Optimization study of hydrogen production system based on peak-valley tariff

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Abstract. This paper discusses a study on the optimization of hydrogen production systems based on peak and off-peak electricity prices and evaluates their potential and benefits in practical applications. By optimizing the operation and energy utilization efficiency of hydrogen production systems, taking full advantage of electricity price differences can reduce energy costs, improve economics, and promote the development of clean energy hydrogen production technologies. However, practical applications still face technical, economic, and market challenges that require further research and practical implementation to address. With technological breakthroughs and policy support, the optimization of hydrogen production systems based on peak-to-off-peak tariffs is expected to play a crucial role in the clean energy transition and sustainable development. Overall, the optimization of hydrogen production systems based on peak-to-off-peak tariffs has the potential to reduce the cost of hydrogen production, improve economics and sustainability. This approach can fully leverage inexpensive electricity during off-peak hours, enhance the operational efficiency of hydrogen production systems, and reduce reliance on conventional energy sources. However, practical applications must consider technical, economic, and market constraints. Through further research and practical implementation, these challenges can be overcome to achieve the feasibility and sustainability of optimizing hydrogen production systems based on peak-to-off-peak electricity prices. This will promote the application and sustainability of clean energy, making a significant contribution to the energy transition.

Keywords: Peak valley electricity price; Hydrogen production by Electrolysed water; Hydrogen production system; optimization

1 Introduction

With the increasing global energy demand and the urgent need for renewable energy, hydrogen production has a wide application prospect as a clean energy storage and conversion technology. Traditional methods of hydrogen production include pyrolysis, electrolysis, and chemical reactions. However, these methods have shortcomings such

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as high energy consumption, expensive costs, and carbon emission problems. In recent years, with the rapid development of renewable energy, emerging technologies such as water electrolysis and hydrogen production driven by solar and wind energy have gradually gained attention. These technologies are emission-free and renewable, offering new opportunities for achieving a clean energy economy.

Optimization studies of hydrogen production systems aim to improve energy use efficiency, reduce production costs, and minimize reliance on conventional energy sources. The peak-valley tariff policy, as an energy pricing strategy, can optimize the balance of energy supply and demand by adjusting the difference in electricity prices during peak and off-peak hours. Combining the peak-valley tariff policy with the optimization of the hydrogen production system is expected to further improve the economics and sustainability of the hydrogen production process.

In the field of hydrogen production system optimization research, several studies have been carried out on optimization methods to improve the efficiency and economy of hydrogen production processes. Some of these studies involve the exploration of economic aspects.Pablo [1] developed a Monte Carlo-based model to study the economic and technical factors that may influence the success of a green hydrogen strategy in Poland, as well as the economics at different stages of technology development and market adoption.Touili [2] conducted an economic analysis of Morocco's ability to produce hydrogen from solar energy and found that Morocco has a high potential for hydrogen production. Qingchao Liu [3] compared and analyzed the cost of hydrogen production by traditional means and by photovoltaic power generation, and concluded that photovoltaic hydrogen production has become economically feasible, and expected that the competitiveness of photovoltaic hydrogen production will be further enhanced as the cost of photovoltaic power generation decreases. In addition, some other studies have analyzed the economics of hydrogen production systems, such as the analysis of the cost of hydrogen production by electrolysis from renewable energy sources, and the economics of hydrogen production from photovoltaic power, wind power and biomass gasification [4-7].

In addition to economic studies, there are also some studies dedicated to the optimal configuration of hydrogen production systems. These studies use different optimization algorithms and methods to find the optimal capacity configuration solution for the hydrogen production system. For example, some studies have investigated the optimal capacity configuration of wind-light-hydrogen energy systems using methods such as adaptive particle swarm algorithms [8], genetic algorithms, and energy management algorithms [9]. These studies considered multiple objectives, including revenue maximization and multi-objective optimization of costs and benefits [10-13]. These optimal configuration studies can further improve the performance and economic efficiency of hydrogen production systems.

The results of economic studies and optimal allocation methods can offer guidance for the development and application of hydrogen production technologies, fostering the growth of the renewable energy hydrogen production industry and enhancing the efficiency and sustainability of energy systems. However, there is a lack of studies investigating the integration of peak-valley tariff policies into the optimization of hydrogen production systems, which could fully leverage the potential benefits arising from electricity price disparities. Hence, this study aims to bridge this research gap and explore peak-valley tariff-based optimization methods for hydrogen production systems, thus promoting the sustainable development of clean energy.

