# On the Consistency of Renewable-to-Hydrogen Pricing

Litao Zheng, *Student Member*, *IEEE*, Jianxiao Wang, *Member*, *IEEE*, *Member*, *CSEE*, Yang Yu, *Member*, *IEEE*, Gengyin Li, *Member*, *IEEE*, Ming Zhou, *Member*, *IEEE*, Qing Xia, *Senior Member*, *IEEE*, and Guizhi Xu

***Abstract*—With the proposal of carbon neutrality goals and hydrogen energy development strategies in various countries, the development and construction of hydrogen supply chains have become important priorities. However, existing research has paid little attention to the hydrogen market and pricing. Therefore, a hydrogen pricing method based on *marginal pricing theory* is proposed in this paper, which adapts to hydrogen systems with renewable-to-hydrogen as a major source, in the future. A hydrogen energy market is established to define the industrial chain of hydrogen and the hydrogen trading process. The hydrogen market-clearing model is formulated considering a dynamic line pack. Due to its nonconvexity, the model is equivalently converted into mixed-integer second-order cone programming, and the optimality gap is minimized by introducing a penalty term. Based on the clearing solution, the concept and calculation method of the locational marginal hydrogen price (LMHP) are proposed with respect to the locational marginal price (LMP) in electricity markets. Case studies based on a modified Belgium 20-node gas network and Pennsylvania, New Jersey, and Maryland (PJM) market operation data demonstrate the consistency between LMHP and LMP.**

***Index Terms*—Hydrogen market, locational marginal price, renewable-to-hydrogen, second-order cone programming, Weymouth equation.**

## I. Introduction

FACED with the global problem of carbon emissions and greenhouse effects, many countries have put forward their plans and goals of energy conservation and emission reduction in recent years [1]. The goal of carbon neutrality has been formally put on the agenda of most countries. The combustion of fossil energy is a major source of carbon emissions. To achieve the goal of carbon neutrality, there is an urgent need to reduce dependence on fossil energy, find green substitute energy, and establish a green, safe, and stable energy system [2].

In the context of carbon neutrality, the development of hydrogen energy is an irreplaceable means to promote the transition of the energy system to a clean, low-carbon, safe, and efficient energy system [3]. With properties of high calorific value, convenient conversion, and so on, hydrogen is becoming a new type of secondary energy source with equal emphasis on electricity [4], [5]. According to the Hydrogen Council, the world is predicted to begin using hydrogen energy on a large scale starting in 2030. By 2050, hydrogen energy will account for 18% of the world's final energy consumption and contribute 20% to the global carbon dioxide emission reduction [6]. Major developed countries in the world have attached great importance to the development of hydrogen energy.

In 2017, Japan issued its basic strategy of hydrogen energy and planned to open the international hydrogen supply chain by 2030 and build a medium- and long-term "hydrogen energy society" by 2050 [7]. The Department of Energy (DoE) of the United States issued the "Hydrogen Program Plan" in 2020, to vigorously promote the development of the hydrogen industry [8]. In 2020, the European Commission issued the policy document "A hydrogen strategy for a climate-neutral Europe", announcing the establishment of the EU hydrogen industry alliance [9].

According to the current development trend, hydrogen energy will soon form a complete energy system, including production, transportation, storage, utilization, etc., and will also enable a better trading mechanism. The great development potential of hydrogen has attracted numerous researchers, and several research results has been published. In [10] a wind power hydrogen coupling network is established that includes electrolyzers, pipelines, compressors, vessels, refueling stations, etc. A renewable hydrogen energy network is given in [11]. It describes the superstructure of a biomass-based hydrogen energy system in detail, which includes different biomass resources and various technologies. In [12], several renewable energy sources, including wind power and photovoltaic power are used as primary energy sources, while electrolyzers, fuel cells, hydrogen storage, and batteries are used as ways to absorb renewable energy, and a hydrogen-electric coupling energy system is constructed. These articles

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L. T. Zheng, J. X. Wang (corresponding author, e-mail: wangjx@ncepu.edu.cn; ORCID: https://orcid.org/0000-0001- 9871-5263), G. Y. Li and M. Zhou are with State Key Laboratory of Alternate Electrical Power System with Renewable Energy Sources, North China Electric Power University, Beijing 102206, China.

Y. Yu is with Institute for Interdisciplinary Information Sciences, Tsinghua University, Beijing 100084, China.

Q. Xia is with State Key Lab of Power Systems, Department of Electrical Engineering, Tsinghua University, Beijing 100084, China.

G. Z. Xu is with Global Energy Interconnection Research Institute co., Ltd., State Grid Corporation of China, Beijing 102211, China.

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provide many valuable suggestions for the construction of future hydrogen energy systems, however, most of them focus on the integration of hydrogen and renewable energy; relatively fewer articles have focused on hydrogen trading and the hydrogen market, even though hydrogen trading and market are an important part of the hydrogen system.

In [13], an interactive system of wind power and hydrogen is constructed and a hydrogen energy market including contract trading and free trading is built. In [14], a local energy market is constructed considering distributed generators, loads, hydrogen vehicles, hydrogen storage systems, etc. An iterative clearing method is proposed based on the merit order principle. In [15], the relationship between wind power generation and hydrogen production is studied, and the pricing method of hydrogen is given considering the factors of investment, operation, maintenance, and electricity price. In [16] the operation mechanism of the UK natural gas market and capacity market is summarized and the composition, transaction mode, and pricing model of the market are analyzed. In [17] the structure and pricing model of the Australian natural gas market is introduced and the natural gas price is decomposed into multiple components under the cost-plus pricing method. In [18] a dynamic pricing method of natural gas is proposed, comprehensively considering the coupling and dynamic response of power systems and natural gas systems. Based on the American natural gas market, in [19] the natural gas price is studied and the risks under this pricing method analyzed. In [20] the supply system of China's natural gas system and the pricing mechanism of natural gas is described and several problems that exist in actual operation are revealed. These articles lay a favorable foundation for future hydrogen market structures and hydrogen pricing.

However, current hydrogen pricing mostly constitutes cost-plus pricing [15], [21]. Few studies have focused on the consistency between hydrogen production costs and electricity prices in the case of a high proportion of renewable-to-hydrogen (Re2H), as well as the hydrogen pricing method. With the traditional cost-plus pricing method, price information has a strong time-lag effect, which often cannot reflect the supply-demand relationship of hydrogen energy systems in time. Moreover, this pricing method lacks competitiveness and vitality. Manufacturers often do not obtain enough production incentives, which affects the development of the whole system and market. In addition, a single cost-plus pricing method easily leads to a monopoly. The price tends to deviate from the actual market value, which is not suitable for highly flexible hydrogen energy systems in the future. In addition, in future hydrogen systems that consider Re2H as the main source of hydrogen, the production cost of hydrogen will fluctuate with the uncertainty of renewable energy, which will exacerbate the problem that the cost-plus pricing method cannot reflect the real-time value of hydrogen in time. Moreover, the influence of pipeline line packs on transmission systems is rarely considered in the above articles. The time delay and buffering effects brought about by the line pack of the pipeline cannot be ignored, and they have an impact on the nodal marginal cost of hydrogen.

