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Two-Layer Optimization Planning Model for Integrated Energy Systems in Hydrogen Refueling Original Station

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Abstract: With the aggravation of global environmental pollution problems and the need for energy restructuring, hydrogen energy, as a highly clean resource, has gradually become a hot spot for research in countries around the world. Facing the requirement of distributed hydrogen in refueling the original station for hydrogen transportation and other usage, this paper proposes a comprehensive energy system planning model for hydrogen refueling stations to obtain the necessary devices construction, the devices' capacity decisions, and the optimal operation behaviors of each device. Comparing to traditional single hydrogen producing technics in the traditional planning model, the proposed model in this paper integrates both water-electrolysis-based and methanol-based manufacturing technics. A two-level optimization model is designed for this comprehensive system. The result of the numerical study shows that the proposed model can achieve a better optimal solution for distributed hydrogen production. Also, it considers the single producing situation when price of one primary resource is sufficient higher than the other.

Keywords: integrated energy system; hydrogen storage; hydrogen production from methanol; hydrogen production from water electrolysis

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1. Introduction

Carbon neutrality has become the consensus of smart cities to deal with global climate change, and all countries in the world are actively taking measures to achieve the goal of carbon neutrality [1–5]. Hydrogen energy is both a clean and zero-carbon new energy source and an important energy storage carrier, with the dual attributes of fuel and raw material, and is an important means of carbon substitution [6–8]. With the great development of new energy, the proportion of renewable energy such as wind power and photovoltaic will climb significantly in the process of building new power systems [9]. To increase the utilization of renewable energy and energy efficiency, integrated energy systems are gradually implemented in various industries so that the usage of all energies can be coordinated together for an entire aim, such as minimum operational energy cost or maximum utilization of renewable energies [10,11]. Within this direction, the integrated energy system in hydrogen manufacturing is an important physical carrier to support the future energy internet [12–14]. By optimizing the scheduling of the integrated energy system with a hydrogen production device, the performance of the integrated energy system will improve in terms of energy efficiency, environmental friendly, and technical economy [15–17].

Currently, hydrogen manufacturing technologies can be categorized into the following types, including water-electrolysis-based manufacturing, coal-based manufacturing, natural-gas-based manufacturing, industrial by-production manufacturing, and methanol-based manufacturing. Coal-based manufacturing and natural gas-based manufacturing are the earliest technics with widespread implementation [18]. The applications of these two technics deeply rely on the price and sufficiency of local primary resources. For example, the coal-based manufacturing is popular in China because of the low price of hard coke and the sufficiency of coal [19]. Furthermore, carbon emissions of these two technics are comparatively high [20,21]. Water-electrolysis is a later-developed hydrogen manufacturing technics with potential of low carbon emission. Its cost and decarbonization can be synchronized with main electricity consumers by increasing more renewable energy in local power generation. Specifically, the cost and carbon emissions from water-electrolysis can be additionally reduced if the manufacturing factory installs or purchases more power generation from PV plants or wind generation plants [22–25]. Methanol is another later-developed hydrogen manufacturing technics with the potential of decarbonization. This potential comes from two aspects. On the one hand, methanol-based hydrogen manufacturing produces the least carbon emissions, compared with other traditional ways [26]. On the other hand, methanol can also be produced by pure clean energy, such as wind energy [27]. Manufacturing with methanol is also an economic advantage in some areas, such as China [28,29].

For integrated energy systems at the beginning of their establishment, research on their optimization methods is of great importance to improve the system's performance. To adapt to the scenario of distributed power access such as wind power and photovoltaic, an integrated electricity-gas energy system planning method considering the reliability of energy supply was proposed in Reference [30] and solved by a mixed integer linear programming method. To determine the optimal configuration of energy equipment types and capacities in the integrated energy system, Reference [31] proposed an integrated energy system equipment selection and capacity planning method considering the coupling of electricity, heat, and gas. An optimization model for the economic operation of the integrated energy system was developed using the "economically optimal" operation strategy, that is, a multivariate energy storage system was introduced, and the optimization problem of economic operation was solved by an improved group search optimization algorithm to minimize the operating cost [32–34].

According to a literature review, the existing integrating system with hydrogen manufacturing only includes single manufacturing technics [15]. These methods default to the advantages of the selected technics. However, practically, the cost of primary resources is dynamic, such as the price of coal, natural gas, methanol, electricity, and petroleum. A planning model with single technic consideration may lose its rationality when the relative price level of resources changes. Especially the electricity price is dynamic within a day, such as from Time-Of-Use (TOU) tariff or Real-Time-Price (RTP) tariff. There would be a situation that electricity price is higher than other resources in some cases but oppositely lower in other time within a day. In this situation, combination of technics could produce a better solution than with single technic.

Faced with the disadvantages above, this paper initiates a planning model for a comprehensive energy system for hydrogen refueling stations. The hydrogen manufacturing section in this model considers production technics from both water electrolysis and methanol. A two-level optimization structure is constructed for the planning model, achieving optimal device parameter selection and optimal operation behavior together. The numerical study shows that the optimization capability of multiple resources is better than a single technic consideration.

The remainder of this paper is organized as follows: Section 2 describes the integrated energy system architecture. Furthermore, Section 3 presents the formulation of the proposed two-layer optimization model of hydrogen energy for integrated energy systems. In

Section 4, the results of the numerical analysis are presented. Finally, the conclusion is given in Section 5.

2. Integrated Energy System with Hydrogen Production Unit

The proposed model is designed for the system structure shown in Figure 1. The proposed optimal operation model of the system is formulated hereunder. There are two energy types in this integrated system. One is electricity, and the other is methanol. From Figure 1, equipment for water-electrolysis hydrogen production is connected to a power bus, which is also connected to the power grid, distributed PV generation, and power storage. The electricity price from the power grid is a typical dynamic tariff (such as TOU or RTP), which fluctuates hourly. The price of methanol remains unchanged for a day.

