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Optimized Operation Plan for Hydrogen Refueling Station with On-Site Electrolytic Production

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Abstract: The cost reduction of hydrogen refueling stations (HRSs) is very important for the popularization of hydrogen vehicles. This paper proposes an optimized operation algorithm based on hydrogen energy demand estimation for on-site hydrogen refueling stations. Firstly, the user's hydrogen demand was estimated based on the simulation of their hydrogenation behavior. Secondly, mixed integer linear programming method was used to optimize the operation of the hydrogen refueling station to minimize the unit hydrogen energy cost by using the peak–valley difference of the electricity price. We then used three typical scenario cases to evaluate the optimized operation method. The results show that the optimized operation method proposed in this paper can effectively reduce the rated configuration of electrolyzer and storage tank for HRS and can significantly reduce the unit hydrogen energy cost considering the construction cost compared with the traditional method. Therefore, the optimization operation method of a local hydrogen production and hydrogen refueling station proposed in this paper can reduce the cost of a hydrogen refueling station and accelerate the popularization of hydrogen energy vehicles. Finally, the scope of application of the proposed optimization method and the influence of the variation of the electricity price curve and the unit cost of the electrolyzer are discussed.

Keywords: hydrogen refueling station; optimized operation algorithm; electricity price; electrolyzer

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1. Introduction

As a zero-carbon energy source, hydrogen has drawn increased attention from researchers. Currently, four types of hydrogen production are dominant: hydrogen from fossil fuels, hydrogen from industrial by-products, hydrogen from electrolytic water, and hydrogen from biomass and other forms of hydrogen production [1]. Among these hydrogen production methods, electrolytic water hydrogen production is the most industrialized and is more commonly used in various hydrogen production stations [2]. The purity of hydrogen production from electrolytic water can reach 99.999 vol.% [3]. The current utilization of hydrogen energy is mainly for hydrogen-fueled vehicles and hydrogen fuel cells.

Hydrogen-powered vehicles (FCEVs) use clean energy hydrogen as fuel and have been gradually showing a trend in which they replace conventional fuel vehicles [4]. Compared with EVs, FCEVs have several superior features, including fast refueling rate, high mileage range, and zero pollution [5].

Similar to the way in which traditional vehicles are refueled at gas stations, FCEVs are refueled in hydrogen refueling stations. Hydrogen from hydrogen stations is often produced in situ or transported from hydrogen production sites via pipelines, trailers, etc. Due to the variety of equipment, complex operation mode and many economic factors in hydrogenation stations, a study on how to optimize the operation process of hydrogenation stations is conducive to the improvement of the profitability and safety of hydrogen refueling stations (HRSs).

Since the current industrial hydrogen production efficiency is low and the electric energy used to produce hydrogen consumes more, some researchers use the electric energy from new energy and use the new energy power for hydrogen production through converter control and optimal dispatching, which can satisfy new energy consumption and hydrogen energy demand at the same time. A previous study used game theory for the cooperative operation of the WT and HRSs to optimize the operation of HRSs [6]. Another study examined a wide range of hydrogen-related technology options and developed a hydrogen supply chain planning model to meet H2 demand and determined the least-cost mix of H2 generation, storage, transmission, and compression facilities [7]. A further study proposed a strategy for the coordination of the hydrogen generation, transportation, and storage stages considering the constrained operations of an electric power system (EPS), transportation system, and variable renewable energy [8].

Since new energy generation sites are often far away from urban areas and hydrogen refueling stations need to be built at transportation hubs, hydrogen needs to be transported by pipeline or vehicle transport, which brings a larger cost. Therefore, some researchers have achieved the effect of producing hydrogen at low electricity prices and using the stored hydrogen to meet hydrogen energy demand during periods of high electricity costs by equipping hydrogen refueling stations with a larger capacity of hydrogen storage and taking advantage of fluctuations in the electricity prices of the power grid. This is a feasible entry point to the optimization of operating costs by using the peak–valley difference of electricity price [9]. In [10], the dramatically changeable electricity prices make it possible for HRS to participate in the power market and obtain profits. An optimal scheduling method is proposed in [9] to reduce the power purchase cost by exploiting the lower electricity market prices. Ref. [11] proposes an operating reserve provision model to intensify the economic feasibility of the investment.

However, few studies have considered hydrogen energy demand estimates when performing optimal scheduling of hydrogen refueling stations. As an energy terminal, the operational constraints of a hydrogen refueling station are closely related to its hydrogen energy demand, and changes in hydrogen energy demand have a large impact on its optimal scheduling results. Ref. [12] proposes an estimation method for hydrogen demand, according to the simulation of FCEVs' driving behavior, verifying the validity of the estimation method.

Based on the above analysis, this paper proposes an economic optimization operation method for hydrogen refueling stations considering hydrogen energy demand to minimize life-cycle cost and realizes this optimization operation method in multiple scenarios in comparison with the traditional method. This paper proposes the range constraints of hydrogen flow and electric power considering the safety and stability of the system and realizes the optimized operation of the system with minimal unit hydrogen energy cost at daily time scales by using the accurate estimation of the hydrogen energy demand of users.

The main contributions of this paper are summarized below:

1. An on-site hydrogen refueling station system considering various scenarios is proposed, which flexibly operates in different scenarios.
2. An operation optimization method considering the hydrogen demand is developed to minimize the life-cycle cost. The optimal hydrogen generation plan is proposed based on three given scenarios. With the developed optimization method, the peak-to-valley difference in the grid tariff can be fully utilized by the system.
3. The economic efficiency of the proposed system is shown to be better than the traditional system. The optimization method is shown to reduce unit hydrogen energy cost to a certain degree.
4. The scope of application of the proposed optimization method is discussed. The effect of its optimization on the variation of the electricity price curve and the unit cost of the electrolyzer is analyzed.