In the process of hydrogen trading, the price of hydrogen plays a significant role. For energy systems, price is one of the most important factors directly related to the economic interests of market participants. A reasonable pricing mechanism helps guide consumer behavior and optimize energy utilization [22]. On the other hand, it helps build a good market environment, plays a positive feedback role in the production, transportation, and marketing of hydrogen energy, and drives the development of the entire industry [23]. Therefore, it is necessary to construct the future hydrogen market and propose a more appropriate pricing method.

The existing power market and natural gas market are good precedents, which can provide valuable references for the construction of hydrogen markets. The marginal price pricing method of buses that have been widely implemented is very well-suited [24]. Given these successful practices, we introduce the market and competition in hydrogen systems and propose a new pricing method for hydrogen, in this paper. The contributions are summarized as follows:

1) This paper is the first attempt to propose a marginal pricing-based hydrogen market considering a comprehensive hydrogen supply chain. Based on marginal pricing theory, the concept of locational marginal hydrogen price (LMHP) is proposed to reflect the natural law of hydrogen price changing with electricity price when Re2H dominates the production of hydrogen energy in the future.

2) A mathematical model of a hydrogen energy system is established considering a dynamic line pack. The LMHP is derived from the node hydrogen supply and demand equation, which can reflect the hydrogen supply, demand, pipe capacity, and line pack.

3) Due to the existence of the Weymouth equation, the model is quite nonlinear and nonconvex. The model is equivalently transformed into a mixed-integer quadratic programming (MIQCP) problem, and then a minimum penalty is introduced through second-order cone programming (SOCP) to guide the reduction of the optimal gap.

## II. Hydrogen Market

In this section, a hydrogen market framework is designed for hydrogen energy systems, as shown in Fig. 1. The hydrogen system is connected to power systems, and includes the four parts of the hydrogen industry chain: production, storage, transportation, and utilization. Three major market participants are included: hydrogen producers, retailers, and customers.

Hydrogen producers act as the source of hydrogen in the market. Currently, the main sources of hydrogen are water electrolyzation, fossil energy, biomass energy, etc. According to the development trends and strategic carbon neutrality goals of various countries, renewable energy will play a leading role in the future energy system. In green and low-carbon energy systems in the future, Re2H through water electrolysis will be one of the main sources of hydrogen. Therefore, in this paper, it is assumed that the main source of hydrogen in the hydrogen energy system, is green hydrogen, and the rest is a small amount of industrial byproduct hydrogen. Renewable energy power plants produce low-cost green electricity through renewable energy sources such as solar power, wind power,

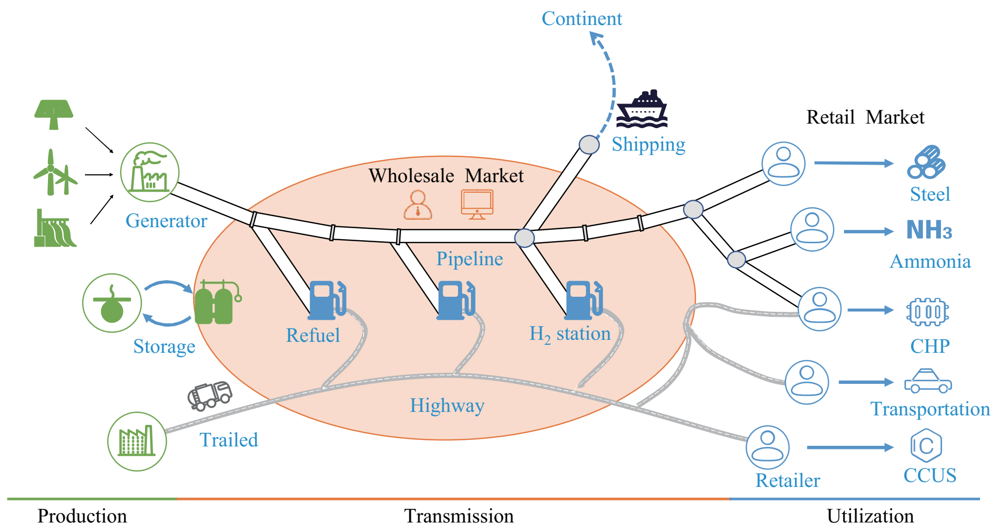


Fig. 1. Overview of the future hydrogen market.

and hydropower, and then use the generated electricity to electrolyze water to produce green hydrogen. The use of low-priced renewable energy electricity to produce hydrogen reduces the production cost of hydrogen while simultaneously providing a way to accommodate renewable energy for the power system and improve the stability of the power grid. At present, the main electrolytic hydrogen production methods include alkaline water electrolysis (AWE), proton exchange membrane (PEM) electrolysis, and solid oxide electrolysis (SOE). The technology of AWE is relatively mature, and the production cost is somewhat lower, but its conversion efficiency is poor. PEM electrolysis has a large current density, high efficiency, small volume, and good flexibility, and meets the needs of renewable energy consumption and future development trends. It is likely to become the main method of green hydrogen production in the future. Nevertheless, the production cost of PEM electrolysis is currently relatively high. While having good stability and high efficiency, SOE is still in the experimental stage. The transportation of hydrogen energy is also a cardinal part of its economy. In view of economic considerations, pipelines and trucks will be used for short- and medium-distance transportation, and long-distance transportation will be completed by ship. Hydrogen retailers buy hydrogen from hydrogen producers through the wholesale market and then sell them to various hydrogen energy users in the retail market. Hydrogen energy finds use in steel-making, ammonia production, cogeneration, hydrogen energy transportation, and carbon capture, utilization, and storage (CCUS) [25].

From the perspective of the market, the whole hydrogen market can be divided into wholesale markets and retail markets. The orange area in Fig. 1, represents the wholesale market. In addition to hydrogen producers and hydrogen retailers, the wholesale market also includes major users, financial traders, and hydrogen storage companies. Financial traders are mainly engaged in financial trade and profit from seasonal price differences and day price differences. The hydrogen storage company can alleviate the contradiction between supply and demand in the hydrogen energy system, maintain the balanced and stable operation of the system, and provide certain auxiliary services for the hydrogen energy system. An independent system operator (ISO) takes charge of the operation of the wholesale market. Many manufacturers and retailers participate in the market at the same time to ensure full competition in the market. The transaction in the wholesale market is carried out in the form of centralized bidding, which is in much the same way as the electricity market. The retail market involves free trade between retailers and users.