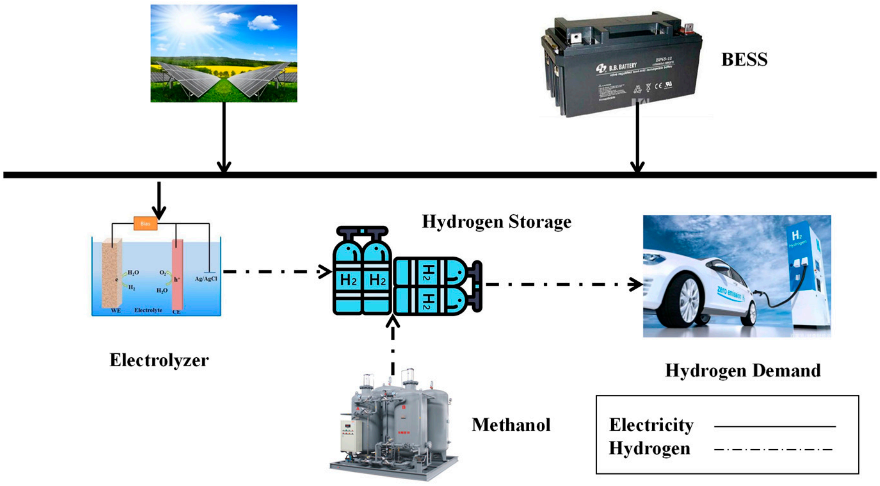

Figure 1. Integrated Energy System Structure.

The aim of the integrated energy system in Figure 1 is to make sure the following questions related to the price of electricity, the price of methanol, price of devices, and the characteristics of each device are considered.

(a) Do all the devices in Figure 1 need to be constructed? Which of them are necessary?
(b) What is the capacity of each necessary device? What is the total cost in manufacturing construction?
(c) What is the operational behavior of each device? What is the total cost of operation?
(d) How do I find out the total minimum cost after considering all the above issues?

2.1. Integrated Energy System Structure

The integrated energy system with hydrogen production unit proposed in this paper consists of energy conversion equipment and energy storage. The energy conversion equipment includes photovoltaic, electrolytic water hydrogen production units, and methanol hydrogen production units, and the energy storage includes battery energy storage (BES), and hydrogen storage tanks (HST). The hydrogen demand is met by the electrolytic water hydrogen production system and the methanol hydrogen production system, as well as the integrated energy system that consists of energy storage and the hydrogen production link to participate in the demand-side response.

In the system, the electrolytic water hydrogen production system adopts the proton exchange membrane electrolytic water hydrogen production equipment, which is supplied by the photovoltaic power generation unit, the energy storage, and the super grid. The hydrogen produced is directly supplied to the hydrogen load; the methanol hydrogen production system adopts the methanol and water vapor reforming hydrogen production processes. The raw material for hydrogen production, methanol, is directly sourced from the methanol market.

2.2. Hydrogen Production from Water-Electrolytic

The electrolytic cell in the electrolytic water hydrogen production system converts electrical energy into hydrogen using electrolytic water. Hydrogen production from electrolytic water is the most promising hydrogen production technology because of its high purity and no carbon dioxide emissions during the process. According to different diaphragms, electrolytic water technology can be divided into alkaline electrolytic water hydrogen production, proton exchange membrane electrolytic water hydrogen production, and solid oxide electrolytic water hydrogen production. Among these, alkaline electrolytic water hydrogen production is the most mature and highly commercialized. However, it requires a high-temperature heat source and materials with high anti-aging abilities in a high-temperature environment.

The proposed mathematical model for hydrogen production by electrolysis of water using a proton exchange membrane, as shown in Equation (1).

$$m_{PEM,t} = \varepsilon \cdot \eta_{PEM} \cdot P_{PEM,t} \cdot \Delta t \tag{1}$$

2.3. Hydrogen Production by Methanol

Methanol hydrogen production has the advantages of flexible hydrogen production scale, low construction investment cost, easy access to raw materials, high unit energy density of methanol, easy storage and transportation, low carbon emissions in the hydrogen production process, and belongs to "blue hydrogen". Methanol steam reforming technology is a relatively mature methanol hydrogen production technology at present. This reaction involves the conversion of methanol and steam into hydrogen and carbon dioxide under certain pressure and temperature conditions, using Cu, Pd, etc. as catalysts. This hydrogen production method has the advantages of mild reaction conditions, high hydrogen production, and low CO content. Methanol reforming hydrogen production is not only used in hydrogen refueling stations to produce hydrogen but also used in some new energy vehicles to directly supply hydrogen fuel cells with methanol reforming hydrogen. The mathematical model to be adopted in this paper is shown in Equation (2).

$$m_{MR,t} = \eta_{MR} \cdot P_{MR,t} \tag{2}$$

3. Two-Layer Optimization Model of Hydrogen Energy for Integrated Energy Systems

3.1. Two-Layer Optimization Model

A two-layer optimization solution method is designed: a genetic algorithm is used to solve the main optimization planning model, and a linprog function is used to solve the sub-optimization operation optimization problem. The optimal capacity configuration results of each device obtained by the main optimization are used as input parameters for the lower-layer optimization. The sub-optimization receives the planning action from the main optimization, uses the optimization method to find the optimal operating capacity, and returns it to the main optimization. By interacting and continuously cycling until optimal, the optimal configuration of the system is achieved. The model adds an independent variable that allows the algorithm to be compatible with only one type of hydrogen production equipment during the optimization process; for example, when the price of methanol is relatively high, the methanol hydrogen production equipment can be built without it at all. The optimization flow of the algorithm is shown in Figure 2.