The aim of this article is to study the optimization method of a hydrogen production system based on peak-valley tariffs and evaluate its potential and benefits in practical applications. By developing mathematical models and applying optimization algorithms, we aim to explore how to maximize the advantages of peak-to-valley tariffs to optimize the operation and energy use efficiency of hydrogen production systems. Additionally, we will conduct a case study to verify the feasibility and practicality of the proposed method through data analysis and results evaluation. The ultimate goal is to provide a reference for cost reduction and efficiency improvement in hydrogen production systems.

2 Peak and Valley Tariffs and Hydrogen Production Systems

The peak-valley tariff mechanism is a policy measure aimed at achieving a balance between energy supply and demand by adjusting the price difference of electricity during peak and off-peak hours. During periods of low demand when power supply is relatively abundant, users are encouraged to concentrate their electricity consumption by reducing the price of electricity. Conversely, during peak hours when power supply is constrained, users are incentivized to reduce their electricity consumption through higher electricity prices. The peak-valley tariff mechanism is characterized by price differentiation, elastic demand, and the balancing of supply and demand.

Currently, there are four main types of electrolytic water hydrogen production: alkaline water electrolysis (AWE), proton exchange membrane water electrolysis (PEM), anion exchange membrane water electrolysis (AEM), and solid oxide water electrolysis (SOE). As shown in Fig. 1 , each of these four types of electrolytic water hydrogen production systems has its own advantages and disadvantages[14].

	AWE	PEM	AEM	SOE
Electrolyte diaphragm	30%KOH Asbestos film	Proton Exchange Membrane	Anion exchange membrane	Solid Oxide
Current density($A \cdot cm^{-2}$)	<0.8	1~4	1~2	0.2-0.4
Electricity consumption efficiency/($kW \cdot h \cdot N^{-1} \cdot m^{-3}$)	4.5~5.5	4.0~5.0	-	Expected efficiency of approximately 100%
Operating temperature/°C	≤90	≤80	≤60	≥800
Hydrogen production purity	≥99.8%	≥99.99%	≥99.99%	-
Relative equipment size	1	~1/3	-	-
Operating characteristics	Need to control the pressure difference, gas production needs to be dealkalized	Fast start/stop, water vapor only	Fast start/stop, water vapor only	Start/stop inconvenience, water vapor only
Maintainability	Strong alkali corrosion strong	No corrosive media	No corrosive media	-
Environmental friendliness	Asbestos film is harmful	No contamination	No contamination	-
Technology Maturity	Full industrialization	Initial commercialization	Laboratory stage	Initial Demonstration
Single machine size/($N \cdot m^{3} \cdot h^{-1}$)	≤1000	≤200	-	-

Fig. 1. Four types of water electrolysis technology characteristics.

Alkaline water electrolysis is the most mature and cheapest water electrolysis technology, which uses alkaline solution as electrolyte, nickel-based alloy as electrode material, working temperature at 60-90°C, pressure at 1-30 bar, current density less than 0.8 A/cm^2, energy consumption at 4.5-5.5 kWh/Nm^3 H_2, its technology is stable and low cost, and the actual case of the article uses alkaline Therefore, this section focuses on alkaline water electrolysis technology.

The alkaline electrolytic water hydrogen production system is relatively simple and mainly consists of water make-up system, lye circulation system, electrolytic tank, gas-liquid separation device, hydrogen purification device, etc. The electrolyte is all potassium hydroxide solution (KOH) with a concentration of about 30%. The flow chart of alkaline electrolytic water hydrogen production process system is shown in Fig. 2 .

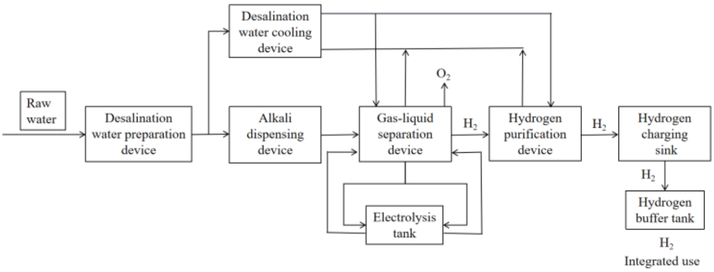

Fig. 2. Alkaline electrolytic water to hydrogen process flow chart.