From the perspective of the time horizon, the hydrogen market can be divided into medium- and long-term markets and spot markets. Among them, the medium- and long-term markets can also be subdivided into annual markets and quarterly markets; the spot market can be divided into monthly markets, intraday markets, and balanced markets.

In addition, the hydrogen energy market can be spatially divided into domestic markets and foreign markets. Foreign market transactions are mainly bilateral transactions, and hydrogen is transported by ship or pipeline. Domestic market transactions are mostly conducted through wholesale and retail markets, and here pipelines and trailers are the two major modes of transportation.

In the hydrogen market, all the participants aim to maximize their profits during every transaction. On the one hand, to raise their revenue, hydrogen producers want to set a high price. On the other hand, hydrogen retailers want to lower the hydrogen price in the wholesale market. Therefore, only when a fair and rational pricing method is applied in the market can fairness and efficiency be guaranteed [26]. Thus, to build an efficient and fair hydrogen market, the first step is to determine a reasonable pricing method.

## III. System Model

### *A. Assumptions & Simplifications*

In this section, a hydrogen market-clearing model is proposed. Some prerequisite assumptions and simplifications are made based on the hydrogen energy market framework, as follows:

(1) In the hydrogen energy market proposed above, the sources of hydrogen include electrolyzed water and a small amount of industrial byproduct hydrogen. To study the characteristics of the hydrogen market with water electrolyzation as the main source of hydrogen, we focus on electrolyzers in this paper, ignoring industrial byproduct hydrogen. In other words, the hydrogen produced from electrolysis is regarded as the only source of hydrogen.

(2) In the aforementioned hydrogen market, road transportation is suitable for contract transactions, and pipeline transportation is suitable for centralized transactions. The following discussion focuses on the hydrogen market transaction method under pipeline network transportation, assuming that the hydrogen in the transaction is transmitted through the pipeline.

### B. Constraints of Hydrogen System

#### 1) Hydrogen Production Constraints

Electrolyzers work as hydrogen sources in hydrogen systems and are used to convert electric energy into hydrogen. Its mathematical model is as follows:

$$H_{i,t}^{\mathrm{G}} = \frac{\gamma P_{i,t} \times 3600}{H_{\mathrm{CV}}} \tag{1}$$

$$\underline{H}_i^{\mathrm{G}} \leq H_{i,t}^{\mathrm{G}} \leq \overline{H}_i^{\mathrm{G}} \forall i, \forall t \tag{2}$$

where $P_{i,t}$ is the power consumed by the electrolyzer, $H_{i,t}^{\mathrm{G}}$ is the output of the electrolyzer, $\gamma$ is the conversion efficiency between electric energy and hydrogen energy, and $H_{\mathrm{CV}}$ is the calorific value of hydrogen. $\overline{H}_i^{\mathrm{G}}$ and $\underline{H}_i^{\mathrm{G}}$ are the upper and lower limits of outputs of electrolyzers, respectively. Equation (1) shows the conversion between electricity and hydrogen. Equation (2) represents the output limits for water electrolyzation.

#### 2) Hydrogen Flow Constraints

The hydrogen flow in the pipe network is constrained by the nodal pressure, gas state equation, and others, which can be described by the following formulas:

$$\underline{\pi}_i \leq \pi_{i,t} \leq \overline{\pi}_i \quad \forall i, \forall t \tag{3}$$

$$\underline{H}_l \leq H_{l,t} \leq \overline{H}_l \quad \forall l, \forall t \tag{4}$$

$$H_{l,t} = \frac{H_{l,t}^{\mathrm{I}} + H_{l,t}^{\mathrm{O}}}{2} \tag{5}$$

$$\mathrm{sign}(H_{l,t}) H_{l,t}^2 = W_l^2 (\pi_{i,t}^2 - \pi_{j,t}^2) \quad \forall l, \forall t \tag{6}$$

$$\sum_{i \in n} H_{i,t}^{\mathrm{G}} - \sum_{l:\varphi_{\mathrm{I}}(l)=n} H_{l,t}^{\mathrm{I}} + \sum_{l:\varphi_{\mathrm{O}}(l)=n} H_{l,t}^{\mathrm{O}} = H_{i,t}^{\mathrm{D}} \quad \forall i, \forall t \tag{7}$$

where $I$ is the set of electrolyzers, $L$ is the set of hydrogen transmission pipelines, and $T$ is the set of time slots. $H_{l,t}$ is the average hydrogen flow in the transmission pipeline. $\overline{H}_l$ and $\underline{H}_l$ are the upper and lower limits of the average hydrogen flow. $H_{l,t}^{I}$ and $H_{l,t}^{\mathrm{O}}$ are the input and output hydrogen flow of node $i$, respectively, $\pi_{i,t}$ is the air pressure at node $i$, and $\overline{\pi}_i$ and $\underline{\pi}_i$ are its upper and lower limits, respectively. In addition, $\pi_{i,t}$ and $\pi_{j,t}$ are used to represent the air pressure at the head and end nodes corresponding to pipe $l$, respectively, and $\mathrm{sign}(H_{l,t})$ implies the hydrogen flow direction in branch $l$, which is determined by the pressure of the two nodes. When the flow in the pipe is in the positive direction, the pressure at the beginning node of the pipe is greater than that at the end node, $\mathrm{sign}(.)$ is +1, and when the flow in the pipe is in the opposite direction, $\mathrm{sign}(.)$ is $-1$. $W_l$ is the coefficient of the Weymouth equation, which depends on the length, diameter, and friction of the pipeline. $H_{i,t}^{\mathrm{D}}$ is the hydrogen demand at node $i$.

Equation (3) represents the limits for nodal air pressure. Equation (4) indicates the limits for hydrogen flow in the pipeline. Equation (5) implies the relationship between the average hydrogen flow and flow at the head and end nodes of the pipeline. Equation (6) is the Weymouth formula, which describes the relationship between nodal pressures and pipeline flow. The limits for flow balance at each node are shown in (7). Equation (7) shows that in each time period, the hydrogen intake and hydrogen output of each node remain equal.