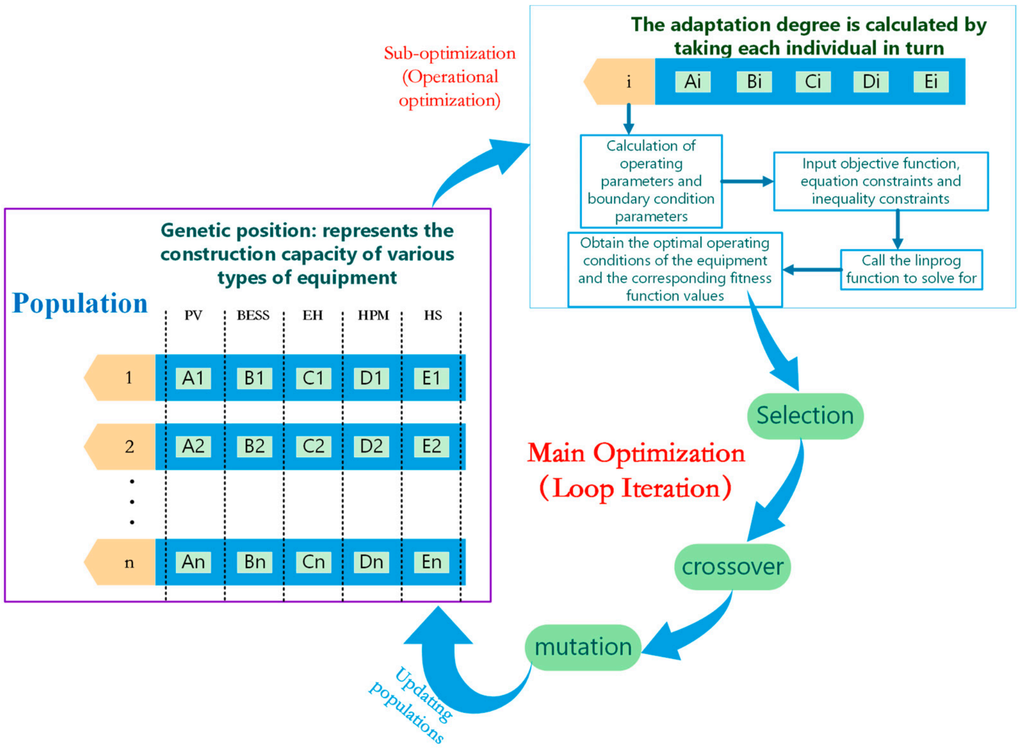

Figure 2. Model Framework Diagram.

3.1.1. Main Optimization Stage

The goal of the upper layer optimization is to obtain the optimal capacity allocation scheme for the system. The planning stage aims to minimize the construction and operation costs of the system. The optimal solution is obtained by a typical genetic algorithm.

3.1.2. Sub-Optimization Stage

The sub-optimization stage takes the system power balance and equipment operating state as constraints and minimizes the operating cost as the constraint objective. Optimization is performed for multiple sets of configuration scenarios selected in the main optimization planning stage, and the operating results of multiple planning scenarios for the system are derived.

3.2. Main Optimization Function

3.2.1. Objective Function

The main function of the model affirms the objective function of minimizing the sum of construction cost $Cost_{con}$ and operation cost $Cost_{opt}$ as the objective function. The aim is to minimize the total investment cost of the system. The argument of the main optimization is $P_{con}^{ph}, W_{con}^{ba}, P_{con}^{PEM}, P_{con}^{MR}, m_{con}^{Hyt}$.

$$Min : \mathrm{Obj\_1} = Cost_{con} + Cost_{opt} \tag{3}$$

$$\begin{cases} Cost_{con} = \alpha\left(\lambda^{ph} \cdot P_{con}^{ph} + \lambda^{ba} \cdot W_{con}^{ba} + \lambda^{PEM} \cdot P_{con}^{PEM} + \lambda^{MR} \cdot P_{con}^{MR} + \lambda^{Hyt} \cdot m_{con}^{Hyt}\right) \\ \mathrm{Cost_{opt}} = Ofun\left(P_{con}^{ph}, W_{\mathrm{con}}^{ba}, P_{con}^{PEM}, P_{con}^{MR}, m_{con}^{Hyt}, \Phi\right) \\ \Phi = \left\{\mathrm{Pr}E_t, \mathrm{Pr}M_t, m_{HR,t}, P_{ph,t}^{\mathrm{punit}}, P_{load,t}, P_{ba,\ \max}, \mathrm{Init}_{ba}, P_{PEM,\min}, P_{PEM,\max}, \right. \\ \left. P_{MR,\ \min}, P_{MR,\ \max}, \mathrm{Init}_{Hyt}, m_{Hyt,\max}, \varepsilon, \eta_{PEM}, \eta_{MR}\right\} \end{cases} \tag{4}$$

3.2.2. Optimization Constraints

The following are the constraints on the construction capacity of photovoltaic equipment, the construction capacity of electric energy storage, the construction capacity of proton exchange membrane water electrolysis hydrogen production equipment, the construction capacity of methanol reforming hydrogen production equipment, and the construction capacity of hydrogen storage tanks.

