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Scheduling study of off-grid wind power hydrogen production system under battery and electrolyzer degradation conditions based on genetic algorithm optimization

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Abstract To cope with the energy crisis and environmental challenges, wind power hydrogen generation system has become an important direction for new energy utilization with its clean and efficient features. In this paper, a scheduling control method based on improved genetic algorithm is proposed for off-grid wind power hydrogen generation system under battery and electrolyzer degradation conditions. A system model considering the degradation characteristics of batteries and electrolysers is constructed, a rule-based control strategy is adopted to coordinate the energy interaction between source-load-storage, and a nonlinear adaptive cross-variance probability mechanism is designed to achieve efficient optimization of the system configuration. The results show that the spatial evaluation index SP and generation distance GD of the improved genetic algorithm on the ZDT3 test function are 0.0045 and 0.0012, respectively, which are significantly better than the traditional genetic algorithm. An arithmetic analysis based on wind speed data in a sea area shows that the optimized system is able to achieve a levelized hydrogen cost of 22.84 Yuan/kg and a 4.53% probability of missing hydrogen supply. The sensitivity analysis found that the system LHSP remained below 18% and the LCOH ranged from 18 to 34 yuan over the parameter variation interval of [-45%,45%], indicating that the system has strong hydrogen supply capability and investment robustness. The study provides an effective method for the efficient operation and economic evaluation of off-grid wind power hydrogen production system, which is of reference value for promoting the integration of renewable energy and hydrogen energy.

Index Terms off-grid wind power hydrogen production, electrolyzer degradation, improved genetic algorithm, energy interaction, hydrogen supply reliability

I. Introduction

In order to accelerate the promotion of energy transformation, to achieve carbon peak, carbon neutral goals, vigorously develop renewable energy such as wind energy is an important way to wind-based renewable energy will be the core component of China's construction of a clean, low-carbon energy system. Wind resources have greater volatility and randomness, although it can effectively optimize the energy structure, but the safe and reliable operation of the power grid has brought many adverse effects, resulting in the prevalence of wind abandonment phenomenon [1], [2]. At the same time, hydrogen energy has the characteristics of green low-carbon, high efficiency, rich storage and transportation methods, and has a wide range of application areas and development prospects [3]. Adopting off-grid wind power to produce hydrogen can effectively promote wind power consumption and energy structure optimization, which can not only improve the utilization rate of wind power, realize the local consumption of clean energy, but also effectively explore the new direction of energy strategy of “green hydrogen” [4]-[6].

However, renewable wind energy as an input will make the battery and electrolyzer under frequent start-stop transient operating conditions, and such fluctuating and intermittent inputs will degrade the performance of the battery and electrolyzer [7]-[10]. Electrolyzer degradation modeling is needed to assess the health of the battery and the electrolyzer to avoid the collateral damage of the electrolyzer damage to the whole system [11]-[13]. For this purpose, the structure and mechanism of battery and electrolyzer degradation can be analyzed, and the degradation mechanism can be analyzed from the physical level and the chemical level, respectively [14], [15]. Optimization-seeking algorithms are also introduced for system-level capacity allocation and operation optimization, and interval-maximum predictions are proposed to meet the time and accuracy requirements for engineering applications [16], [17].

Hydrogen energy, as a clean and efficient secondary energy carrier characterized by high energy density, low combustion pollution and wide sources, is regarded as an important part of the future energy system. Under the current double pressure of global climate change and energy structure transformation, the development of renewable energy hydrogen technology has become a consensus of the low-carbon development strategy of countries around the world. Wind energy resources are abundant and widely distributed, and converting wind energy into hydrogen can not only solve the problem of wind power consumption, but also realize the long-term storage and diversified use of energy. Wind-powered hydrogen production system can effectively overcome the intermittency and volatility of renewable energy and improve the efficiency of energy utilization by converting electric energy into chemical energy through electrolysis of water. Especially in remote areas with insufficient grid coverage, off-grid wind power hydrogen generation system can realize energy self-sufficiency and provide clean energy supply for the local area. Currently, the main challenges facing wind power hydrogen production technology include low system efficiency, high hydrogen production cost, and serious degradation of system components. Especially under off-grid operation conditions, the randomness and volatility of wind energy puts higher requirements on the stable operation of the system due to the lack of support from a large power grid. In addition, the performance of the energy storage battery and electrolyzer, which are the core components of the system, will be degraded continuously due to the influence of the working environment and the working mode, which in turn affects the hydrogen yield and economy of the whole system. Therefore, how to design an efficient scheduling control method for off-grid wind power hydrogen production system under the condition of considering the degradation characteristics of the energy storage battery and electrolyzer has become the focus and difficulty of the current research.