#### 3) Line Pack Characteristic Constraints

The line pack is an important feature of pipe network transmission systems. The line pack is the pipeline storage capacity derived from the compressibility of gas during pipeline transmission. It acts as an energy storage device in the process of hydrogen energy transmission. Its mathematical model is as follows:

$$Q_{l,t} = Q_{l,t-1} + H_{l,t}^{\mathrm{I}} - H_{l,t}^{\mathrm{O}} : d \tag{8}$$

$$Q_{l,t} = \frac{K_l}{2} (\pi_{i,t} + \pi_{j,t}) \tag{9}$$

$$0 \leq Q_{l,t} \leq \overline{Q}_l \tag{10}$$

$$\sum_{l \in k} Q_{l,1} = \sum_{l \in k} Q_{l,T} \tag{11}$$

where $Q_{l,t}$ is the line pack of pipeline $l$ in period $t$. $\overline{Q}_l$ represents the upper limits of the line pack. $K_l$ is a constant coefficient related to the physical properties of the pipeline. $Q_{l,1}$ and $Q_{l,T}$ are the line packs at the beginning and end of the day, respectively.

Equation (8) describes the coupling relationship between pipeline line packs and gas flow between different periods. Equation (9) shows the relationship between the line pack of pipe $l$ and the air pressure at both ends. Equation (10) implies the limits of line pack. To ensure the normal operation of the pipe network system, it is assumed that the total amount of line packs at the beginning and end of each day is equal, as shown in (11).

### C. Locational Marginal Hydrogen Price

To calculate the LMHP, the optimal gas flow (OGF) problem needs to be solved first. The OGF problem seeks to minimize the hydrogen production costs subject to the aforementioned hydrogen system operating constraints with fixed hydrogen demand, rendering:

$$\mathrm{Obj} = \min \sum_t \sum_i \alpha p_{i,t}^{\mathrm{LMP}} H_{i,t}^{\mathrm{G}} \tag{12}$$

subject to (1)–(11), where $\alpha$ represents the conversion coefficient between the price of electricity used by the water electrolysis device and the cost per unit of hydrogen produced, and $p_{i,t}^{\mathrm{LMP}}$ is the locational marginal price (LMP) of node $i$ in period $t$. Thus, $\alpha p_{i,t}^{\mathrm{LMP}}$ reflects the cost per unit of produced hydrogen at node $i$.

In power systems, the LMP is defined as the marginal increase in the operational costs for the additional per-unit power load at each bus. In economics, the dual multiplier of resources is defined as the shadow price, which reflects the total cost increase in the objective function caused by the marginal consumption of different resources. Mathematically, the LMP of a bus equals its dual multiplier of the power balance equation in the economic dispatch model [27], as shown in (13):

$$\sum P_i^{\mathrm{G}} = \sum P_i^{\mathrm{D}} : \rho \tag{13}$$

where $P_i^{\mathrm{G}}$ and $P_i^{\mathrm{D}}$ are the power generation and load of bus $i$ in period $t$, respectively, and $\rho$ is the dual variable corresponding to the equilibrium constraint.

Similarly, a hydrogen market is a network economy. The energy of the system is transmitted with flow, and the flow is constrained by physical characteristics. Energy supply and demand balance needs to be maintained (the hydrogen system has a certain tolerance and does not strictly require real-time balance but needs to maintain a balance within a certain range). Comparing (7) with (13), it is discernible that their essence is to describe the balance between production and demand, and their dual variables can reflect the value of the corresponding commodity.

Therefore, based on marginal price theory, we define the dual variable of the nodal balance equation as the LMHP in the hydrogen system. Mapping to the hydrogen system model constructed in this paper, the LMHP is the dual variable $p^{\mathrm{LMHP}}$ corresponding to (7):

$$\sum_{i\in n} H_{i,t}^{\mathrm{G}} - \sum_{l:\varphi_I(l)=n} H_{l,t}^{\mathrm{I}} + \sum_{l:\varphi_{\mathrm{O}}(l)=n} H_{l,t}^{\mathrm{O}} = H_{i,t}^{\mathrm{D}} :\ p_{i,t}^{\mathrm{LMHP}} \tag{14}$$

which indicates the total cost increase in the objective function caused by the additional per-unit hydrogen consumption.

The LMHP can well reflect the actual value of hydrogen and the supply and demand situation of the hydrogen system, thereby guiding the behavior of market members. When the LMHP is high, it indicates that the hydrogen supply of the node is tight. The high price can encourage the relevant electrolyzers to produce more hydrogen. When the price of a node is low, it indicates that the hydrogen supply of the node is rich and that the low hydrogen price can stimulate the related load to increase the consumption of hydrogen. Such a pricing mechanism can promote market equilibrium and improve market efficiency.

## IV. Solution Algorithm

The Weymouth function in (6) is a nonconvex and nonlinear equation, which has several issues in solving the problem. There are two commonly used methods to address this problem: incremental linearization and SOCP-based relaxation. The former is relatively simple but has difficulty balancing calculation accuracy and solution efficiency concurrently, while the latter is relatively accurate but has a relaxation gap.

Existing literature generally regard the direction of pipe airflow to be fixed, assuming that the direction of hydrogen flow in the pipe does not change within a day. This approach is reasonable, and it also simplifies the calculation of the problem. Nevertheless, in actual operation, hydrogen demand and electricity prices have certain volatility. In the future, when Re2H is used as the main source of hydrogen, the volatility of the two will be superimposed, which will further expand the asymmetry between hydrogen supply and demand, thereby enhancing the change in pipeline air flow. In this case, it is no longer reasonable to regard the direction of the airflow in a day as a fixed value. Therefore, this paper adopts a second-order cone relaxation method with a direction vector, considering the change in the airflow direction within a day. First, the original model is equivalently transformed into MIQCP, and then, the equality constraints are relaxed into inequalities to form mixed-integer second-order cone programming (MISOCP) and finally solved by progressive SOCP algorithm (PSA) progressive iteration. This calculation method improves the applicability of the pipeline network with frequent changes in flow and is in line with the operating characteristics of future hydrogen energy systems.

### A. Weymouth Transformation

To address the nonlinearity of, $\mathrm{sign}(H_{l,t})$ implies the direction in the equation should be removed first. Two 0–1 variables, $I_l^+$ and $I_l^-$, are introduced to represent the direction of flow in the pipeline. Then, is transformed into the following expression:

$$(I_l^+ - I_l^-)(\omega_{i,t} - \omega_{j,t}) = (1/W_l)^2 H_{l,t}^2 \tag{15}$$

$$I_l^+ + I_l^- = 1 \tag{16}$$

where $w_{i,t}$ is the square of the nodal air pressure $\pi_{i,t}$.

The related upper and lower bound constraints become:

$$-(1 - I_l^+)\overline{H}_l \le H_{l,t} \le (1 - I_l^-)\overline{H}_l \tag{17}$$

$$\omega_i^{\min} \le \omega_{i,t} \le \omega_i^{\max} \tag{18}$$

In this way, the direction sign problem in the original equation is solved, and the change in the direction of the airflow in the pipeline is taken into account. The original problem is equivalently transformed into MIQCP. However, equation (15) is still a nonconvex constraint.