$$P_{con,\min}^{ph} \leq P_{con}^{ph} \leq P_{con,\max}^{ph} \tag{5}$$

$$W_{con,\min}^{ba} \leq W_{con}^{ba} \leq W_{con,\max}^{ba} \tag{6}$$

$$P_{con,\min}^{PEM} \leq P_{con}^{PEM} \leq P_{con,\max}^{PEM} \tag{7}$$

$$P_{con,\min}^{MR} \leq P_{con}^{MR} \leq P_{con,\max}^{MR} \tag{8}$$

$$m_{con,\min}^{Hy\mathrm{t}} \leq m_{con}^{Hy\mathrm{t}} \leq m_{con,\max}^{Hy\mathrm{t}} \tag{9}$$

3.3. Sub-Optimization Function

3.3.1. Objective Function

The sub-optimization model is designed to minimize the operating costs during daily operations. The argument of sub-optimization is $P_{\mathrm{bat},}$ $P_{PEMt}, P_{MR,t}$

$$\begin{aligned} \text{Min}: \underset{\text{arg: } P_{\text{bat}}\ P_{PEM}, P_{MR,t}}{\text{Obj\_ 2}} &= \textstyle\sum_{t=1}^{T} [\mathrm{Pr}E_t \times \left(P_{PEM,t} + P_{\mathrm{load},t} - P_{\mathrm{ba},t} - P_{ph,t}\right) \times \Delta t \\ &\quad + \mathrm{Pr}\ M_t \times P_{MR,t} \times \Delta t] \end{aligned} \tag{10}$$

3.3.2. Optimization Constraints

(1) Electricity can only be purchased from the grid:

$$P_{buy,t} = P_{PEM,t} + P_{load,t} - P_{ph,t} - P_{ba,t} \tag{11}$$

$$P_{buy,t} \geq 0 \tag{12}$$

(2) Electrical energy storage operating constraints:

$$-P_{ba,max} \leq P_{ba,t} \leq P_{ba,max} \tag{13}$$

$$0 \leq Init_{ba} + \sum_{t=1}^{k} P_{ba,t} \leq W_{ba,max} \tag{14}$$

$$\sum_{t=1}^{T} P_{ba,t} = 0 \tag{15}$$

(3) Hydrogen production from water-electrolytic operating constraints:

$$P_{PEM,min} \leq P_{PEM,t} \leq P_{PEM,max} \tag{16}$$

(4) Hydrogen production by methanol operating constraints:

$$P_{MR,min} \leq P_{MR,t} \leq P_{MR,max} \tag{17}$$

(5) Hydrogen storage tank operating constraints:

$$\begin{cases} 0 \leq Init_{Hyt} + \sum_{t=1}^{k} NI_t \leq m_{Hyt,max}, \forall k \in (1,2,\cdots,T) \\ NI_t = m_{PEM,t} + m_{MR,t} - m_{HR,t} \end{cases}$$
$$\Rightarrow \sum_{t=1}^{k} m_{HR,t} \leq \sum_{t=1}^{k} (m_{PEM,t} + m_{MR,t}) + Init_{Hyt} \leq \sum_{t=1}^{k} m_{HR,t} + m_{Hyt,max} \quad (18)$$

(6) System balance constraints:

$$\sum_{t=1}^{T} (m_{PEM,t} + m_{MR,t}) = \sum_{t=1}^{T} m_{HR,t} \quad (19)$$

4. Numerical Study

4.1. Background

In this section, two typical numerical studies are performed with the help of specific arithmetic examples. The first one is a feasibility study, which is used to verify the ideas and feasibility of the model presented in the previous sections. The second one is a sensitivity study, which is used to analyze how the results of the cases change when some important parameters in the model are changed. The sensitivity study in this paper considers the volatility of the methanol price, and the study continuously adjusts the price per kg of methanol from 1.6 CNY to 6 CNY continuously, compares and analyzes the optimization results obtained, and then obtains the scope of application.

In the case study, considering the actual situation of peak and valley tariffs, the dispatching period is set to 24 h, the unit dispatching time is 1 h, and the tariff is set with the Guangdong Provincial Development and Reform Commission for the peak and valley tariff of Guangzhou City. The tariff is 0.6475 CNY/kWh for the rest of the day. The daily output of hydrogen is referred to as the daily demand of a hydrogen refueling station in Guangzhou, and the total daily demand is set to 990 kg. The peak-valley tariff curve and hydrogen demand curve of a dispatching cycle are shown in Figure 3. The standardized photovoltaic output power is shown in Figure 4.

Tables 1–3 give the maximum and minimum capacity constraints for equipment construction, equipment investment costs, and modeling and simulation parameters, respectively. According to the peak and valley electricity price curves of the selected city, it can be calculated that the local average daily electricity price is 0.6459 CNY/kWh. For the electric hydrogen refueling station, if the average electricity price is 0.6459 CNY/kWh and it takes 5 kWh of electricity to produce 1 Nm^3 hydrogen, assuming that a volume of 11.2 m^3 is needed to store 1 kg of hydrogen, therefore the amount of electricity is 5 × 11.2 kWh to produce 1 kg of hydrogen that it, the cost is 5 × 11.2 × 0.6459 CNY which is 36.17 CNY.

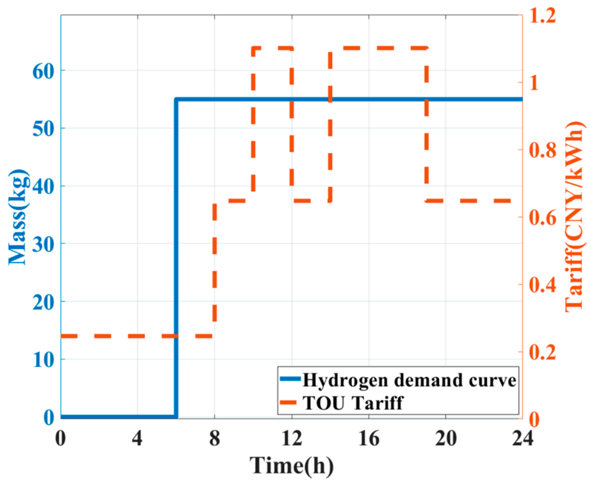

Figure 3. TOU tariff and hydrogen demand curves.