Aiming at the above problems, this study proposes a scheduling control method for off-grid wind power hydrogen generation system based on improved genetic algorithm. First, the overall structural model of off-grid wind power hydrogen production system is constructed, and the selection basis and working principle of each unit of the system are clarified; second, a mathematical model considering the degradation characteristics of the storage battery and the electrolyzer is established, and a source-charge-storage coordination strategy based on rule-based control is put forward; then, a dual-objective optimization framework of levelized hydrogen cost and hydrogen supply missing probability is designed, and the traditional genetic algorithm is improved by A nonlinear adaptive cross-variance probability mechanism is introduced to improve the convergence and diversity of the algorithm; finally, the effectiveness of the improved algorithm is verified by the ZDT test function, and arithmetic case analysis and sensitivity study are carried out based on actual wind speed data.

II. Structure of off-grid wind power hydrogen production system

II. A. Overall system structure

The off-grid wind power hydrogen production system firstly converts the captured wind energy into electricity through the wind turbine and direct-drive permanent magnet wind turbine generator of the direct-drive permanent magnet wind power generation system unit, and then converts the alternating current (AC) from the wind turbine into direct current (DC) through AC/DC converter to connect to the DC bus, and then stabilizes the DC bus voltage by using the storage battery device, and finally converts the stabilized DC bus voltage into the suitable DC voltage for the back-end hydrogen production load voltage level through the DC voltage step-down converter. Finally, the stabilized DC bus voltage is converted into a DC voltage suitable for the back-end hydrogen production load voltage level by a DC step-down converter.

The overall structure of the off-grid wind power hydrogen production system is shown in Figure 1. The direct-drive permanent magnet wind power generation system unit, hydrogen electrolyzer unit, and energy storage battery system unit are directly coupled to the DC bus, and the DC bus voltage is reduced to a low voltage and high current suitable for hydrogen production loads by using a high-variable-ratio DC step-down converter for power supply.

The off-grid wind power hydrogen production system uses direct-drive permanent magnet wind turbines as the main “source”, PEM electrolyzers as the hydrogen production equipment, energy storage batteries and hydrogen storage devices for energy storage, and a high-variable-ratio DC step-down converter as the power converter that realizes the system's conversion from DC bus voltage to low-voltage high-current. The main purpose of the system is to realize large-scale, low-cost, low-energy, industrialized hydrogen production in the context of energy structural reform, and to convert renewable wind energy, which is not easy to store, into clean and efficient hydrogen energy storage and comprehensive utilization. The main tasks of its control system are to capture the maximum wind energy, improve the utilization rate of wind energy, coordinate the power balance of each unit of the system, and ensure the safe and stable operation of the system.