### B. Second-order Cone Relaxation

To make (15) convex, auxiliary variable $\varphi_{l,t}$ is introduced here, and then the second-order cone relaxation can be performed on the above formula. Equation (15) is replaced by the following equation:

$$\varphi_{l,t} \ge (1/W_l)^2 H_{l,t}^2 \tag{19}$$

$$\varphi_{l,t} \ge \omega_{j,t} - \omega_{i,t} + (I_l^+ - I_l^- + 1)(\omega_i^{\min} - \omega_j^{\max}) \tag{20}$$

$$\varphi_{l,t} \ge \omega_{i,t} - \omega_{j,t} + (I_l^+ - I_l^- - 1)(\omega_i^{\max} - \omega_j^{\min}) \tag{21}$$

$$\varphi_{l,t} \le \omega_{j,t} - \omega_{i,t} + (I_l^+ - I_l^- + 1)(\omega_i^{\max} - \omega_j^{\min}) \tag{22}$$

$$\varphi_{l,t} \le \omega_{i,t} - \omega_{j,t} + (I_l^+ - I_l^- - 1)(\omega_i^{\min} - \omega_j^{\max}) \quad (23)$$

In this way, the problem is transformed into a MISOCP problem. It should be noted that the above conversion is completely equivalent if and only if constraint (19) takes the equal sign. In other words, there may exist a relaxation gap via the proposed second-order cone relaxation.

### C. Progressive SOCP algorithm

To improve the feasibility of the solution while reducing the optimality gap, constraint (24) is introduced in addition to (19):

$$\varphi_{l,t} \le (1/W_l)^2 H_{l,t}^2 \quad (24)$$

However, the introduced equation (24) is a nonconvex equation, which complicates the problem. Therefore, in the iterative calculation of the PSA, equation (24) is linearized and transformed into the following form:

$$\varphi_{l,t}^k - (1/W_l)^2 \left[ (H_{l,t}^{k-1})^2 + 2H_{l,t}^{k-1}(H_{l,t}^k - H_{l,t}^{k-1}) \right] \le \mu_{l,t}^k \quad (25)$$

This linearization is obtained by performing a first-order Taylor expansion of (24). At the same time, a nonnegative auxiliary variable $\mu_{l,t}^k$ is introduced into the formula. The superscript $k$ of the variable in the formula represents the number of iterations. In PSA, auxiliary variables $\mu_{l,t}^k$ can provide a relaxation range for the initial iterative calculation. In the iterative process, the auxiliary variable continues to decrease and finally approaches zero so that the result of equation is close to the equality constraint, to reduce the relaxation gap.

$$\mu_{l,t}^k \ge 0 \quad (26)$$

The calculation process of the PSA is shown in Fig. 2:

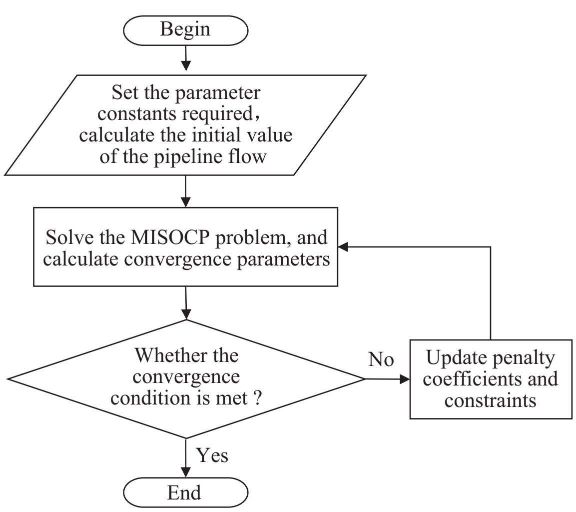


Fig. 2. Algorithm flowchart.

*Step 1:* Set the constant parameters required for iterative calculation, including the initial value of the penalty factor $\tau_0$, the maximum value of the penalty factor $\tau_{\max}$, the increase coefficient of the penalty factor $\theta$, and the convergence criteria $\varepsilon^S$ and $\varepsilon^\mu$. Calculate the initial value $H_{l.t}^0$ of the pipeline flow.

*Step 2:* Solve the MISOCP problem as follows:

$$\text{Obj} = \min S^k = \min \sum_t \sum_i \alpha p_{i,t}^{\text{LMP}} H_{i,t}^{\text{G}k} + \sum_t \sum_l \tau^k \mu_{l,t}^k \quad (27)$$

subject to (1)–(5), (7)–(11), (16)–(23), (25), and (26).

*Step 3:* Calculate the distance between the result of this time and the result of the previous iteration to determine whether the convergence criterion is satisfied:

$$|\text{Obj}^k - \text{Obj}^{k-1}| \le \varepsilon^{\text{S}} \quad (28)$$

$$\left| \sum_{t,l} \mu_{l,t}^k \right| \le \varepsilon^\mu \quad (29)$$

Equations (28) and (29) are the convergence criteria of the PSA. When the objective function values of two adjacent calculations are close enough and the auxiliary variables $\mu_{l,t}^k$ are small enough, the iteration converges, and the calculation results meet the accuracy requirements. When the convergence criterion is met, the calculation is ended. If the convergence condition is not met, the number of iterations is updated to $k = k + 1$, and the penalty factor is updated to $\tau^k = \min(\theta\tau^{k-1}, \tau_{\max})$. Then, return to step 2 to perform iterative calculation again until the result converges.

Among the parameters, the initial value $H_{\text{l,t}}^0$ of the hydrogen pipeline flow can be calculated with formula (12) as the objective function and (1)–(5), (7)–(11), and (16)–(18) as the constraint conditions.

## V. Case Studies

### A. Data Description

In this section, a modified Belgian 20-node gas system is adopted to validate the effectiveness of the proposed framework and method. The topology of the hydrogen system is shown in Fig. 3.

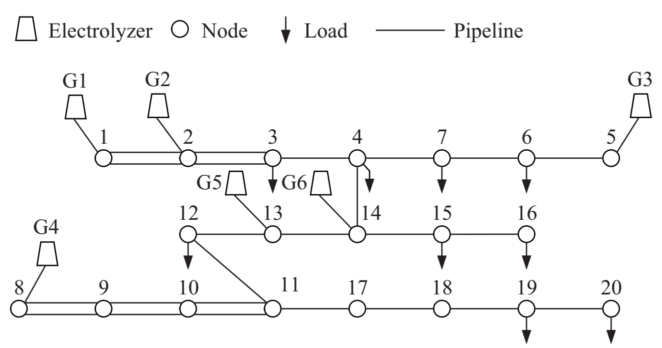


Fig. 3. Topology of the modified Belgian 20-node gas system.