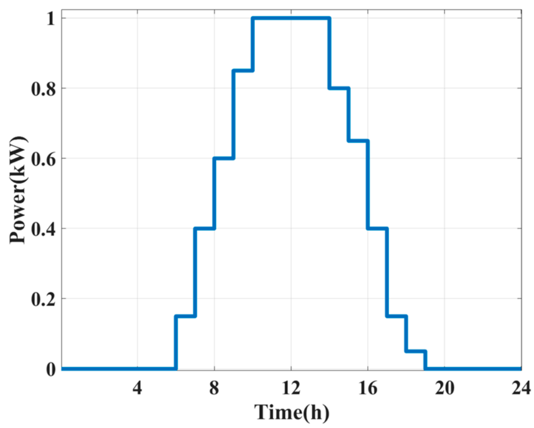

Figure 4. The curves of standardized Photovoltaic output power.

Table 1. Maximum and minimum capacity constraints for equipment construction.

Equipment	Minimum Capacity	Maximum Capacity
PV devices (kW)	0	161
BESS (kWh)	0	2000
HPWE (Nm^3/h)	0	2000
HPM (Nm^3/h)	0	2000
HST (kg)	0	540

Table 2. Equipment investment costs.

Equipment	Cost
PV devices (CNY/kW)	8000 [35]
BESS (CNY/kWh)	5000 [36]
HPWE [CNY/(100 Nm^3/h)]	1,410,000 [37]
HPM [CNY/(200 Nm^3/h)]	2,116,000 [37]
HST (CNY per unit)	500,000 [38]

Table 3. Modeling and simulation parameters.

Basic Electric Load Power Excluding PV, Power Storage and Hydrogen Producing Devices	30 kW
Charging and discharging multiplier of electric energy storage equipment	0.25 C [39]
Pressure level of HST	45 MPa [40]
Equipment service life	20 years
Lower limit of operating power of hydrogen production equipment	20% of maximum capacity
Upper limit of operating power of hydrogen production equipment	90% of maximum capacity
Initial energy storage capacity of energy storage equipment	10% of maximum capacity
Electricity consumption for producing 1 Nm^3 hydrogen (kWh)	5 [37]
Methanol consumption for producing 1 Nm^3 hydrogen (kg)	0.72 [37]

For the methanol hydrogen refueling station, if the price of methanol is 2.6 CNY/kg and 0.72 kg of methanol is consumed to produce 1 Nm^3 of hydrogen, the cost of producing 1 Nm^3 of hydrogen is $2.6 \times 0.72 \times 11.2 = 20.97$ CNY. From the comparison of the overall average price of energy, it can be seen that methanol hydrogen production has a greater advantage in terms of cost savings compared to electric hydrogen production, so hydrogen production and hydrogen refueling stations should use methanol hydrogen production to save costs.

4.2. Results and Feasibility Analysis

Table 4 shows a benchmark performance comparison. Two base cases for integrated energy systems with single water-electrolysis hydrogen production and single hydrogen production on methanol are selected. From this benchmark study, the proposed model achieves a better performance in total daily cost than the other two single technic methods. From Table 4, the proposed model has achieved the minimum cost on a total of 22,035 CNY/day, which is combined with 20,279 CNY/day operational cost and 1756 CNY/day equivalent of daily construction investment. Figure 5 shows that the capacity of the BESS and HS is fully utilized, thus reducing the operating cost of the proposed model.

Table 4. Comparison of equipment construction capacity and cost under different hydrogen production methods.

Index	HPNG	HPM	HPWE	Optimal Results from the Proposed Model
PV capacity (kW)	51	51	161	161
BESS capacity (kWh)	117	117	2000	258
HPWE capacity (Nm^3/h)	0	0	900	100
HPM capacity (Nm^3/h)	600	600	0	600
HST capacity (kg)	162	162	540	135
OPEX (CNY/typical day)	23,070	20,875	23,031	20,279
CAPEX (CNY)	13,161,000	10,341,000	33,978,000	12,836,000
Total daily cost (CNY)	24,873	22,291	27,686	22,035
Equivalent hydrogen production cost (CNY/kg)	25.12	22.52	27.97	22.26
Payback Period(days)	613	437	1579	529

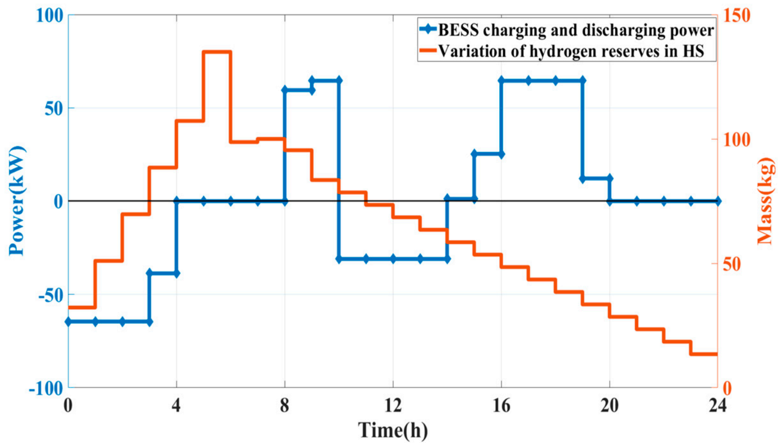

Figure 5. The variation of BESS and HS.