The rest of this paper is structured as follows. The proposed HRS system modeling is presented in Section 2. Section 3 introduces a hydrogen demand estimation method for HRS with a certain amount of FCEVs. An optimization model to minimize the hydrogen unit costs is presented in Section 4. Case studies, economic analysis and discussion are conducted in Section 5. Finally, conclusions are given in Section 6.

2. System Modeling

Since the technology of the alkaline electrolyzer is relatively mature, alkaline electrolyzer is used in the hydrogen refueling station system studied in this paper. The on-site hydrogen refueling station discussed in this paper consists of four main components: alkaline electrolyzer, hydrogen storage tank and grid-connected part, which is shown in Figure 1.

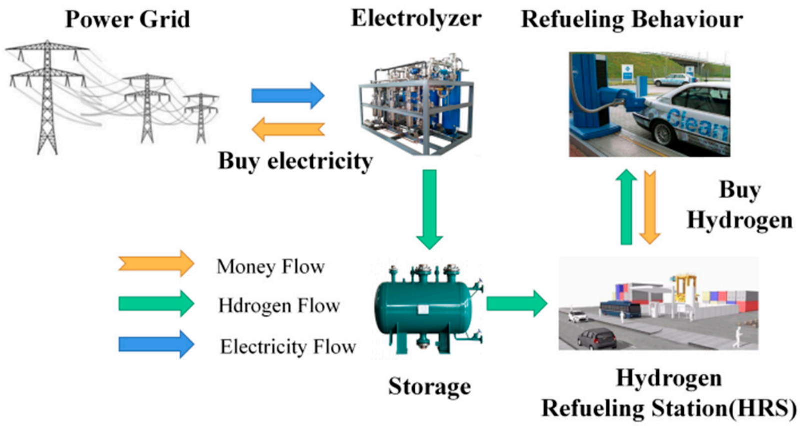

Figure 1. Proposed HRS system modeling.

2.1. Electrolyzer Modeling

Using an alkaline electrolyzer, the reversible voltage (minimum starting voltage) u_{rev} can be calculated as Equation (1).

$$u_{rev} = \frac{-\Delta G}{2F} - k_{rev}(T_{EL} - 298.15) \quad (1)$$

where, ΔG is the standard free energy of liquid water generation, -237.14 kJ/mol; F is the Faraday constant, 96,485; T_{EL} is the electrolyzer operating temperature; k_{rev} is the empirical temperature coefficient, -1.93×10^{-3} V/K [3].

Due to the presence of reversible voltage, the electrolyzer needs to reach a certain power to start working when producing hydrogen, so there is a limit to the power of hydrogen production, and it is generally believed that the power of hydrogen production can fluctuate between 20% and 100%.

The operating function of the electrolyzer cell is shown in Equation (2), where LHV_{H2} represents the low heat value of hydrogen, η_{EL} represents the work efficiency of the electrolyzer.

$$V_{h,storage,in}(t) = \frac{\eta_{EL} P_{ele}(t)}{LHV_{H_2}} \quad (2)$$

2.2. Hydrogen Storage Tank Modeling

The rated hydrogen storage capacity of a hydrogen storage tank at a certain volume is related to its internal pressure, as shown in Equation (3). The gas pressure $P_{HT}(t)$ in the hydrogen storage tank at time t is related to the amount of hydrogen stored, $n_{HT}(t)$, and is calculated using the ideal gas equation.

$$P_{HT}(t) = \frac{n_{HT}(t) R T_{H2}}{V_{HT}} \quad (3)$$

where T_{H2} is the hydrogen temperature, V_{HT} is the volume of the hydrogen storage tank, and $n_{HT}(t-1)$ is the amount of hydrogen in the tank at the moment $t-1$.

In the configuration optimization and operation optimization of the hydrogen refueling station, the accuracy of hydrogen energy demand estimation is particularly important. The deviation of demand estimation may lead to the optimization operation results being inconsistent with the actual demand or failing to minimize the cost. Therefore, the operation optimization method of the hydrogen refueling station system proposed in this paper requires accurate hydrogen energy demand estimation results.

3. Hydrogen Demand Estimation Method

Hydrogen demand is an especially important input in the process of performing the optimal operation of hydrogen energy systems, and most of literature use a time-series forecasting approach to estimate the hydrogen energy demand [9]. However, since there are various influencing factors for hydrogen demand, including residents' behavior, weather, and hydrogen price, it is difficult to realize an accurate hydrogen demand estimation with time-series forecasting approach [13].

Ref. [12] promotes a hydrogen estimation method based on residents' behavior and the vehicles for the hydrogen refueling service.

Firstly, the vehicles are divided into three types: private cars, taxis, and buses, classified by their travel habits. Secondly, the lifestyles of their owners are simulated based on probability calculations. Finally, hydrogen demand is estimated with the sum of the three types of vehicles.

Private cars always leave home in the morning and return home in the evening. The time they leave home and return home satisfies a normal distribution, while the distance they travel each day will satisfy a log-normal distribution. Based on the simulation of the driving behavior of private cars and the setting of the minimum acceptable hydrogen storage capacity, the average hydrogen energy demand of private cars can be obtained.

For hydrogen taxis, more hydrogen energy is consumed because cabs will travel longer compared to private cars and will leave earlier in the morning and return home later in the evening [13].

Hydrogen buses are often subject to unified scheduling by bus companies, with fixed daily refueling times and fixed driving routes.

The behavior of three types of hydrogen vehicles is simulated, while the three elements of hydrogen energy demand when users refuel are proposed: the user is on the road, the user's hydrogen storage reaches the level of hydrogen to be refueled, and the user's probability of refueling based on the current situation. The final hydrogen energy demand estimation equation is shown in (4).

$$\begin{aligned} f_{hydrogen}(t, N_1, N_2, N_3) &= \sum_{i=1}^{i=N_1} \kappa^i_{pri}(t)\lambda^i_{pri}\chi^i_{pri} \\ &+ \sum_{i=1}^{i=N_2} \kappa^i_{taxi}(t)\lambda^i_{taxi}\chi^i_{taxi} \\ &+ \sum_{i=1}^{i=N_3} \kappa^i_{bus}(t)\lambda^i_{bus}\chi^i_{bus}, t \in (0, 24] \end{aligned} \tag{4}$$

where $\kappa^i_{pri}(t)/\kappa^i_{taxi}(t)/\kappa^i_{bus}(t)$ represents the possibility on road at time t for ith three types of HV, $\lambda^i_{pri}(t)/\lambda^i_{taxi}(t)/\lambda^i_{bus}(t)$ represents the possibility for drivers to fuel the HVs, $\chi^i_{pri}(t)/\chi^i_{taxi}(t)/\chi^i_{bus}(t)$ represents the fuel quantity for three types of HV; N_1, N_2, N_3 are the amount of three types of HVs served by the HRS.