Combining peak-valley tariff policies with hydrogen production systems has potential advantages and interrelationships. Firstly, the peak-valley tariff mechanism can incentivize customers to concentrate their electricity consumption during low valley hours by adjusting electricity prices. This, in turn, presents opportunities for hydrogen production systems. As the process of hydrogen production typically demands a substantial amount of electricity, scheduling the production during low valley hours can lead to lower electricity prices and reduced hydrogen production costs.

Secondly, the flexibility of the hydrogen production system aligns with the peak and off-peak electricity pricing mechanism. The hydrogen production system can be adjusted and optimized based on the fluctuation of electricity prices. For instance, during periods of low electricity prices, the system can increase hydrogen production to maximize the utilization of affordable electricity. Conversely, during peak hours when electricity prices are high, the system can reduce or halt hydrogen production to minimize costs and alleviate the strain on the electricity grid.

Finally, integrating peak and off-peak tariffs with hydrogen production systems can also promote the utilization of clean energy. By implementing peak and off-peak tariffs, customers are encouraged to concentrate their electricity consumption during off-peak hours, which presents an opportunity for widespread adoption of renewable energy sources like solar and wind power. These renewable energy sources typically generate more electricity at specific times of the day, and when combined with a hydrogen production system, they can effectively generate and store significant amounts of renewable energy during off-peak hours, facilitating efficient energy usage and storage..

3 Hydrogen production system optimization method

3.1 EOptimization objectives of hydrogen production system based on peak and valley tariffs

The goal of optimizing a peak-valley tariff-based hydrogen production system is to maximize the benefits of the system, which include economy, energy utilization efficiency, and system stability, within the framework of the peak-valley tariff policy. This is achieved through the reasonable arrangement of operation time, energy dispatch, and energy storage utilization in order to reduce the cost of hydrogen production. These costs include electricity purchase, investment, and maintenance costs of the energy storage system. Additionally, the optimization involves the strategic arrangement of operation modes and energy dispatch strategies based on changes in peak and valley tariffs to improve energy utilization efficiency. This includes maximizing hydrogen production efficiency during low-demand hours and reducing or pausing production during peak-demand hours. Furthermore, the impact of the hydrogen production system on the power system is considered, and the operation demand of the hydrogen production system is balanced with the stability requirements of the power system to ensure coordinated operation of both systems.

3.2 Mathematical modeling and constraints

The main constraints of the system are the amount of hydrogen produced and the operating load of the electrolyzer, while the objective is to optimize the cost of hydrogen production. The mathematical model of the system is as follows:

$$LCOH = \frac{CAPEX + \sum_{T=1}^{n} \frac{OPEX_T}{(1+i)^T} + \frac{OF_T}{(1+i)^T}}{\sum_{T=1}^{n} \frac{V_T}{(1+i)^T}} \quad (1)$$

Where: $LCOH$ is the levelized unit cost of hydrogen production. $OPEX_T$ is the running cost. OF_T is the start-stop cost. V_T is the amount of hydrogen produced.

$$OPEX_T = OM_T + Ele_T + KOH_T + Water_T \quad (2)$$

Where: OM_T is the maintenance cost. Ele_T is the cost of electricity. KOH_T is the material cost. $Water_T$ is the cost of water.

3.3 Case study and analysis of results

3.3.1 Data pre-processing.

Take a hydrogen production plant in Lanzhou as an example, the project is 100MW of photovoltaic power generation on the grid, replacing the grid power for hydrogen production, requiring an annual production of not less than 8000 tons of hydrogen. The project uses 75MW alkaline electrolyzer, which is divided into 3 sets of 25MW system for configuration. Each set contains five 1000Nm³/h electrolyzers, one gas-liquid separation system and one purification system.

As shown in Table 1, the system operation is adequately configured based on the key technical parameters of the hydrogen production system, energy efficiency, and other factors, to optimize the hydrogen production system during peak and off-peak electricity prices.

Table 1. Main technical parameters and configuration of hydrogen production system.