For single technic on methanol, the total cost is 22,291 CNY/day, which is combined by 20,875 CNY/day and 1416 CNY/day equivalent daily construction investment. Comparing to the proposed model, the construction investment for single methanol decreases for the proposed model, which not only invests 600 Nm^3/h hydrogen production capability from methanol but also invests 100 Nm^3/h hydrogen production capability from water electrolysis. However, this 1756 − 1416 = 340 CNY/day extra investment brings an extra cost reduction of 20,875 − 20,279 = 596 CNY/day. This extra cost reduction comes from the fact that hydrogen production costs from the valley price of TOU are cheaper than from methanol. This is the reason that the result of the proposed model is lower than production from single methanol.

For a single technic on water-electrolysis, the total cost is 27,686 CNY/day, which is combined by 23,031 CNY/day and 4655 CNY/day equivalent daily construction investment. No matter whether the daily operational cost and the equivalent daily construction investment are higher than the proposed method.

The proposed integrated technics considering method can achieve a better optimal than traditional planning from a single technic. Table 4 shows the result of benchmark experiments. The cost effectiveness of the entire integrated system for hydrogen production can be revealed by 'Equivalent hydrogen production cost' in the last row of Table 4. It shows that the equivalent production cost of the proposed method is the lowest.

Combining with the above discussions, it demonstrates that the cost of hydrogen production is from low to high in the order of electric hydrogen production in the valley section, methanol hydrogen production, electric hydrogen production in the flat section, and electric hydrogen production in the peak section. Therefore, for a hydrogen production and hydrogen refueling station containing both electric and methanol hydrogen production equipment, theoretically, as long as the hydrogen is produced to the maximum extent by electric hydrogen production in the valley period of the electricity price and then methanol hydrogen production is used to meet the hydrogen shortage in the rest of the period, the operating cost will be minimized. However, considering the impact of the battery and photovoltaic equipment, as well as the maximum and minimum power constraints on the operation of the equipment, it will be shown below that the two-tier demand-side response model can enable the hydrogen production and hydrogen refueling station to operate in the most economical way under this condition.

First of all, the electric hydrogen production mode is analyzed. From Figure 6, it can be seen that although the equipment is subject to the minimum operation power constraint and the electric hydrogen production power is not zero from 8:00 to 24:00, most of the electricity demand in the station is satisfied by the valley electricity stored in the battery and the electricity generated by the photovoltaic power generation equipment because the station is equipped with a battery and photovoltaic power generation, which maximizes the cost advantage of the valley electric hydrogen production. At the same time, the negative impact of the power constraint of the equipment on the operation cost is minimized, so that the station can operate with the lowest electric energy cost, and the overall cost of electric hydrogen production is 14.46 CNY/kg, which is lower than the cost of methanol hydrogen production. For the convenience of the readers, more details will be given to show the results obtained. By combining the power curve of electric hydrogen production equipment, the power curve of photovoltaic power generation, and the power curve of electric energy storage equipment, the electric hydrogen production equipment will consume a total of 5297.45 kWh in a typical day. The power supply equipment includes the grid, photovoltaic power generation equipment, and electric energy storage equipment. The total amount of hydrogen produced is $5297.45/(11.2 \times 5) = 94.60$ kg. Among them, 3797.8 kWh are bought at the valley electricity price, 500 kWh are bought at the flat rate, and 99.9 kWh are bought at the peak tariff. There are 899.75 kWh from the PV plant. Therefore, the cost of electricity for the system in a typical day is $3797.8 \times 0.2461 + 500 \times 0.6475 + 99.9 \times 1.1008 = 1368.36$ (CNY). That is, the average cost for electricity to produce 1 kg of hydrogen in a typical day is $1368.36/94.60 = 14.4647$ CNY/kg.

Next, we analyze the methanol hydrogen production method. From the above analysis related to the hydrogen production cost, we know that in order to have the lowest operating cost, the methanol hydrogen production equipment should be operated mainly in the flat and peak periods of electricity prices to meet the hydrogen production shortage at the station. However, since the price of methanol remains constant during a dispatching cycle, the cost of methanol hydrogen production is only related to the total methanol demand, which in turn is only related to the hydrogen shortage that can be obtained from the operation of the electric hydrogen production equipment and is not related to the power situation of the methanol hydrogen production equipment at each time. The operating power of the two types of hydrogen production equipment is shown in Figure 7 below. Therefore, the overall electric hydrogen cost is lower than the methanol hydrogen cost, and the operating cost will be minimized as long as the electric power cost of hydrogen production in a dispatching cycle is minimized. Since it has been proven that the overall electric hydrogen production cost is lower than the methanol hydrogen production cost when the electric power cost is minimized, the two-tier demand-side response model proposed in this paper can make the hydrogen production and hydrogen refueling stations operate at the lowest economic cost.

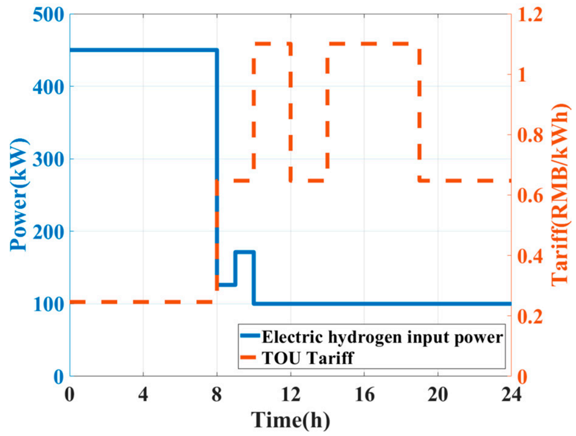

Figure 6. Electric hydrogen input power and TOU tariff.