4. Optimization Formulation

This paper proposes an optimized operation and configuration method for the on-site hydrogen refueling station, minimizing the total cost of the system. With decided capacities of system devices, hydrogen can be generated during the period with low electricity price and be stored in the tank. In times of high electricity prices, HRSs use stored hydrogen to meet hydrogen energy demand. In this way, the unit hydrogen energy cost can be minimized, subject to constraints on the hydrogen demand estimation, the operation of the system and the capacities of the electrolyzer and storage [3]. Since the features of hydrogen demand and electricity price curve change with the season, typical days of four seasons were selected to optimize the system operation and configuration in this paper. Figure 2 shows the structure of the proposed optimization model.

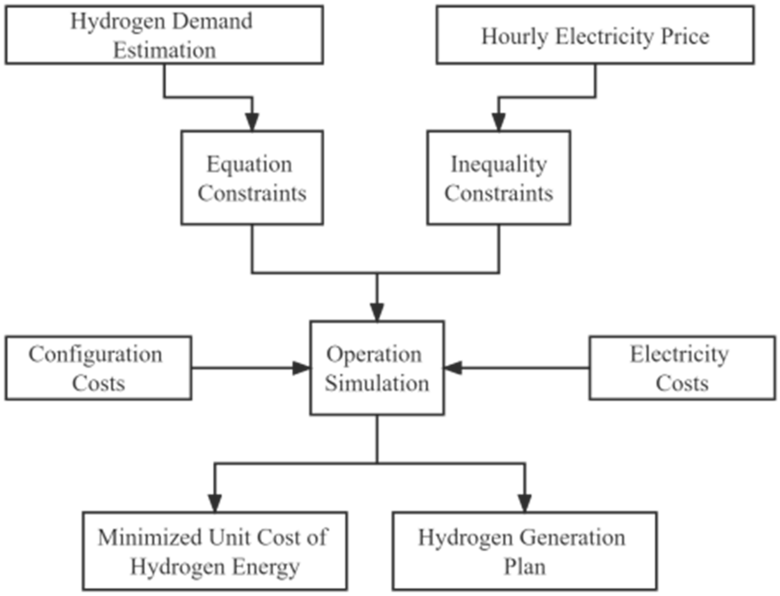

Figure 2. Structure of the proposed optimization model.

4.1. Objective Function

For on-site HRSs, there are no transportation costs, the total costs mainly consider the construction costs of electrolyzer and storage, as well as electricity costs to generate hydrogen [9]. The objective of the optimization method proposed in this paper is to minimize the total costs including operational and construction costs on multiple time scales while meeting the hydrogen energy demand of the users. The objective function for the proposed model can be described as Equation (5).

$$\min_{P_{ele}(t),P_{ele,\max},V_{h,store,\max}} \sum_{t=0}^{N*T} \left(C_{ele}(t) + \widetilde{C}_{config}\right) \tag{5}$$

where $P_{ele}(t)$ represents the hydrogen generation plan, device represents the set of devices in the system, including electrolyzer and the storage device. $C_{ele}(t)$ represents the cost of electricity from the power grid and $\widetilde{C}_{config}$ represents the equivalent cost of construction at period t. T is the step size considered for optimization, which is an hour in this paper, and $N \times T$ represents the time scale considered for optimization. $P_{ele}(t)$, $P_{ele,\max}$, $V_{h,store,\max}$ are the variables to be optimized. The optimization objective is to minimize the total costs including the construction costs during the $N \times T$ time scale of HRS.

4.1.1. Electricity Costs

For hydrogen refueling stations that use electricity from the grid to produce hydrogen on site, most of the cost comes from the cost of electricity [14]. Both hydrogen production and compression require electrical energy, and the unit electricity cost for production and unit electricity cost for compression are respectively $c_e(t)$ and $\omega_c c_e(t)$. Therefore, the cost of electricity in the operating cost can be expressed as (6).

$$C_{ele}(t) = P_{ele}(t) \cdot (c_e(t) + \omega_c c_e(t)) \tag{6}$$

where $P_{ele}(t)$ represents the electricity applied to generate hydrogen in period t.

4.1.2. Construction Costs

The configuration costs of HRS include the electrolyzer costs, storage tank costs, compressor costs and other devices. In the proposed model, the capacity of electrolyzer and storage tank are optimized to minimize the total costs and reduce the configuration costs.

$$\begin{cases} \widetilde{C}_{config} = \frac{(A/P,r,n)(\beta_{P\max}P_{ele,\max}+\beta_{Q\max}Q_{h,store,\max})}{365*24/(N*T)} \\ (A/P,r,n) = \frac{r\times(1+r)^n}{(1+r)^n-1} \end{cases} \tag{7}$$

In which, $\beta_{P\max}$ represents the unit construction cost of electrolysis, $\beta_{Q\max}$ represents the unit construction cost of the storage tank, r represents the annual rate, and n represents the lifetime of HRS.

4.2. Operation Constraints

Operation constraints of the system should be considered during the optimization progress, including hydrogen demand constraints, power range constraints for the electrolyzer, power exchange constraints with grid, and capacity constraints for the storage tank [3]. Normally, the operational constraints of the system can be divided into equation constraints and inequality constraints.