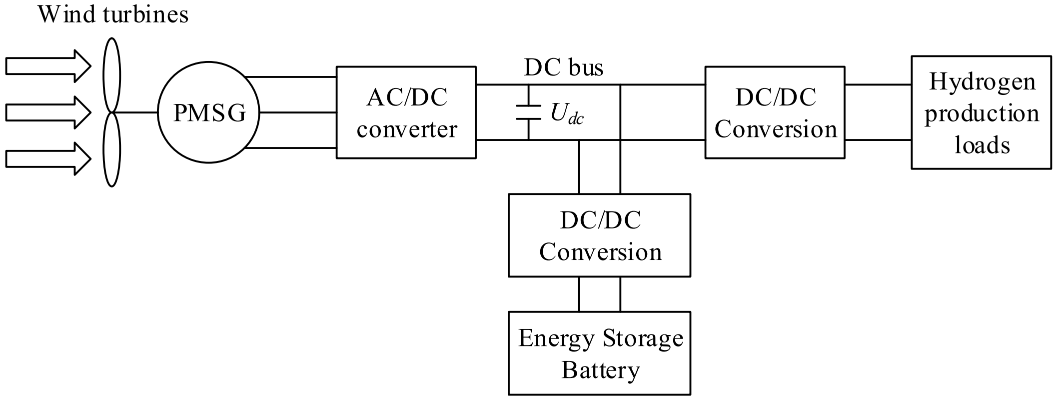


Figure 1: The overall structure of the wind power manufacturing hydrogen system of non- network

II. B. Selection of system units

II. B. 1) Wind power systems

At present, wind turbines can be mainly divided into constant speed and constant frequency and variable speed and constant frequency, and the generators commonly used in variable speed and constant frequency power generation systems are: direct-drive permanent magnet synchronous wind turbines, double-fed wind turbines, brushless double-fed wind turbines, and cage-type asynchronous generators.

The use of direct-drive permanent magnet synchronous wind turbine in wind power generation system has the advantages of high system efficiency, long service life, low cost, strong environmental adaptability and good operational reliability. Therefore, in this paper, direct-drive permanent magnet synchronous wind turbine is selected as the “source” energy device to generate electricity to provide the required power for the hydrogen production load later.

II. B. 2) Hydrogen production electrolyzers

Hydrogen as an important new clean energy in the future, its production often need to use electrolyzer equipment to realize, electrolyzer equipment is usually water molecules through electrolysis in the anode so that OH- lose electrons and generate oxygen, in the cathode so that the H + to get electrons and thus generate hydrogen. Currently commonly used hydrogen production electrolyzer according to its electrolyte can be divided into alkaline electrolyzer (AE), proton exchange membrane electrolyzer (PEME), solid oxide electrolyzer (SOE) three categories. PEME has a higher working current density, system efficiency is relatively high, the purity of hydrogen is higher, the dynamic response speed is faster, etc., in this paper, we will choose the PEM electrolyzer as an analysis of the object of the study.

II. B. 3) Energy storage batteries

Due to the wind power hydrogen system on the energy storage technology needs are more stringent, special, and the new electrochemical energy storage technology because of its larger capacity, small size, high energy conversion efficiency, fast dynamic response speed, long service life, relatively low cost, safety and reliability, etc. Advantages of its renewable energy applications in the field of the most potential for development of the energy storage technology. Therefore, this paper uses lithium batteries as energy storage batteries for analysis and research.

II. B. 4) High Ratio DC Buck Converter

The full-bridge DC/DC converter has high efficiency, good fault tolerance, and high step-down ratio and good reliability, and it is selected as the high-variable-ratio DC step-down converter for this system. Equations (1) to (3) are the voltage ratio, current ripple, and main switching tube voltage stress calculation formulas of the full-bridge DC/DC converter, respectively:

$$\frac{U_{el}}{U_{dc}} = \frac{2D}{n} \tag{1}$$

$$\Delta i_L = \frac{(1-D)U_{dc}}{Lf_s}\frac{D}{n} \tag{2}$$

$$U_{s_1} = U_{s_2} = U_{s_3} = U_{s_4} = U_{dc} \tag{3}$$

where U_{el} is the voltage across the hydrogen production load (V), U_{dc} is the DC bus voltage (V) and the input voltage of the buck circuit. Δi_L is the inductor current ripple (A), D is the duty cycle, L is the inductance (H), f_s is the switching frequency (Hz), and U_S is the voltage stress of the switching tube (V).

III. Scheduling control method for off-grid wind power hydrogen production system

Taking into account the degradation characteristics of batteries and electrolyzers, hydrogen demand is taken as the load side, wind power and photovoltaic as the energy side, and lithium batteries and hydrogen storage tanks as the energy storage side, and a scheduling control method of off-grid wind-power hydrogen production system is proposed, which is solved by an improved genetic algorithm.