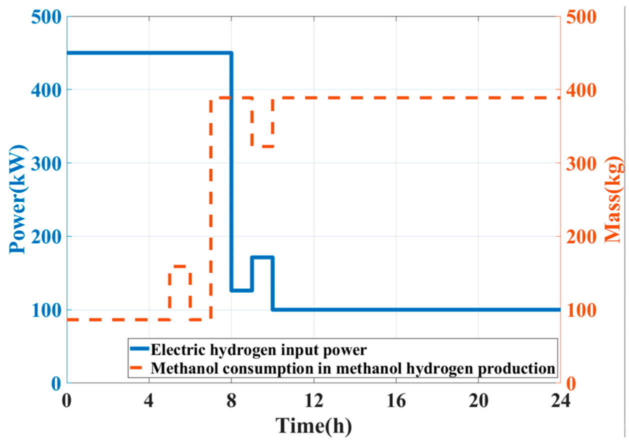

Figure 7. HPWE power and the amount of methanol consumed for HPM.

At the same time, the iterative convergence of the optimization algorithm shown in Figure 8 demonstrates that the algorithm we select is reasonable and effective.

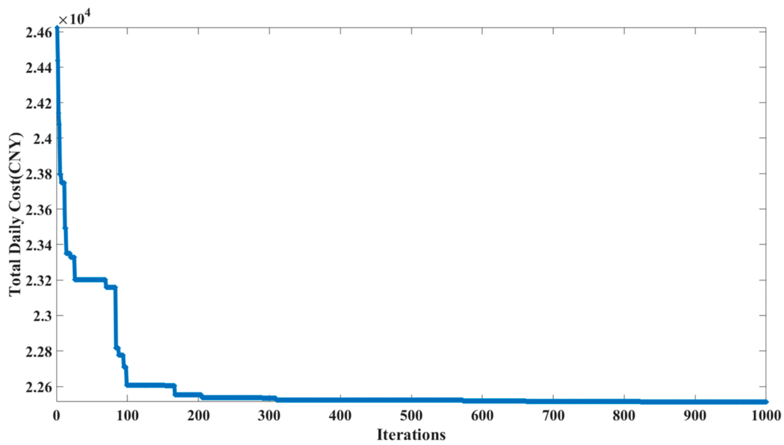

Figure 8. The iterative convergence of the optimization algorithm.

4.3. Analysis of Sensitivity Test Results

Table 5 shows the optimal construction of hydrogen production and hydrogenation stations derived with the model during the increasing price of methanol from a lower price.

Table 5. Optimal construction of hydrogen production and hydrogenation stations at different methanol prices.

Methanol Prices (CNY/kg)	The Maximum Capacity of the Equipment				
	PV Devices (kW)	BESS (kWh)	HPWE (Nm^3/h)	HPM (Nm^3/h)	HST (kg)
1.6	44	78	0	600	162
2.1	161	262	100	600	108
2.6	161	258	100	600	135
3	161	260	100	600	135
3.5	161	2000	800	200	486
4	161	2000	900	100	540
4.5	161	2000	900	0	540
6	161	2000	900	0	540

From Table 5, we can see that the construction capacity of various equipment will change to some extent with the change in methanol price and can be mainly divided into the following three cases.

When the price of methanol hydrogen is 1.6 CNY/kg, the price of methanol hydrogen will be lower than the cost of electric hydrogen at any time, and the methanol hydrogen production method has absolute advantages. At this time, 600 Nm^3/h methanol hydrogen production equipment and a hydrogen storage tank with a capacity of 162 kg are built in the station; no electric hydrogen production equipment is built, and only a small amount of photovoltaic and electric storage equipment is used to reduce the cost of electricity for the basic electric load in the station.

When the price of methanol is between 2.1 CNY/kg and 4.0 CNY/kg, the cost of electric hydrogen production in the peak and valley tariffs is lower than the cost of methanol hydrogen production, and the electric hydrogen production method has certain advantages, which can be further divided into two cases. The first one is that the cost of electric hydrogen production is slightly lower than the cost of methanol hydrogen production in the peak and valley tariffs, and at this time, the station is still dominated by methanol hydrogen production, and the capacity of both hydrogen storage and electric energy storage is smaller, but the photovoltaic equipment has reached its maximum allowed construction. The second one is that the cost of electric hydrogen production is significantly lower than the cost of methanol hydrogen production in the peak and valley tariffs, and the station will be dominated by electric hydrogen production at this time. The capacity of both hydrogen storage and electric energy storage is large, so basically, they have taken the maximum value.

When the price of methanol is more than 4.5 CNY/kg, the cost of electric hydrogen production is lower than that of methanol hydrogen production in the peak and valley tariff flat, and the electric hydrogen production method has a greater advantage. All electric hydrogen production methods are used in the station at this time, and a total of 900 Nm^3/h of electric hydrogen production equipment is built. The cost of electricity in the station during the peak period of electricity prices can be well reduced, thus giving the full advantages of the electric hydrogen production method in terms of cost.

From the above three cases, it is clear that when the price of methanol is extremely low or extremely high, it is not possible to reduce the economic cost by using both electricity and methanol hydrogen production in the station, and then the hydrogen production station should use only the methanol hydrogen production method or only the electric hydrogen production method. Only when the cost of methanol hydrogen production is between the cost of electricity hydrogen production in the valley and the flat of the peak and valley tariff, the station can have the best economic cost by using electricity and methanol hydrogen production at the same time.

