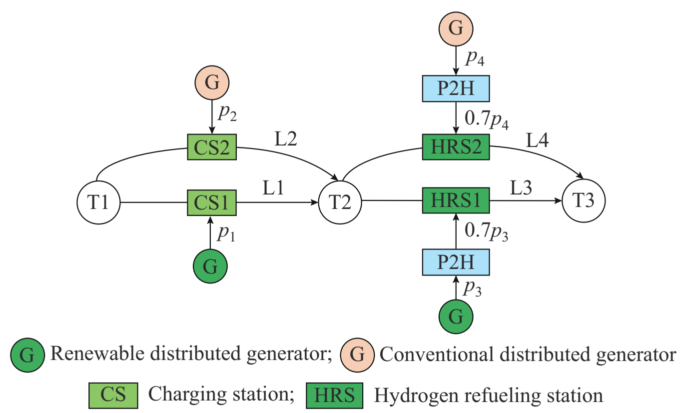


Fig. 4. Hybrid model of 3-node traffic network.

The traffic network consists of three nodes T1-T3 and four links L1-L4. The charging stations CS1 and CS2 are located on links L1 and L2, respectively, while the hydrogen refueling stations HRS1 and HRS2 are situated on links L3 and L4, respectively. The capacity of each charging station is 400 vehicles, while the capacity of each hydrogen refueling station is 100 vehicles. The traffic demand is 400 vehicles, with an average charging demand $E$ of 10 kW and an average hydrogen demand $H$ of 1 kg.

The static traffic network model is illustrated as follows.

$$\min\left(80p_2+80p_4+\sum_{rs}u_{rs}^{e}\pi^{e}q_{rs}+\sum_{rs}u_{rs}^{h}\pi^{h}q_{rs}\right) \qquad (15)$$

s.t.

$$\pi^e q_{rs}=\sum_{k\in K_{rs}^e} f_{k,rs}^e \tag{16}$$

$$\pi^h q_{rs}=\sum_{k\in K_{rs}^h} f_{k,rs}^h \tag{17}$$

$$x_a^{rg}=\sum_{rs}\sum_{k\in K_{rs}^h} f_{k,rs}^h\delta_{a,k,rs}^h+\sum_{rs}\sum_{k\in K_{rs}^e} f_{k,rs}^e\delta_{a,k,rs}^e \quad a\in T_A^{rg} \tag{18}$$

$$x_a^{che}=\sum_{rs}\sum_{k\in K_{rs}^e} f_{k,rs}^e\delta_{a,k,rs}^e \quad a\in T_A^{che} \tag{19}$$

$$x_a^{chh}=\sum_{rs}\sum_{k\in K_{rs}^h} f_{k,rs}^h\delta_{a,k,rs}^h \quad a\in T_A^{chh} \tag{20}$$

$$t_a^{rg}=t_a^0\left[1+0.15\left(\frac{x_a^{rg}}{c_a^{rg}}\right)^4\right] \quad a\in T_A^{rg} \tag{21}$$

$$t_a^{che}=t_a^{c0}\left(1+J\frac{x_a^{che}}{c_a^{che}-x_a^{che}}\right) \quad a\in T_A^{che} \tag{22}$$

$$t_a^{chh}=t_a^{h0}\left(1+J\frac{x_a^{chh}}{c_a^{chh}-x_a^{chh}}\right) \quad a\in T_A^{chh} \tag{23}$$

$$c_{k,rs}^h=\sum_{a\in T_A^{rg}}(\omega t_a^{rg}+\theta_a^{rg})\delta_{a,k,rs}^h+\sum_{a\in T_A^{chh}}(\omega t_a^{chh}+\lambda_h H+\theta_a^{chh})\delta_{a,k,rs}^h \tag{24}$$

$$c_{k,rs}^e=\sum_{a\in T_A^{rg}}(\omega t_a^{rg}+\theta_a^{rg})\delta_{a,k,rs}^e+\sum_{a\in T_A^{che}}(\omega t_a^{che}+\lambda_e E+\theta_a^{che})\delta_{a,k,rs}^e \tag{25}$$