The system has 6 water electrolyzers, 9 hydrogen loads, 20 nodes, and 24 pipelines. The LMP used in this section is collected from the operation data of PJM [28]. The electricity price of the six hydrogen production nodes is set to a certain ratio to simulate the hydrogen production cost of different nodes. The hydrogen demand is obtained by taking the data of the Belgian 20-node gas system as a reference and using the annual load data in PJM to simulate the change trend of hydrogen load in a year [29]. The data are shown in Fig. 4 and Fig. 5. Considering the calculation speed and actual operation, the flow direction of some pipelines in the case studies is set as a fixed value. The energy conversion efficiency of electrolysis is set at 80% according to the PEM electrolysis method [30].

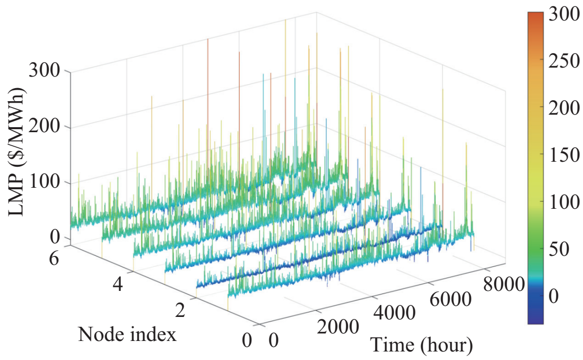


Fig. 4. LMP data used in the case studies.

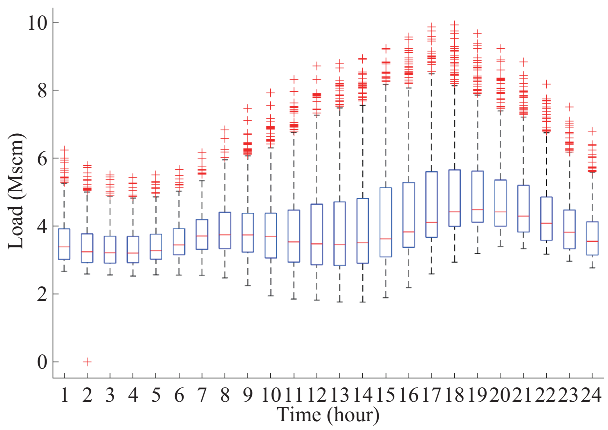


Fig. 5. Yearly load at a node.

In this paper, we consider the influence of line packs when studying the trend of the hydrogen network and the marginal price of nodes. To analyze the impact of line packs on system operation, this section introduces the case without line packs as a comparative analysis. Without considering the line packs, the model of the system turns into the following form:

The flow at the beginning and end of the pipeline is considered equal. Equation (5) is replaced by:

$$H_{l,t} = H^{\mathrm{I}}_{l,t} = H^{\mathrm{O}}_{l,t} \tag{30}$$

The coupling between different periods is eliminated. Equations (8) and (11) are removed. The constraint information with and without the line pack is shown in the following table:

TABLE I
TWO CASES DESIGNED FOR COMPARISONS

| | M1 | M2 |
|---|---|---|
| Line pack | √ | × |
| Constraints | (1)–(11) | (1)–(4), (6)–(7), (9), (10), (29) |

According to the algorithm and data mentioned above, the LMHP and pressure of each node, the hydrogen flow and line pack of each pipeline, and the production capacity of each electrolyzer can be calculated.

## B. Analysis of Line Pack

### 1) Comparison between M1 and M2

The line pack is an important characteristic of hydrogen pipeline transmission systems. The presence of line packs in the transmission process brings about time delay effects and buffering characteristics and plays an energy storage role in the hydrogen transmission process. This means that it is not necessary for the transmission system to strictly guarantee the real-time balance between hydrogen production and hydrogen demand. The existence of line packs changes the distribution of the entire airflow in a spatiotemporal principle. If the storage feature of line packs is used reasonably, the line packs act like a hydrogen storage tank and serve the optimal operation of the hydrogen transmission system.

By comparing the operation results of the hydrogen system under the two scenarios with and without line packs, the impact of the line packs can be clearly revealed.

Table II shows the average electricity price, peak-valley difference, and total cost in the first week with and without the line pack. It is evident that the average hydrogen price of M1 is lower than that of M2, and the overall operating cost also drops from \$1.310 × $10^3$ to \$1.248 × $10^3$. The most obvious is the effect of peak shaving and valley filling due to the arrival of the line packs. Compared with the \$0.581/kg in M2, in the case of M1, the peak-to-valley difference is only \$0.341/kg, which is a decrease of 39.8%. Fig. 6 shows the curve of the total cost and daily peak valley difference in one week under the conditions of M1 and M2. It is evident that the line pack effectively reduces the total cost and peak valley difference. The effect of peak shaving and valley filling is reflected here. The next section reveals how the line pack responds to the hydrogen price and the process of peak shaving and valley filling.

TABLE II
RESULTS OF TWO CASES WITHIN ONE WEEK

| Case | Average Price ($/kg) | Peak-valley Difference ($/kg) | Total Cost (× $10^3$\$) |
|---|---|---|---|
| M1 | 0.734 | 0.341 | 1.248 |
| M2 | 0.783 | 0.581 | 1.310 |

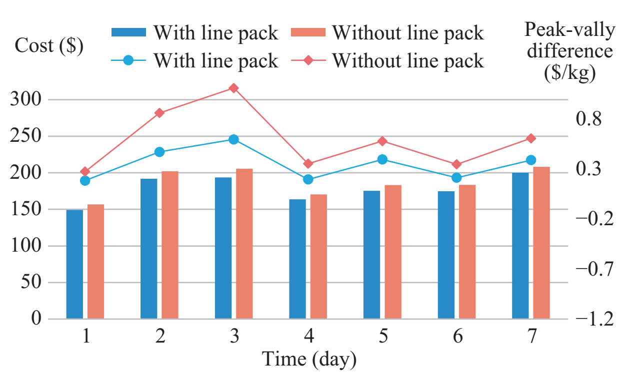


Fig. 6. Total cost and peak-valley price difference of MI and M2 in one week.