No.	Key Parameters	Parameter Description
1	Hydrogen production rate	Hydrogen production rate of single electrolyzer: 1000Nm³/h
2	System power consumption	100% load: 57.98 kWh/kgH_2 (5.16 kWh/Nm³H_2), 4.6 kWh for the power stack and 0.56 kWh for the auxiliary equipment AC power consumption; 10% load power consumption: 51.24 kWh/kgH_2 (4.56 kWh/ Nm³ H_2)
3	Load regulation range	10%-100% (2.5-25MW), corresponding to 50% of the minimum load of a single stack
4	Cold start time	40 min (access to purification) + 20 min (access to storage tank) = 1h
5	Hot start time	10 min (access to purification) + 20 min (access to storage tank) = 0.5h 10% load operation, pulling load to 100% load: 90 seconds
6	Electrolysis system acquisition cost	120 million

By collecting peak and valley electricity price data for each month of the year in the Hedong region of Gansu, the average price of each month was calculated and the average price curve was drawn, as shown in Fig. 3 .

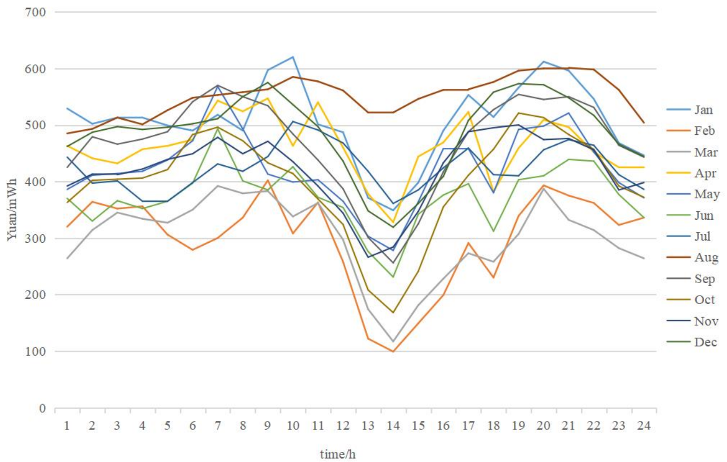

Fig. 3. Average price curve of Hedong in Gansu by month during the year.

3.3.2 Analysis of hydrogen production model results.

Matlab was used to import the arithmetic data into the model for solving and analyzing the annual optimal cost, as well as for examining the sensitivity of cost factors. The obtained results are as follows.

(1) Annual optimal cost

The lifespan of the electrolysis tank is 15 years, with an initial investment cost of 120 million Yuan. The annual optimal cost for producing 8000 tons of hydrogen is approximately 178 million Yuan, resulting in a unit cost of hydrogen production of about 22.27 Yuan/kg. From Figure 4, which displays typical daily electricity price data and an hourly start-stop situation graph, it can be observed that a total of 6975 hours of operation are required to achieve an annual production of no less than 8000 tons of hydrogen. Consequently, the electrolysis tank needs to operate for approximately 19.1 hours per day.

Time	January	February	March	April	May	June	July	August	eptembe	October	November	December
1	529	320	264	463	386	370	443	485	425	363	392	462
2	502	364	314	441	411	330	397	493	479	402	413	487
3	513	352	345	432	414	366	401	513	466	404	412	497
4	513	356	334	457	418	352	365	501	475	406	422	492
5	499	306	327	463	438	365	365	526	488	421	439	496
6	490	279	350	474	472	397	398	548	541	483	449	502
7	518	300	392	543	568	493	431	553	570	496	478	511
8	490	336	379	524	493	401	418	558	550	472	449	550
9	597	402	383	547	413	385	444	563	534	433	471	575
10	620	308	338	463	399	426	506	585	484	414	435	536
11	501	363	362	540	403	372	491	577	438	369	392	497
12	487	258	297	460	365	354	468	561	387	324	344	436
13	371	122	174	378	303	276	418	522	301	208	266	348
14	349	99	117	328	278	231	361	522	256	168	284	319
15	398	149	181	444	364	342	385	546	325	241	347	361
16	490	199	228	469	458	376	424	562	417	355	433	409
17	553	291	273	523	458	396	459	563	488	411	488	508
18	514	230	258	382	380	312	412	576	527	457	495	558
19	566	339	307	459	492	403	410	596	554	521	500	573
20	612	393	387	509	498	410	456	600	545	513	474	571
21	596	375	332	496	521	439	474	601	550	483	476	548
22	546	362	314	452	452	436	464	598	531	457	456	517
23	468	323	282	425	398	377	412	562	464	392	385	466
24	446	336	264	425	371	336	386	504	443	372	398	444

Unit: Yuan/mWh

Hot start time

Cold start time

Three electrolytic cells operating at 100% load

Three electrolytic cells operating at 10% load

Fig. 4. Typical daily tariff data and hourly start/stop.