$$0\le f_{k,rs}^h\perp c_{k,rs}^h-u_{rs}^h\ge 0 \tag{26}$$

$$0\le f_{k,rs}^{e}\perp c_{k,rs}^{e}-u_{rs}^{e}\ge 0 \tag{27}$$

$$p_1=x_{CS1}^{che}E \tag{28}$$

$$p_2=x_{CS2}^{che}E \tag{29}$$

$$0.7p_3=x_{HRS1}^{che}H\xi \tag{30}$$

$$0.7p_4=x_{HRS2}^{che}H\xi \tag{31}$$

$$0\le p_1,p_2,p_3,p_4\le\bar{p} \tag{32}$$

where $p_1$, $p_2$, $p_3$, and $p_4$ are the charging/refueling demands at the corresponding stations; $q_{rs}$ is the total travel demand; $u_{rs}^e$ and $u_{rs}^h$ are the minimum travel costs of EVs and HFCVs, respectively; $\pi^e$ and $\pi^h$ are the penetration rates of EVs and HFCVs, respectively; $f_{k,rs}^e$ and $f_{k,rs}^h$ are the traffic flows of EVs and HFCVs that choose on path $k$, respectively; $K_{rs}^e$ and $K_{rs}^h$ are the path sets of EVs and HFCVs, respectively; $x_a^{rg}$ is the traffic flow on regular links; $x_a^{che}$ is the traffic flow of EVs on charging links; $x_a^{chh}$ is the traffic flow of HFCVs on hydrogen refueling links; $\delta_{a,k,rs}^e$ and $\delta_{a,k,rs}^h$ are the coupling relationships between link $a$ and path $k$ of EVs and HFCVs, respectively; $T_A^{rg}$, $T_A^{che}$, and $T_A^{chh}$ are the sets of regular links, charging links, and refueling links, respectively; $t_a^0$ is the free travel time on regular links; $t_a^{rg}$, $t_a^{che}$, and $t_a^{chh}$ are the travel duration at each regular link, queuing time spent at each charging link, and queuing time at each refueling link, respectively; $c_a^{rg}$, $c_a^{che}$, and $c_a^{chh}$ are the capacities of regular link, charging link, and refueling link, respectively; $t_a^{c0}$ and $t_a^{h0}$ are the free flow travel time of EVs and HFCVs at the charging and hydrogen refueling links, respectively; $c_{k,rs}^h$ and $c_{k,rs}^e$ are the total travel costs of EVs and HFCVs, respectively; $J$ is typically set to be 0.05; $\omega$, $\lambda_h$, and $\lambda_e$ are the unit time cost of travellers, reference electricity price of CSs, and reference hydrogen price of HRSs, respectively; $\theta_a^{rg}$, $\theta_a^{che}$, and $\theta_a^{chh}$ are the congestion toll (CT) for links, charging service fee (CSF) for CSs, and HRSF for HRSs, respectively; $x_{CS1}^{che}$ and $x_{CS2}^{che}$ are the charging demands at CS1 and CS2, respectively; $x_{HRS1}^{che}$ and $x_{HRS2}^{che}$ are the refueling demands at HRS1 and HRS2, respectively; and $\xi$ is the efficiency of the P2H conversion.

The objective function (15) represents the overall expenditure of the traffic network. Constraints (16) and (17) depict the correlations between travel demands and path flows. Constraints (18)-(20) elucidate the connections between link flows and path flows. Constraint (21) conveys the relationship between link travel time and link traffic flow. Constraints (22) and (23) specify the corresponding waiting time of EVs and HFCVs at CSs and HRSs, respectively. Constraints (24) and (25) outline the travel costs for EVs and HFCVs, respectively. Constraints (26) and (27) articulate expressions of Wardrop's first principle, which affirms that a traffic network attains an equilibrium state when all travelers on their roads possess complete knowledge of the traffic conditions and strive to choose the shortest path. Constraints (28)-(32) establish the interplay between power generation and traffic flow.

Similarly, we consider three comparative cases, namely Cases 1-3, where the available power generation from RESs (i.e., the value of $\bar{p}$) is set to be 1, 2, and 4 MW, respectively. Case 2 represents the reference scenario, while Case 1 and Case 3 correspond to scenarios involving intermittent RES generation. Tables II and III show the comparison of operating results of traffic network and service fees of different stations in the three cases, respectively. CSF1 and CSF2 are the service fees of the CS1 and CS2, respectively; and HRSF1 and HRSF2 are the service fees of the HRS1 and HRS2, respectively.

TABLE II
COMPARISON OF OPERATING RESULTS OF TRAFFIC NETWORK OBTAINED IN CASES 1-3

| Case | Operating result (number of vehicles) | | | |
|---|---|---|---|---|
| | CS1 | CS2 | HRS1 | HRS2 |
| Case 1 | 100 | 220 | 11 | 69 |
| Case 2 | 200 | 120 | 22 | 58 |
| Case 3 | 294 | 26 | 45 | 35 |

TABLE III
COMPARISON OF SERVICE FEES OF DIFFERENT STATIONS IN CASES 1-3

| Case | Service fee ($/h) | | | |
|---|---|---|---|---|
| | CSF1 | CSF2 | HRSF1 | HRSF2 |
| Case 1 | 2.88 | 0 | 1.56 | 0 |
| Case 2 | 0 | 1.74 | 0.78 | 0 |
| Case 3 | 0 | 9.12 | 0 | 0.18 |

The comparison of the distribution results of Cases 1-3 reveals that:

1) With the increased output of RESs, more EVs and HFCVs are dispatched to stations powered by renewable distributed generator (i.e., CS1 and HRS1) to accommodate clean energy. This demonstrates the flexible response characteristics exhibited by EVs and HFCVs.

2) In Case 1, when RES is scarce, service fees are imposed at CS1 and HRS1 to guide vehicles towards stations powered by conventional distributed generator. Conversely, in Case 3, when RES becomes more abundant, the situation is reversed. This demonstrates the capacity of service fees to regulate the flow of vehicles.