### 2) Impact of LMHPs on Line Packs

Figure 7 shows the change curve of LMHP and line pack on the first day. The existence of line packs in the gas network can play a role similar to energy storage, and this role can be guided and controlled by the LMHP. However, the line pack in the pipeline is affected not only by LMHP but also by the load and other operating constraints. Therefore, to sort out the relationship between LMHP and line pack and to facilitate the analysis of the change trend of line packs, a new index named incremental correlation coefficient (ICC) is introduced in this paper. Its value is equal to the product of the LMHP increment and line pack increment between two adjacent time nodes. Its positive and negative values reflect the similarities and differences between the change trend of LMHP and line pack, and the value can reflect the speed of the change trend to a certain extent. In the middle of the day, the ICC index is negative, which means that in the corresponding period, the LMHP and line pack show a negative correlation, and the response to the change curve is as follows: the change trend of the line pack is the opposite of the change trend of the LMHP. This phenomenon reflects the characteristics of storage in the line pack quite well: when the price is low, the power of water electrolyzers increases and the hydrogen production increases, the low-cost hydrogen produced by multiple production methods is stored in the pipeline. When the price is high, the production of hydrogen decreases, then the hydrogen in the pipeline is output to the load, and the line packs decrease. In this process, the line pack plays a role in peak shaving. Through the line pack, hydrogen is transmitted in a spatiotemporal principle, which increases the production of low-cost hydrogen and improves the overall economy of the system. While the ICC is positive at the beginning and end of the day. The trend of line packs changing with hydrogen price is not easily detectable in these time periods. The reason for this phenomenon is that the system imposes a constraint that the total amount of line packs in the first and last periods must be equal, which limits the response of the line packs to hydrogen prices at the beginning and end of the day. In a few periods, abnormal ICC values also occur, which is caused by a sudden increase or decrease in load.

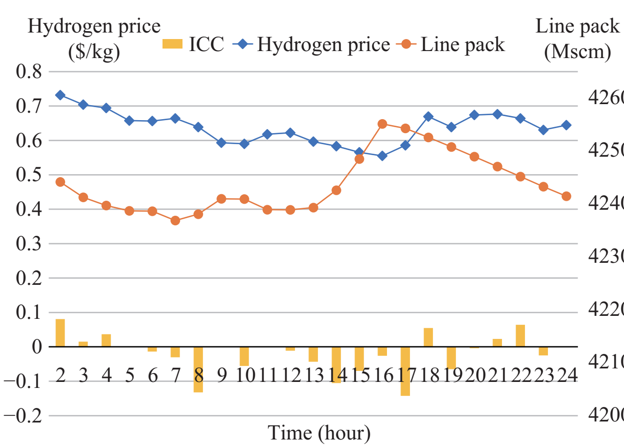


Fig. 7. Hydrogen price and line pack on the first day.

### C. Consistency Between LMP and LMHP

Figure 8 shows the LMHP of each node for different periods of a day. According to the information in the figure, the distributions of the LMP and LMHP are very similar. Due to the influence of transmission congestion, the price presents regional characteristics. For example, nodes 8–12 have very close LMHPs because their marginal hydrogen sources are the same. However, different from the LMP, even though their marginal hydrogen sources are the same, there are some differences in the prices between nodes. This is due to the buffer characteristics brought by the line pack in the pipe network system, which makes the LMHP have one more delay component than the LMP. While in the view of time line, the LMHP is mainly affected by the production cost of the corresponding hydrogen source, namely, the LMP has a great impact on the LMHP.

Figure 9 shows the relationship between the daily average of the system hydrogen price and the daily average of the system electricity price. The scatter diagram illustrates that the time series of the two prices shows a strong positive correlation. In the hydrogen system constructed above, Re2H works as the main source of hydrogen, hence, the electricity price is directly linked with the production cost of hydrogen. Therefore, the volatility of the electricity price in the power system is transmitted to the hydrogen energy system through

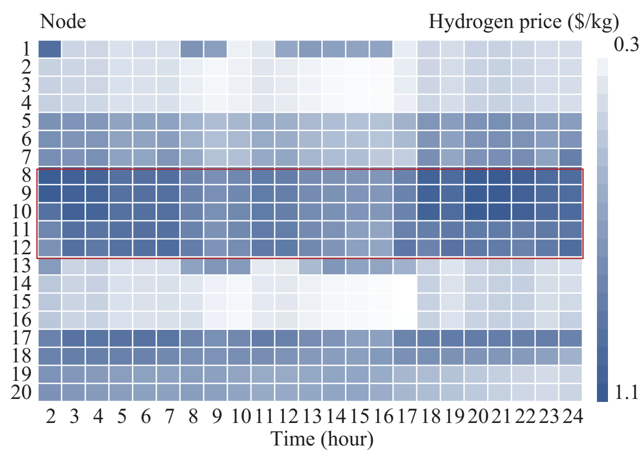


Fig. 8. Distribution of hydrogen price on the first day.

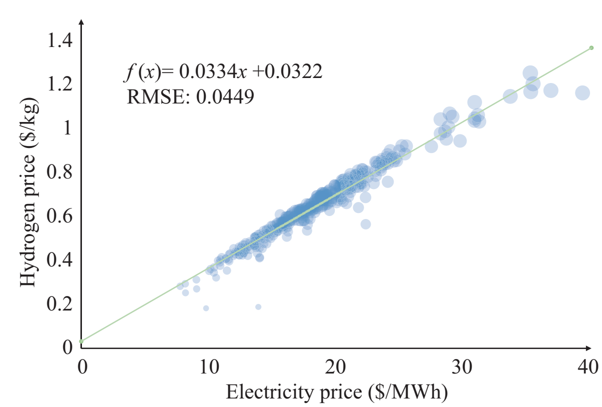


Fig. 9. Relationship between the hydrogen price and electricity price.

the electrolyzer device. Such a positive correlation ensures the LMHP reliably reflects the real-time production price of hydrogen, and the relationship between supply and demand can guide the consumption on the demand side. Simultaneously, the coupling relationship between the power system and hydrogen energy system is strengthened, which is conducive to promoting the energy balance of the integrated energy system.

To further study the influencing factors of hydrogen price, we conducted studies on electricity price and hydrogen price of several nodes. Fig. 10 is a scatter diagram with the LMP of hydrogen source 2 as the abscissa and the LMHPs of sources 1 and 2 as the ordinate. The figure reveals the concept of marginal unit. It is evident that hydrogen price distribution of node 1 has two prominent straight lines, which correspond exactly to the LMPs of nodes 1 and 2. The marginal unit of node 1 changes between sources 1 and 2. The LMHP fluctuates between two characteristic straight lines. This phenomenon also reflects the impact of congestion on LMHPs. The electricity price of source 1 is higher than that of source 2, hence, sometimes the hydrogen of node 1 is provided by source 2. Thus, the LMHP is related to the electricity price of node 2. When the system is congested, the supply of source 2 is insufficient. At this time, the hydrogen of node 1 is provided by source 1, and the LMHP is associated with the LMP of node 1.