4.2.1. Equation Constraints

(1) Hydrogen demand balance constraints

The hydrogen refueling station must meet the hydrogen energy needs of the users at every interval during the optimization process, as Equation (8).

$$V_{h,load}(t) = V_{h,storage,out}(t) \tag{8}$$

where $V_{h,load}(t)$ represents the hydrogen demand in period t, $V_{h,storage,out}(t)$ represents the output hydrogen from THE storage tank in period t.

(2) Hydrogen storage tank constraints

For each time period t, the input–output balance constraint of the hydrogen storage tank is shown in Equation (9).

$$Q_{h,store}(t) = Q_{h,store}(t-1) + \mu_{h,in}V_{h,store,in}(t) - \mu_{h,out}V_{h,store,out}(t) \tag{9}$$

where, $Q_{h,store}(t)$ and $Q_{h,store}(t-1)$ represents the hydrogen storage amount in period t and period $t-1$, $V_{h,store,in}(t)$ and $V_{h,store,out}(t)$ represent the amount of hydrogen flowing into and out the hydrogen storage tank in period t, and $\mu_{h,in}$ and $\mu_{h,out}$ represent the efficiency of hydrogen flow in and out of the storage device, respectively.

The hydrogen energy content in the hydrogen storage tank affects the pressure of the tank, as shown in Equation (4). According to Charles's Law [15], when the volume of the hydrogen storage tank is certain, the hydrogen storage state of the hydrogen storage tank can be calculated as Equation (10).

$$SOHT(t) = Pa_{HT}(t)/Pa_N \tag{10}$$

where Pa_N represents the rated storage pressure of the hydrogen storage tank, $Pa_{HT}(t)$ represents the pressure in the hydrogen storage tank at the end of time period t, the range of $SOHT(t)$ is (0, 100%).

(3) Electricity balance constraints

To ensure the balance of the HRS system, power flow generated by each part should satisfy Equation (11).

$$P_{ex}(t) = P_{ele}(t) + P_{ope} \tag{11}$$

where, P_{ope} represents the electrical power required to maintain the daily operation of the hydrogen refueling station, which is set to a constant in this model, $P_{ex}(t)$ represents the power exchanged between the system and the grid.

4.2.2. Inequality Constraints

The inequality constraints considered in this model are mostly range constraints, including a range constraint on electrolyzer power, a range constraint on hydrogen storage tank capacity, and a range constraint on exchanging power with the grid, which are shown in Equation (12).

$$\begin{cases} 0 \leq P_{ele}(t) \leq P_{ele,\max} \\ 0 \leq V_{h,store,in}(t) \leq V_{h,in,\max} \\ 0 \leq V_{h,store,out}(t) \leq V_{h,out,\max} \\ 0 \leq SOHT(t) \leq 1 \\ P_{ex,\min}(t) \leq P_{ex}(t) \leq P_{ex,\max}(t) \end{cases} \tag{12}$$

4.3. Summary

The operation optimization method proposed in this paper first estimates the hydrogen energy demand in the scenario, based on which the peak-valley difference in the electricity price and the hydrogen storage tank are used to achieve hydrogen production and storage at low electricity prices, and use the hydrogen energy in the storage tank to meet the hydrogen energy demand as much as possible at high electricity prices, so as to achieve the purpose of reducing the operation cost. At the same time, the optimization method takes into account the construction cost of the equipment, minimizing the unit hydrogen energy costs.

5. Case Study

The proposed optimization algorithm was developed in MATLAB 7.12 and executed in a computer with the following specifications: Core i5-8265U, 3.40GHz CPU, 8GB RAM, and 64-bit system.

The case study is divided into four steps. Firstly, the hydrogen estimation method is applied to the case scenario. Secondly, the optimization result of the proposed system is presented based on the estimation hydrogen demand. Finally, full life-cycle economic analysis of the proposed HRS system is presented.

5.1. Hydrogen Demand Estimation

In this paper, the hydrogen supply needs of hydrogen refueling stations in the following three scenarios are considered.

Scenario 1: In the suburban area, the number of cabs and private cars in the suburban area is relatively small, but the buses still refill hydrogen at a fixed time every day, at this time the ratio of cabs, private cars and buses served by hydrogen refueling stations is 1:1:5, of which N_1 = 5, N_2 = 5, N_3 = 25.

Scenario 2: Hydrogen refueling stations in city centers generally serve more private cars and cabs, in contrast, buses do not refuel in such high traffic areas so as not to interfere with the refueling needs of other vehicles. In this case, the ratio of cabs, private cars and buses served by hydrogen refueling stations is 10:10:1, of which N_1 = 20, N_2 = 20, N_3 = 2.

Scenario 3: Hydrogen refueling stations serving residential areas tend to have more private car users, and private car owners often choose to refuel at a station near their homes, in which case the demand for hydrogen refueling for private cars will be much greater than for the other two types of vehicles. In this case, the ratio of cabs, private cars and buses served by hydrogen refueling stations is 10:1:2, of which we set N_1 = 50, N_2 = 5, N_3 = 10.

Figure 3 gives a comparison of the daily hydrogen demand at hydrogen refueling stations for the three scenarios. For a clear comparison, the data in the figure are normalized to the total daily demand in each scenario.

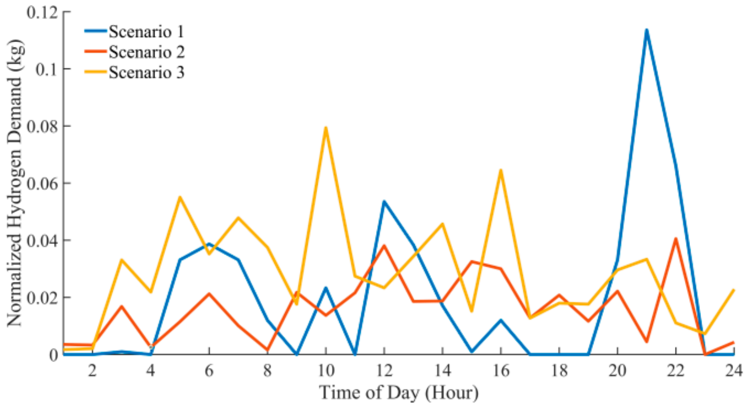

Figure 3. Daily hydrogen demand of different scenarios.