III. A. Hydrogen production environment construction

The mathematical relationship between the output power of a wind turbine and the wind speed can be expressed as:

$$P_{WT}(t)=\begin{cases}0, & v_t<v_{ci}, v_t>v_{co}\\ P_{r,WT}\times\left[\dfrac{v_t^2-v_{ci}^2}{v_r^2-v_{ci}^2}\right], & v_{ci}<v_t<v_r\\ P_{r,WT}, & v_r<v_t<v_{co}\end{cases} \tag{4}$$

$$v_t(H)=v_t(H_{ref})\times\left(\frac{H}{H_{ref}}\right)^{\alpha} \tag{5}$$

$P_{r,WT}$ is the rated power of the turbine (kW), v_{ci}, v_{co} and v_r are the tangential, tangential and rated wind speeds (m·s⁻¹), respectively, $v_t(H)$ is the wind speed at the height at which the hub is located, $v_t(H_{ref})$ is the wind speed measured at the height of the observatory, H_{ref} is the height of the measuring station, taken as 2 m. H is the height at which the hub is mounted, and α is the surface friction coefficient.

In order to evaluate the charging and discharging capacity of Li-ion batteries, the state of charge is usually expressed as:

$$SOC_{BESS}(t)=\begin{cases}SOC_{BESS}(t-1)(1-\sigma)+\dfrac{\eta_{ch}\times P_{BESS}^{ch}(t)\times\Delta t}{C_{BESS}}, & \text{Charging}\\ SOC_{BESS}(t-1)(1-\sigma)-\dfrac{P_{BESS}^{dch}(t)\times\Delta t}{\eta_{dch}\times C_{BESS}}, & \text{Discharge}\\ SOC_{BESS}(t-1), & \text{Standby}\end{cases} \tag{6}$$

$SOC_{BESS}(t)$ is the state of charge of the Li-ion battery at t moment, η_{ch} and η_{dch} are the charging and discharging efficiencies, respectively, $P_{BESS}^{ch}(t)$ and $P_{BESS}^{dch}(t)$ are the charging and discharging powers (kW), respectively, Δt is the sampling time interval (h), and C_{BESS} is the rated capacity of the lithium battery (kWh).

In order to evaluate the storage status of the hydrogen storage tank, the parameter SOC_{HST} is introduced and calculated as:

$$SOC_{HST}(t)=SOC_{HST}(t-1)+\frac{(\dot{m}_{H_2}(t)-\dot{L}_{H_2}(t))\times\Delta t}{C_{HST}} \tag{7}$$

$$\dot{m}_{H_2}(t)=\frac{P_{SOEC}^{act}(t)\times\eta_{sys}}{LHV_{H_2}} \tag{8}$$

$SOC_{HST}(t)$ is the hydrogen storage state at moment t, C_{HST} is the rated capacity of the hydrogen storage tank (kg), $\dot{m}_{H_2}(t)$ and $\dot{L}_{H_2}(t)$ are the hydrogen production and the hydrogen load at moment t (kg·h⁻¹), Δt is the interval sampling time, LHV_{H_2} is the low calorific value of hydrogen, η_{sys} is the system efficiency, and $P_{SOEC}^{act}(t)$ is the actual power of the system in terms of hydrogen production (kW) considering the degradation in the moment t.

In the process of system optimization configuration and operation, considering the inherent degradation characteristics of battery and electrolyzer, it is necessary to design the corresponding degradation factor to calculate the actual hydrogen production power of the system. For this purpose, the actual hydrogen production power of the system as a function of its allocated power is constructed as follows:

$$P_{SOEC}(t)=P_{SOEC}^{act}(t)\times\underbrace{\left(1+\sum_{t-1}\frac{r_{deg}^{t-1}}{1000}\right)\times\left(1+\frac{r_{deg}^{t}}{1000}\right)}_{\text{Degradation factors}} \tag{9}$$

$P_{SOEC}(t)$ is the allocated power (kW) of the system at the moment t, and r_{deg}^{t} is the degradation rate (%/kh) corresponding to $P_{SOEC}(t)$, which is expressed as:

$$r_{deg}^{t}=\begin{cases}0, & \text{Hot standby}\\ a\times P_{SOEC}(t)^2+b\times P_{SOEC}(t)+c, & \text{High Efficiency Interval}\end{cases} \tag{10}$$

In terms of the output constraints of the off-grid wind power hydrogen generation system, existing gasoline refueling data from a service area was used for scaling to characterize the hydrogen refueling requirements of fuel cell vehicles.