5. Conclusions

This paper proposes a model for comprehensive distribution of hydrogen production in refueling stations. By benchmarking to traditional single production technics, this comprehensive model can obtain better optimal solution. By researching this model, it is confident that a planning model with multiple producing technics that allow model solving to decide technics selection performs advantages for better optimum. For the reason that it not only covers all situations under a single technic, but is also able to find out the optimal chance of multiple technics being constructed together. For example, when the cost of unit hydrogen from methanol is higher than the cost of unit hydrogen from electricity with a valley price but lower than the cost of unit hydrogen from electricity with a peak price.

In addition, the two-layer optimization model proposed in this paper allows energy storage and hydrogen production equipment to participate in demand-side response at the same time. This gives the full price advantages of different energy sources, realizes cross-energy forms of demand-side response, and minimizes costs.

Actually, the integrated planning method can find out the construction and operation optimum when the hydrogen cost from water-electrolysis and the cost from methanol is alternatively higher than each other. Also, the single consideration of pure water-electrolysis or methanol-based hydrogen production is also considered in this integrated method. When the manufacturing cost of one resource is substantially higher than another, the proposed model will output a single construction plan for the cheaper resources, which is the same as existing methods.

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Nomenclature

Abbreviations	
PV, Elz	Photovoltaic, Electrolyzer
BESS	Battery energy storage system
HS	Hydrogen storage
EH	Electrolysis hydrogen
HPM	Hydrogen Production from Methanol
HPWE	Hydrogen Production from Water Electrolysis
HPNG	Hydrogen Production from Natural Gas
OPEX	Operating Expense
CAPEX	Capital Expenditure
Indices and Sets	
P_{con}^{ph}	The capacity of photovoltaic equipment construction (kW)
W_{con}^{ba}	Capacity for construction of electric energy storage equipment (kWh)

P_{con}^{PEM}	Capacity for construction of hydrogen production equipment for water electrolysis with proton exchange membrane (kW)
P_{con}^{MR}	Capacity of methanol reforming hydrogen production equipment construction (kg)
m_{con}^{Hyt}	Capacity of hydrogen storage tank construction (kg)
$Cost_{opt}$	Operating cost for one dispatch cycle when the hydrogen refueling station is in optimal operating condition (CNY)
$P_{PEM,t}$	The input power of the hydrogen production equipment for proton exchange membrane water electrolysis in the t-th time period (kW)
$P_{MR,t}$	The input methanol mass of the methanol reforming hydrogen plant at time t (kg)
$P_{ph,t}$	The power generated by the photovoltaic equipment in time period t (kW)
$P_{ba,t}$	The charging and discharging power of the electric energy storage equipment in time period t (kW)
$P_{buy,t}$	The total amount of electricity purchased from the grid at the hydrogen refueling station in time period t (kWh)
$m_{PEM,t}$	The mass of hydrogen produced by the proton exchange membrane water electrolysis hydrogen production plant in time period t (kg)
$m_{MR,t}$	The mass of hydrogen produced by the methanol reforming hydrogen plant in the t time period (kg)
$P_{ba,max}$	Maximum charging and discharging power of the electric energy storage equipment (kW)
$Init_{ba}$	Initial energy storage capacity of the electric energy storage equipment (kWh)
$Init_{Hyt}$	Initial storage capacity of the hydrogen storage tank (kg)
$P_{PEM,min}$	Minimum input power of the proton exchange membrane water electrolysis hydrogen plant (kW)
$P_{PEM,max}$	The maximum input power of the water electrolysis equipment with proton exchange membrane (kW)
$P_{MR,min}$	Minimum input power of methanol reforming hydrogen plant (kW)
$P_{MR,max}$	Maximum input power of the methanol reforming hydrogen plant (kW)
ϕ	Basic operating parameters of a hydrogenation station for a given equipment
T	Scheduling period (hour)
Δt	Unit dispatch time (hour)
PrE_t	Grid electricity price for the t-th period (CNY/kWh)
PrM_t	Market price of methanol at time t (CNY/kg)
$m_{HR,t}$	Hydrogen demand at time t (kg)
$P_{ph,t}^{unit}$	Power generation per unit capacity of PV equipment in time period t (kW)
$P_{load,t}$	Basic electric load power of hydrogen refueling station in time t (kW)
ε	Electric hydrogen conversion factor (Nm^3/kWh)
η_{PEM}	The conversion efficiency of the water electrolysis plant with proton exchange membrane
η_{MR}	Conversion efficiency of methanol reforming hydrogen plant
α	A coefficient for apportioning the CAPEX of equipments to each typical day
λ^{ph}	Unit investment cost of photovoltaic equipment (CNY/kW)
λ^{ba}	Unit investment cost of electric energy storage equipment (CNY/kWh)
λ^{PEM}	Proton exchange membrane water electrolysis hydrogen production equipment unit investment cost (CNY/kW)
λ^{MR}	Unit investment cost of methanol reforming hydrogen production equipment (CNY/kg)
λ^{Hyt}	Hydrogen storage tank unit investment cost (CNY/kg)
$P_{con,max}^{ph}$, $P_{con,min}^{ph}$	Maximum and minimum capacity constraint for investment and construction of photovoltaic equipment (kW)
$W_{con,max}^{ba}$, $W_{con,min}^{ba}$	Maximum and minimum capacity constraint of electric energy storage equipment investment and construction (kWh)
$P_{con,max}^{PEM}$, $P_{con,min}^{PEM}$	Maximum and minimum capacity constraint for investment and construction of hydrogen production equipment with proton exchange membrane water electrolysis (kW)
$P_{con,max}^{MR}$, $P_{con,min}^{MR}$	Maximum and minimum capacity constraints for investment and construction of methanol reforming hydrogen production equipment (kg)
$m_{con,max}^{Hyt}$, $m_{con,min}^{Hyt}$	Maximum and minimum capacity constraints for investment and construction of hydrogen storage tanks (kg)

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