As can be seen from Figure 3, the overall shape of the intra-day hydrogen demand distribution in the three scenarios has similarity and is concentrated in the daytime, but the change in hydrogen demand in scenario 2 is more stable, while the demand in scenario 1 has more spikes. This is due to the fact that the hydrogen refueling time of hydrogen buses is basically consistent, and the refueling time of private cars and cabs is more random, so the distribution of hydrogen demand is relatively stable in the scenarios with a high percentage of cabs and private cars.

5.2. Operation Optimization

The operation of the proposed system can be optimized with the optimization formulations in Section 4. The obtained hydrogen demand curve decides $V_{h,load}(t)$ in Equation (8). Mixed-integer linear programming is applied to solve the optimization model.

5.2.1. Mixed-Integer Linear Programming

Mixed-integer linear programming is a class of NP-hard problem whose objective is to minimize the linear objective under linear constraints while making some or all of the variables integer-valued and is widely used in real-world scenarios such as capacity planning, resource allocation and boxing. The Gurobi solver of MATLAB can handle this type of problem effectively.

Usually, mixed-integer programming problems are divided into linear integer programming and nonlinear integer programming, and the model treated in this paper is a linear integer programming problem.

The canonical form of the integer programming is shown in Equation (13).

$$\begin{array}{rc} & \min c^T x \\ s.t. & Ax \geq b \\ & Cx = d \\ & x \geq 0 \\ & x_i \in Z \end{array} \tag{13}$$

5.2.2. Parameter Settings

Table 1 shows the necessary parameters for operation. The real-time electricity prices over the course of one day are from the Illinois Power Company [14] and are shown in Table 2. The price of electricity is referenced from the literature [12], where the lowest price is 2.2 cents/kWh and the highest price is 5.6 cents/kWh.

Table 1. Necessary parameters for operation.

Parameters	Value
c_h	14.8 dollar/kg [3]
η_{EL}	0.6 [4]
LHV_{H_2}	39.72 kWh/kg [15]
$\eta_{H_2}^{Ele}$	60% [16]
$Q_{in}^{\max}$	$0.2Q_{st}^{\max}$
$Q_{out}^{\max}$	$0.2Q_{st}^{\max}$
ω_c	1 kWh/kg [17]
$\mu_{h,in}$	95%
$\mu_{h,out}$	95%

Table 2. The prices of electricity power for HRS from grid.

Parameters	Peak Period	Low Period	Normal Period
c_e	7.86 Cent/kWh	3.57 Cent/kWh	5.29 Cent/kWh

The electricity price set in this example is shown in Table 2.

In this paper, we set the peak period as 10:00~11:00, 15:00~17:00, the normal period as 8:00~9:00, 13:00~15:00, 17:00~22:00 and the low period as 11:00~13:00, 22:00~8:00 [14].

5.2.3. Optimization Results and Comparison

This paper compares the economics of the current optimized operation methods commonly used in hydrogen refueling stations with the optimized operation method proposed in this paper.

In the conventional method, the hydrogen refueling station chooses to produce hydrogen during the low-price period, i.e., it produces hydrogen in small hours and stops the operation of the electrolyzer in other hours, so as to achieve the lowest operating cost.

For scenario 1, the daily hydrogen energy demand is about 1832 kg, and, according to the tariff curve [12], the electrolyzer operates at maximum power during the low-price period (11:00~13:00 and 22:00~8:00) to meet the whole day's hydrogen energy demand. the average operating power of the electrolyzer is therefore 10,602 kW. The hydrogen storage capacity can be set as the daily demand of the HRS, which is 1832 kg. Similarly, for scenario 2, the daily hydrogen demand is about 4251 kg, the maximum power required for its electrolytic cell is about 24,600 kW and the required hydrogen storage tank capacity is about 4251 kg. For scenario 3, the daily hydrogen demand is about 3684 kg and the maximum power required for its electrolytic cell is about 21,320 kW. The required hydrogen storage capacity is 3684 kg.

The optimized operation method proposed in this paper considers the whole life-cycle cost and achieves the minimization of daily operating costs considering the construction cost and the minimization of the whole life-cycle cost. The optimized configuration results for the three scenarios are shown in Table 3. It can be seen that the rated power of the electrolyzer and the capacity of the hydrogen storage tank configured in the hydrogen refueling station are significantly reduced by using the hydrogen refueling station planning method proposed in this paper, of which the reduction rate is 30.26% for the electrolyzer and 76.19% for the storage tank.

Table 3. Configuration of HRS system.

	Traditional Method			Optimized Method			Mean Reduction Rate
	Scenario 1	Scenario 2	Scenario 3	Scenario 1	Scenario 2	Scenario 3	
$P_{h,\max}$	10.6 MW	24.6 MW	21.3 MW	7.1 MW	16.6 MW	15.7 MW	36.26%
$Q_{store,\max}$	1832 kg	4251 kg	3684 kg	514 kg	1116 kg	696 kg	76.19%

The power diagrams of electrolyzer operation for the three scenarios are shown in Figure 4. As can be seen from Figure 4, the optimized operation method proposed in this paper is able to adjust the electrolyzer power according to the electricity price and can adapt to the distribution of hydrogen energy demand in different scenarios. Compared with the traditional method of producing hydrogen only at the lowest electricity price during a stable low-price period, the optimized method distributes the electrolyzer operation time according to the hydrogen demand estimation, effectively reducing the operation cost.