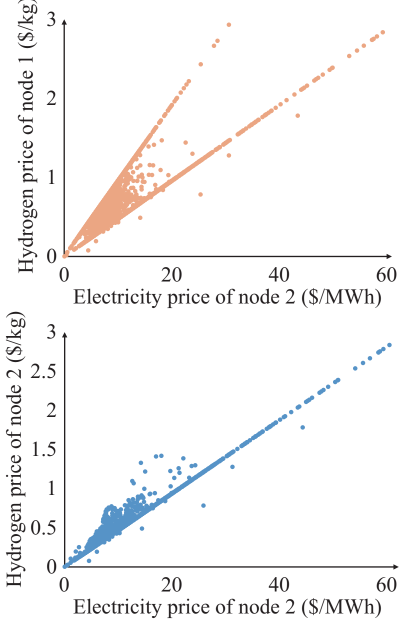


Fig. 10. Relationship between hydrogen price and electricity price in nodes 1 and 2.

Figure 11 shows the relationship between load nodes 6 and 7 and their marginal unit 5. Affected by load fluctuation and line packs, the LMHPs of nodes 6 and 7 fluctuate. The regression curve illustrates that although the LMHP of node 7 corresponds to the same marginal unit, it is slightly higher than that of node 6. This is because the distance between node 7 and marginal unit 5 is farther than that of node 6. Due to the delay effect caused by line packs in the transmission process, a delay component is added to LMHP, resulting in the price

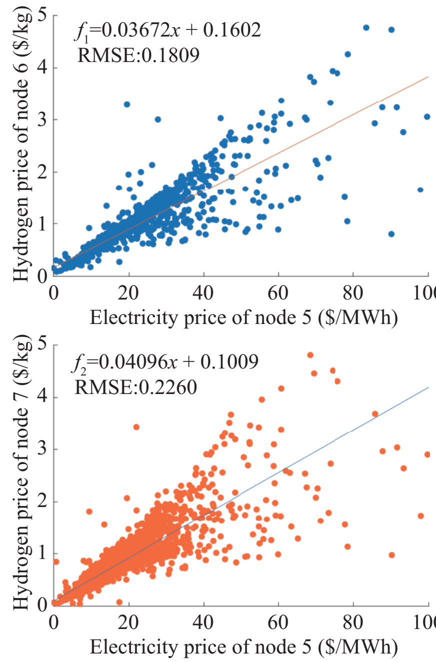


Fig. 11. Relationship between hydrogen price and electricity price in node 5, 6, and 7.

of node 7 being slightly higher than that of node 6.

Based on the above analysis, it is evident that the LMHP is affected by the marginal production cost and the operation of the hydrogen network, which can better reflect the supply and demand relationship of hydrogen and more truly reflect the real-time value of hydrogen.

## VI. Conclusion

In this paper, we established a hydrogen market structure including organizational structure and trading mode. Combined with the characteristics of future hydrogen systems, the dual variable of the nodal balance equation is defined as the LMHP, and the calculation method of the LMHP is derived while using the Weymouth equation, considering flow direction. Based on a modified Belgium 20 node gas network system, the rationality of the pricing method is verified. The comparison of the system data in the two cases of considering and not considering line packs shows that the impact of line packs on the hydrogen pipe network system should not be ignored. The real-time performance of LMHPs can guide the line packs to respond to it and then change the distribution of hydrogen network flow in a spatiotemporal principle, optimizing the operation efficiency of the system, and reducing the operation cost of the system. The data show that in a hydrogen system with electrolyzed water as the main source of hydrogen, there is strong consistency between the node hydrogen price and the LMP. Compared with the traditional cost-plus pricing method, the LMHP can better reflect the real-time supply-demand relationship of hydrogen energy systems, to guide the behavior of market members.

Two issues deserve further study in the future: 1) The congestion component and delay component of the LMHP leads to the imbalance of revenue and expenditure. How to address this part of the price difference is worth considering. 2) A more precise electrolytic cell model should be taken into consideration.

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**Litao Zheng** received his B.S. degree in Electrical Engineering from North China Electric Power University, Beijing, China, in 2020, where he is currently pursuing his M.S. degree. His research interests include electricity market and hydrogen energy.

**Jianxiao Wang** (S'14–M'19) received his B.S. and Ph.D. degrees in Electrical Engineering from Tsinghua University, Beijing, China, in 2014 and 2019. He was a visiting student researcher at Stanford University, CA, USA. He is currently an assistant professor in the School of Electrical and Electronic Engineering, North China Electric Power University, Beijing, China. He was awarded as the Outstanding Ph.D. Graduate of Tsinghua University, and Junior Fellowships for Advanced Innovation Think-Tank Programming by China Association for Science and Technology. His research interests include smart grid operation and planning, hydrogen and storage technology, transportation and energy systems integration, electricity market and data analytics.

**Yang Yu** (Member, IEEE) received the Ph.D. degree from the Department of Civil and Environment Engineering, Stanford University. He is an Assistant Professor with IIIS, Tsinghua University. He was the Best Paper Award co-recipients of 38th Annual Meeting of IAEE, U.S.–China Green Energy Summit 2016, and IEEE PES General Meeting 2020.

**Gengyin Li** (M'03) received his B.S., M.S., and Ph.D. degrees from North China Electric Power University, Beijing, China, in 1984, 1987, and 1996 respectively, all in electrical engineering. Since 1987, he has been with the School of Electrical and Electronic Engineering, North China Electric Power University, where he is currently a professor. His research interests include HVDC transmission, power quality analysis and control, and emerging trans-mission and distribution technologies.

**Ming Zhou** (M'06) received her B.S., M.S., and Ph.D. degrees in Electrical Engineering from North China Electric Power University, Beijing, China, in 1989, 1992, and 2006, respectively. Since 1992, she has been with the School of Electrical and Electronic Engineering, North China Electric Power University, Beijing, China, where she is currently a professor. Her research interests include power system economics, HVDC transmission, electricity market and power quality analysis.

**Qing Xia** (M'01–SM'08) received his Ph.D. degree in Engineering from Tsinghua University, Beijing, China, in 1989. He currently works as a professor at Tsinghua University. His research interests include electricity markets, generation scheduling optimization, power system planning.

**Guizhi Xu** is a doctoral supervisor and professorate senior engineer. She currently works as deputy director of laboratory of new energy storage and energy conversion in State Grid Corporation of China. She is also a member of national fuel cell and liquid-flow battery standard committee, the vice chair of hydrogen energy storage technology subcommittee of IEEE PES energy storage technical committee, a member of CSEE energy storage special committee and a member of energy systems integration technical committee of energy industry. Her research interests include hydrogen energy storage and flexible transmission technology.