III. B. System configuration optimization

III. B. 1) Coordination strategy

A rule-based control operation strategy is proposed to coordinate the energy interaction between source-load-storage. The specific coordination process is as follows:

Step1: Under a given configuration scheme, input the meteorological conditions, hydrogen load, and the initial hydrogen storage state SOC_{HST}^{0} of the hydrogen storage tank, and the initial charge state SOC_{BESS}^{0} of the lithium battery. Calculate the total renewable energy output power $P_{tot}(t)$ at the current moment.

Step2: Determine whether $P_{tot}(t)$ is greater than the minimum system load $P_{SOEC}^{\min}$, i.e., $P_{tot}(t)\geq P_{SOEC}^{\min}$. If yes, it means that the wind power energy can satisfy the power demand of the system, then skip to Step3. If no, it means that the wind power energy cannot satisfy, then skip to Step4.

Step3: Determine whether the hydrogen storage state of the hydrogen storage tank is at the highest level, i.e., $SOC_{HST}(t-1)\geq SOC_{HST}^{\max}$, in order to determine the operating state of the system. If yes, the system is placed on hot standby. If no, the operating power of the system, $P_{SOEC}(t)$, is determined by its maximum operating power, $P_{SOEC}^{\max}$, the renewable energy output power, $P_{tot}(t)$, and the equivalent power of the hydrogen storage tanks in the hydrogen storage state limitation, $P_{SOEC}^{HST}(t)$, i.e., $P_{SOEC}(t)=min\left\{P_{SOEC}^{\max},P_{tot}(t),P_{SOEC}^{HST}(t)\right\}$. After determining the operating state of the system, calculate the residual power $P_{exc}(t)$ and proceed to Step5 to determine the operating state of the lithium battery. Where the residual power $P_{exc}(t)$ is calculated by the formula:

$$P_{exc}(t)=P_{tot}(t)-P_{SOEC}(t) \tag{11}$$

Step4: When the wind power energy cannot meet the minimum power for system operation, i.e., $P_{tot}(t)\leq P_{SOEC}^{\min}$, determine the operating state of the Li-ion battery and the system based on the charge state of the Li-ion battery. Determine whether $SOC_{BESS}(t-1)$ is in the lowest charge state, i.e., $SOC_{BESS}(t-1)\leq SOC_{BESS}^{\min}$. If yes, it means that the combination of Li-ion battery and wind energy cannot guarantee the operation of the system. In order to consume as much renewable energy as possible, the lithium battery then stores electricity according to its storage capacity. If no, go to Step6.

Step5: Determine whether the charge state of the lithium battery is at the highest level, i.e., $SOC_{BESS}(t-1)\geq SOC_{BESS}^{\max}$. If yes, the Li-ion battery is on standby and the excess power is delivered to the higher grid. If no, the Li-ion battery is charged and the charging power is determined by the minimum between the maximum charging power $P_{ch\_\max}$, the power limited by the state of charge $P_{BESS,ch}^{\max}(t)$, and the surplus power $P_{exc}(t)$, i.e., $P_{BESS}^{ch}(t)=\min\left\{P_{ch\_\max},P_{exc}(t),P_{BESS,ch}^{\max}(t)\right\}$, and if there is excess power, it will be transmitted to the higher grid.

Step6: Determine whether the maximum dischargeable power of the lithium battery combined with the wind energy $P_{tot}(t)$ can satisfy the minimum operating power of the system, i.e. $P_{tot}(t)+\min\left\{P_{dis\_\max},P_{BESS,dis}^{\max}(t)\right\} geP_{SOEC}^{\min}$. If yes, the system runs at $P_{SOEC}^{\min}$ and the Li-ion battery discharges. If no, the system is in hot standby, the Li-ion battery is charged, and if there is excess power it is delivered to the higher grid.