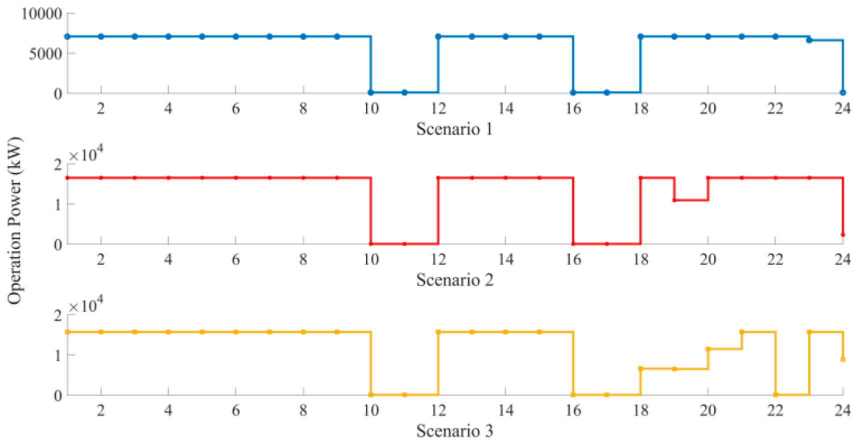

Figure 4. Daily generation power of electrolyzer in the three scenarios.

According to the rated power setting and the operation method of the electrolyzer in the above optimized method, the intra-day hydrogen storage variation of the hydrogen refueling station in the three scenarios can be obtained as shown in Figure 5.

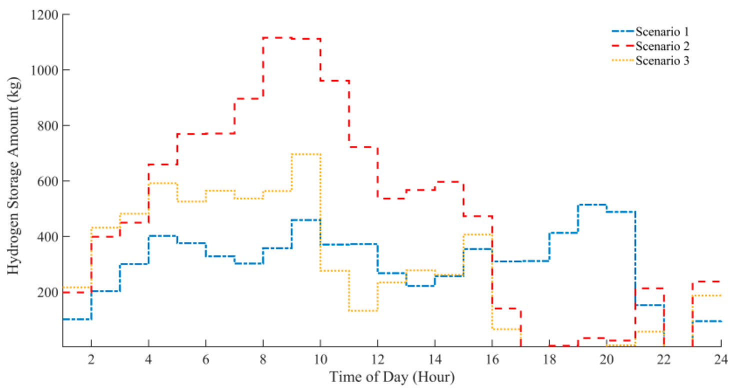

Figure 5. Hourly hydrogen storage of three scenarios.

It can be seen that the hydrogen energy storage capacity of the hydrogen refueling stations in the three scenarios is constantly changing and maintaining the same amount of hydrogen stored and released per day. The storage tank capacity requirements in Table 3 are obtained from the maximum daily hydrogen storage capacity.

This paper compares the optimized operation method proposed in this paper with the operation method that does not consider the construction cost [12], which often leads to a higher overall cost because it ignores the construction cost. Figure 6 shows the daily operating power of the electrolyzer for the proposed optimized operation method and the optimized operation mode without considering the construction cost for scenario 2. It can be seen that the operation mode without considering the construction cost will cause the operation power obtained by the algorithm to be very high at some moments. This will not only reduce the life of the electrolyzer, but also increase the demand for the operating capacity of the electrolyzer and increase the total cost.

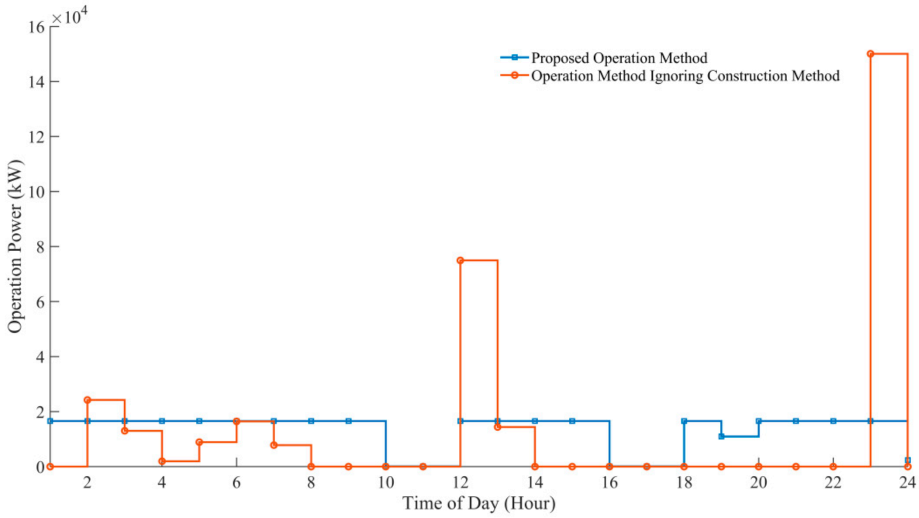

Figure 6. The daily operating power of the electrolyzer of different operation methods for scenario 2.

5.3. Economic Analysis

The optimized operation method for a hydrogen refueling station proposed in this paper is based on the estimation of intra-day hydrogen energy demand, the planning of the operating power of the electrolyzing cell at an hourly level and the use of the peak–valley difference of electricity price to reduce the intra-day operation cost of the hydrogen refueling station. On the basis of considering the construction cost of the hydrogen refueling station, the cost required per unit of hydrogen energy is reduced to achieve the lowest cost in the whole life cycle.

In order to achieve a full life-cycle economic comparison, the unit construction costs of the equipment related to the hydrogen refueling station are given in Table 4. Based on the price parameters in Table 4, the annual hydrogen energy demand for each scenario, the operating costs, and the electrolyzer and hydrogen storage tank capacity configurations for the two operating optimization methods, the cost per unit of hydrogen production using the two optimization methods can be calculated, as shown in (14).

$$\begin{cases} Cost_h = ((A/P,r,n)(\beta_{P\max}P_{ele,\max} + \beta_{Q\max}Q_{h,store,\max}) + \sum Cost_{Daily})/\sum Q_{demand} \\ (A/P,r,n) = \frac{r\times(1+r)^n}{(1+r)^n-1} \end{cases} \quad (14)$$

Table 4. Price parameters of HRS.