(2) Cost factor sensitivity

From the change of hydrogen production cost under different electricity prices in Fig. 5, it is clear that the current electricity price is the key factor leading to the high cost of hydrogen production at this stage. The electricity price sensitivity is high, and as the electricity price decreases, the unit hydrogen production cost of electrolyzer decreases. When the electricity price decreases from RMB 0.4/kWh to RMB 0.3/kWh for 6000 hours of operation, the hydrogen production cost of alkaline electrolyzer will decrease by 23%; when the electricity price decreases to RMB 0.34/kWh, the unit hydrogen production cost decreases to RMB 20.886/kg.

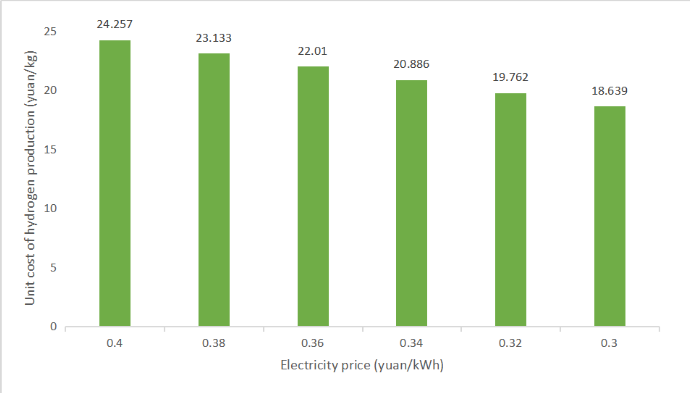

Fig. 5. Variation of hydrogen production cost under different electricity price.

From the effect of different power consumption on the cost of hydrogen production in Fig. 6, it can be seen that the electrolyzer power consumption decreases from 5.2kWh/Nm³ to 4.8kWh/Nm³, the cost of hydrogen production decreases by 7.1% with high sensitivity; when the power consumption level reaches 4.05kWh/Nm³, the unit cost of hydrogen production can be reduced to 20 RMB/kgH2.

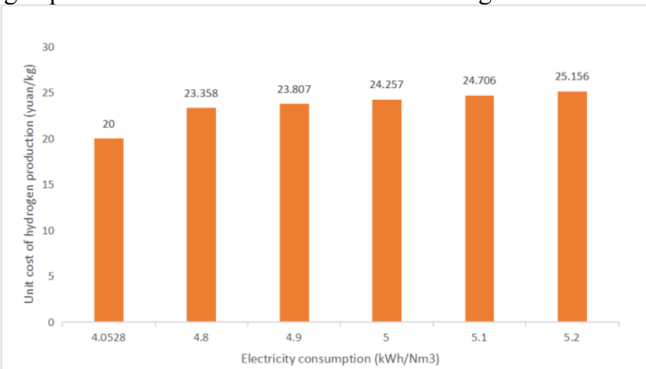

Fig. 6. Impact of different electricity consumption on the cost of hydrogen production.

4 Conclusion

This article discusses the study of optimizing hydrogen production systems based on peak and valley tariffs and evaluates their potential and benefits in practical applications. The article introduces the importance and application prospects of hydrogen production technology and highlights the advantages of this emerging technology. Additionally, the article introduces the peak-valley tariff mechanism and the components and principles of hydrogen production systems. By establishing a mathematical model and applying an optimization algorithm, the method based on peak-valley tariffs can maximize the difference between energy supply and demand, improving the economy and energy utilization efficiency of the hydrogen production system. However, practical application still faces technical, economic, and market challenges. Therefore, further research and practice are needed to address these relevant issues and promote the feasibility and sustainability of peak-to-valley tariff-based hydrogen production system optimization. Research in this area will play a crucial role in facilitating the clean energy transition and sustainable development.

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