These findings demonstrate the flexible response potential of EVs and HFCVs, which necessitates accurate simulation of integrated power–transportation–hydrogen systems to guide travelers in accommodating RESs and achieving cost reduction in system operations.

## IV. Future Research

This paper provides an overview of the integration of green hydrogen into natural gas and transportation systems. Pressing research topics are summarized as follows.

### *A. Energy Market Design Promoting Integration of Green Hydrogen*

The environmental value of green hydrogen in comparison with gray/blue hydrogen has not been taken into account in current hydrogen trading markets. Hence, the green certificate mechanism [96] or emission-based taxation mechanism [97] that has been widely adopted in the power industry could be introduced to the hydrogen industry, which may stimulate the investment in green hydrogen production technologies. Many countries, including US and China, have made ambitious goals in transitioning to hydrogen-integrated energy systems, which would spur growth of green hydrogen markets [98]. Besides, the information exchange and interactions among power, natural gas, and hydrogen markets on different time scales are required since their market clearing results are interrelated [99]. In practice, the power, natural gas, and hydrogen markets are operated by different entities, and their coordination generally requires market-based mechanisms.

Another major issue lies in the mitigation of market power exercised by market agents [100]. For example, the green hydrogen producers (that own RESs and P2H facilities) may provide strategic offers that manipulate market prices in the cases of power/hydrogen supply shortage. Finally, the flexibility market might need to be refined for renewable-dominant energy systems. Readers can refer to [101] and [102] for insights on this topic.

Moreover, the spatial-temporal flexibility of transportation networks emerges as a critical factor in the promotion of green hydrogen. Optimizing the distribution of hydrogen for the transportation sector relies heavily on strategically placing hydrogen refueling stations. This aspect demands a meticulous examination to understand how geographical placement impacts the overall spatial-temporal dynamics of hydrogen supply. Additionally, a thorough exploration of monetary incentives within the transportation sector is crucial. Beyond the broader market design, understanding how financial mechanisms and subsidies can be tailored to specifically encourage the investment of green hydrogen in transportation sectors would be important.

### *B. Risk Assessment and Preventive Control of Hydrogen-integrated Energy Systems*

The increasing multi-energy interdependency might result in significant operational risks, e.g., the natural gas leak that caused rolling blackout in Southern California in 2016 [103]. The operational risk would be further exacerbated in the presence of a significant market share dominated by RESs, whose energy supply exhibits high stochasticity. Therefore, a risk assessment tool is highly desirable for hydrogen-integrated energy systems [104], [105], e.g., analyzing the risk of gas-pipeline operations with stochastic green hydrogen injections. The concept of security region [106], [107] could also be extended to hydrogen-integrated energy systems, which provides visualized feasible operating regions for system operators.

Given the operational risks faced by multi-energy operators, corresponding preventive control strategies need to be implemented to eliminate potential risks [108], [109]. For example, adequate energy storage (hydrogen storage, power storage, or gas line-pack) can be allocated to prepare for energy supply uncertainty or network outages [110]. In addition, preventive reactions by the operators could be combined with the situational awareness tool [111] that provides perception/projection results of current-/near-future operating status based on a vast volume of data collected.

### *C. Application of Artificial Intelligence (AI) Algorithms in Hydrogen-integrated Energy Systems*

The planning/operation problem of multi-energy systems generally needs to consider a massive number of scenarios due to the uncertainty in RES generation, which is computationally challenging for model-based approaches. This technical issue may be addressed by deep learning techniques [112], [113], which use efficient data-driven approaches to solve traditional physics-related problems. For example, deep neural networks have been proposed to solve nonlinear optimal power flow (OPF) problem [114], whose computational efficiency greatly outperforms traditional model-based approaches. Graph neural networks have been developed to predict dynamic traffic flows [115], which represent a powerful tool for modeling spatial-temporal dependencies in traffic data. Additionally, AI algorithms play an important role in enabling autonomous driving and wireless charging of EVs [116], [117].

Another potential application of AI algorithms lies in facilitating the decentralized operation of multi-energy systems that preserves information privacy. For example, [118] proposes a machine-learning aided approach to solve the decentralized OPF problem of multi-region power systems, in which the learning approach is employed to predict the information exchange between different regions. Reference [119] proposes a reinforcement learning approach to operate an EV charing station that interacts with the power grid and EVs.

## V. Conclusion

As the cost associated with green hydrogen investment, production, and transportation is relatively high, the widespread application of green hydrogen remains uncertain. However, green hydrogen can be considered as a promising pathway for future energy transition. This paper reviews current research on power−natural gas−hydrogen coordination and power−transportation−hydrogen coordination. The extant literature has shown that the green hydrogen contributes to the accommodation of intermittent RESs in multi-energy systems as its integration provides additional operating flexibility. We summarize future research directions of hydrogen-integrated energy systems from the perspective of market design, security operation, and AI algorithm application. Finally, we believe that the economic and environmental benefit from the green hydrogen integration identified and the pressing research topics summarized provide a foundational reference for academic investigations and engineering application of green hydrogen.

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