Parameters	Value
$\beta_{P\max}$	USD 454/kW [18]
r	5% [15]
$\beta_{Q\max}$	USD 37.31/kg [15]
n	10 years

The unit cost of hydrogen production for the two modes of operation calculated according to Equation (14) is shown in Figure 7.

The operating cost always accounted for most of the cost of hydrogen refueling station, which accounted for more than 75% in scenario 1, and the optimized operation method effectively reduced the unit hydrogen energy cost in the three scenarios. The unit hydrogen energy cost in scenario 1 was reduced by 23.67%, and the unit hydrogen energy cost in scenario 2 was reduced by 22.95%. The unit hydrogen energy cost of the optimized hydrogen refueling stations is less than $3/kg. In conclusion, the optimized operation method proposed in this paper can reduce the cost brought by the operation and construction of hydrogen refueling station at the same time, thus reducing the unit hydrogen energy cost and improving the net income of hydrogen refueling station. In conclusion, the optimized operation method proposed in this paper can reduce the cost brought by the operation and construction of the hydrogen refueling station at the same time, thus reducing the unit hydrogen energy cost and improving the net income of the hydrogen refueling station.

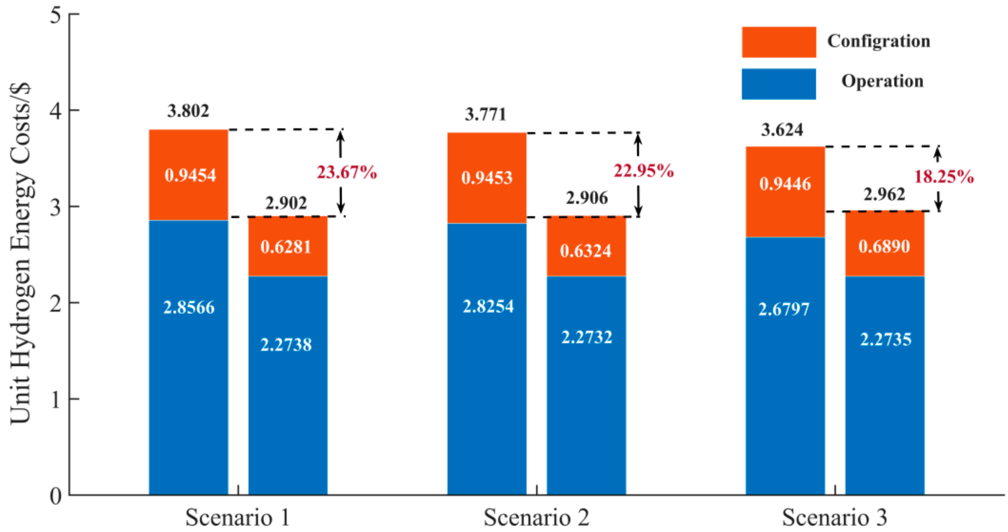

Figure 7. Unit hydrogen energy cost of the traditional operation (**left**) and the optimized operation (**right**).

5.4. Analysis of Influencing Factors

5.4.1. Electricity Price Analysis

In order to verify the effectiveness of the optimal operation method for a hydrogen refueling station proposed in this paper under different electricity price curves and the way it is influenced by the electricity price curve, this paper analyzes the optimization results based on the real-time electricity price in California and the real-time electricity price in Australia. In California, users are classified according to the maximum demand or annual electricity consumption of industrial and commercial users. This mainly includes A-1, A-10, E-19 and E-20 packages. Among these, the A-10 package involves time-of-use electricity price, and its electricity price has a different distribution in winter (1 November–30 April) and summer (1 May–31 October). Since the research time scale of the operation mode in this paper is one day, and the general hydrogen refueling station planning time scale is one year—and as winter and summer occupy a similar proportion of time in a year—this paper uses the average electricity price in winter and summer as the California electricity price for research, as shown in Table 5. The electricity price distribution in Australia is also shown in the table, and its seasonal electricity price differentials are handled in a similar way to California's.

Table 5. The intra-day electricity price of California and Australia.

Country	Season	Peak Period	Low Period	Normal Period
California	Summer	23 Cent/kWh	15 Cent/kWh	17 Cent/kWh
	Winter	——	13 Cent/kWh	15 Cent/kWh
Australia	Summer&Winter	27 Cent/kWh	13 Cent/kWh	21 Cent/kWh
	Others	21 Cent/kWh	13 Cent/kWh	21 Cent/kWh

The summer peak period of California electricity price is from 12:00 to 18:00, the summer trough period is from 21:00 to 8:00, and the rest of the time is the normal period, the winter trough period is from 21:00 to 8:00, and the rest of the time is the normal period without a peak period. In Australia, the peak period is from 14:00 to 20:00, the low period is from 22:00 to 7:00, and the rest of the time is the normal period. It is worth mentioning that this paper does not focus on different characteristic days, so it does not consider the difference between the weekend and the time in the week. In practical application, the weekend electricity price can be considered as the optimization premise.

It can be seen from Table 6 that the optimization method proposed in this paper reduces the unit hydrogen energy cost by 15.23% and 5.54%, respectively, compared with the traditional method under the conditions of California electricity price and Australian electricity price. Among these, due to the large difference between peak and valley electricity prices in Australia, there is a greater possibility to produce hydrogen only at valley electricity prices, while the traditional method is to produce hydrogen at valley electricity price. As a result, there seems to be little difference in their results. The optimized operation method proposed in this paper is used in areas with large peak–valley differences in electricity prices, and the effect on cost optimization is less than that in areas with a small peak–valley difference of electricity prices.

Table 6. Unit hydrogen energy cost of the traditional operation and the optimized operation.

Country	Method	Unit Cost (Operation)	Unit Cost (Construction)	Unit Cost (All)
California	Traditional Method	10.81	1.14	11.95
	Proposed Method	9.33	0.80	10.13
Australia	Traditional Method	9.03	1.61	10.64
	Proposed Method	8.38	1.69	10.07

5.4.2. Electrolyzer Unit Cost Analysis

The unit cost of the electrolyzer has a major influence on the construction cost of the hydrogen refueling station, and this section analyzes the planning and cost optimization results of the proposed optimization method when the unit cost of the electrolyzer changes. Since the technology is constantly developing and the cost of the electrolyzer should decrease in the future, this paper only discusses the results when the unit cost of the electrolyzer is less than the set cost. Figure 8 illustrates the planning results for the three scenarios when the unit cost of the electrolyzer is a different proportion to the set cost (454 $/kW).

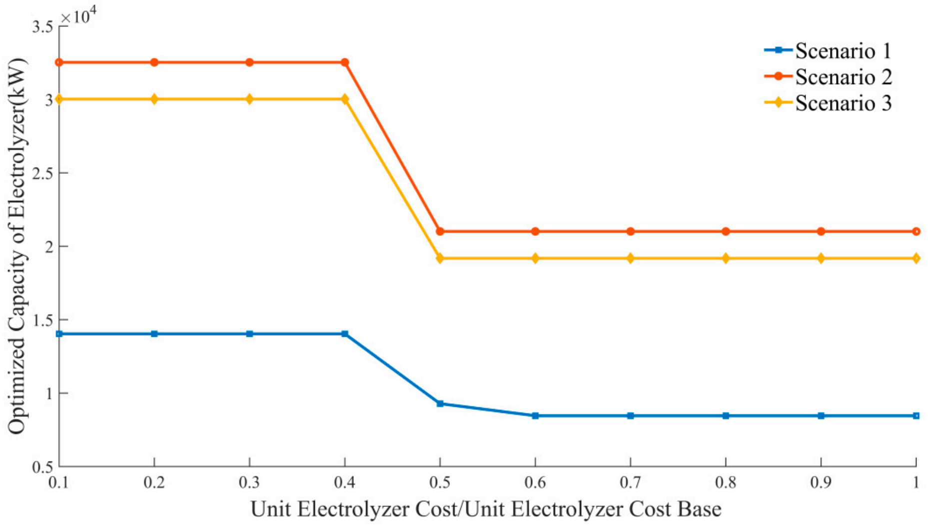

Figure 8. Optimized capacity of electrolyzer with different unit electrolyzer cost.

It can be seen that when the unit cost of the electrolytic cell changes between 0.6 and 1, the capacity planning result of the electrolytic cell remains unchanged; when the unit cost is between 0.4 and 0.6, the capacity planning result of the electrolytic cell changes suddenly, which may be caused by the match between construction cost and operation cost; when the unit cost is between 0.1 and 0.4, the planning capacity of the electrolytic cell also remains constant.

Figure 9 shows the saving rate of the unit hydrogen energy cost under the optimized operation method and the unit hydrogen energy cost under the traditional method when the unit cost of the electrolyzer is changed in scenario 2. It can be seen that the cost reduction rate is maintained in the range of 14.6% to 15.8%, and the unit cost of the electrolytic cell has a small impact on the optimization effect. In the range of the mutation of the electrolytic cell configuration, the cost reduction rate is the smallest. It can be seen that the optimization method proposed in this paper can adjust the configuration according to the unit cost of the electrolytic cell, so as to achieve the purpose of reducing the total cost. However, the traditional method cannot adaptively adjust the capacity configuration of the electrolyzer according to the unit cost of the electrolyzer.

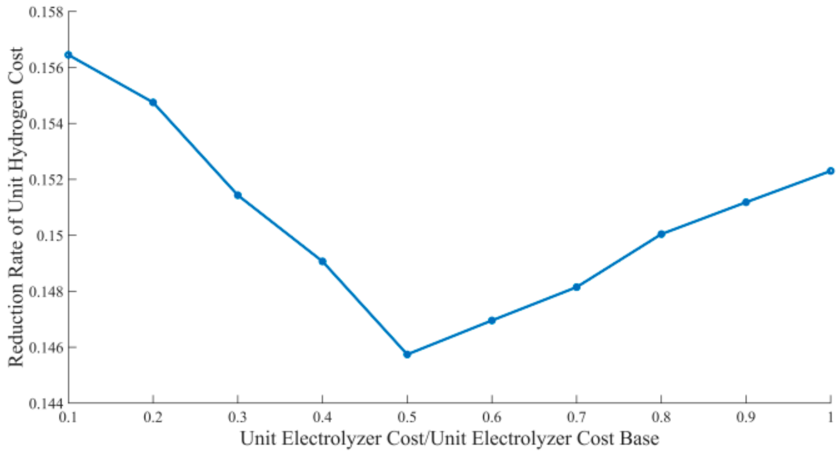

Figure 9. Reduction rate of unit hydrogen cost with different unit electrolyzer cost.

6. Conclusions

This paper proposes an optimized operation algorithm based on hydrogen demand estimation for in-situ hydrogen refueling stations. The optimized operation algorithm estimates the hydrogen demand distribution based on the location of hydrogen refueling stations and the number and type of vehicles served, and, on this basis, uses a linear programming method to optimize the operation of hydrogen refueling stations using the peak-to-valley difference in electricity prices, with the optimization objective of minimizing the daily cost. The case study shows that after using the optimization method, the initial construction capacity demand of the system is significantly reduced, the rated capacity of the electrolyzer and hydrogen storage tank is reduced, of which the reduction rate is 36.26% for the electrolyzer and 76.19% for the storage tank. Thus, the construction cost is greatly reduced. At the same time, the optimized operation method proposed in this paper can effectively reduce the unit hydrogen energy cost. In three typical scenarios, the unit hydrogen energy cost is reduced by 23.67%, 22.95% and 18.25% when compared with the traditional method. Finally, this paper discusses the application scope of the proposed optimized operation method and obtains the conclusion that the larger the difference between peak and valley electricity prices in the region, the smaller the cost reduction effect of the proposed optimized operation method. At the same time, when the unit price of the electrolyzer decreases, the impact of the proposed method on the unit hydrogen energy cost reduction effect is discussed.

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