Step7: Calculate the amount of hydrogen produced in each of the above scenarios, when the hydrogen load demand is satisfied, $H_{loss}(t)=0$. On the contrary, the hydrogen supply is insufficient, and the amount of missing hydrogen corresponds to the calculation of Eq:

$$H_{loss}(t)=\dot{L}_{H_2}(t)\Delta t-(\dot{m}_{H_2}(t)\Delta t+(SOC_{HST}(t-1)-SOC_{HST}^{min})C_{HST}) \tag{12}$$

Step8: $t=t+1$, determine whether the simulation moment t reaches $t_{\max}$. If yes, the simulation ends. If no, continue to return to Step2 loop until $t_{\max}$ is reached.

The maximum equivalent power $P_{SOEC}^{HST}(t)$ of the system operation limited by the hydrogen storage state of the hydrogen storage tank can be expressed as:

$$P_{SOEC}^{HST}(t)=\left(\frac{(SOC_{HST}^{\max}-SOC_{HST}(t-1))\cdot C_{HST}}{\Delta t}+\dot{L}_{H_2}(t)\right)\cdot\frac{LHV_{H_2}}{\eta_{sys}} \tag{13}$$

In addition the maximum charging and discharging power $P_{BESS,dis}^{\max}(t)$ and $P_{BESS,ch}^{\max}(t)$ of the lithium battery charge state limitation can be expressed as:

$$P_{BESS,dis}^{\max}(t)=\frac{(SOC_{HST}(t-1)-SOC_{BESS}^{\min})}{\Delta t}\cdot\eta_{dch}\cdot C_{BESS} \tag{14}$$

$$P_{BESS,ch}^{\max}(t)=\frac{(SOC_{BESS}^{\max}-SOC_{BESS}(t-1))}{\Delta t}\cdot\frac{C_{BESS}}{\eta_{ch}} \tag{15}$$

In addition, the maximum charging and discharging power $P_{ch\_\max}$ and $P_{dis\_\max}$ of the Li-ion battery cell are determined by the charging and discharging multiplicity R_{BESS} together with the Li-ion battery capacity C_{BESS}.

III. B. 2) Evaluation guidelines

Hydrogen supply shortage probability and levelized hydrogen cost are used to evaluate the configuration options of the system.

The Lack of Hydrogen Supply Probability (LHSP) is used as a reliability metric for assessing the hydrogen supply, which can be characterized as the ratio of the unsatisfied hydrogen load to the annual hydrogen demand, i.e:

$$LHSP=\frac{\sum_{t=1}^{8760}H_{loss}(t)}{\sum_{t=1}^{8760}\dot{L}_{H_2}(t)} \tag{16}$$

where $\dot{L}_{H_2}(t)$ is the hydrogen load at moment t and $H_{loss}(t)$ is the gap in hydrogen supply at moment t. In addition, a reliability metric is usually constrained to ensure that hydrogen can be supplied properly, which can be expressed as:

$$LHSP\le LHSP_{limit} \tag{17}$$

where $LHSP_{limit}$ 1 is the constraint value of LHSP, which is usually specified as zero.

The levelized cost of hydrogen (LCOH) is used as an indicator for evaluating the economics of hydrogen production, which can be characterized as the ratio of the total annualized cost of the system to the annual hydrogen demand, i.e:

$$LCOH=\frac{C_{tot}}{\sum_{t=1}^{8760}\dot{m}_{H_2}(t)} \tag{18}$$

$$C_{tot}=\sum_{k=PV,WT,SOEC,BESS,HST}NPC_k\cdot CRF \tag{19}$$

$$CRF=\frac{i\cdot(1+i)^l}{(1+i)^l-1} \tag{20}$$

$$i=\frac{g-f}{1+f} \tag{21}$$

C_{tot} is the total annualized cost $(\$/year)$ CRF is the capital recovery factor, which is related to the system project life l and the real interest rate i, which in turn is related to the annual interest rate g and the inflation rate f. NPC_k is the total cost of each unit in the design cycle of the hydrogen production system, including investment cost, operation and maintenance cost, and replacement cost, which is calculated by the formula:

$$NPC_k=C_k^{inv}+C_k^{om}+\sum_{n=1}^{N_s}\frac{C_k^{rep}\cdot x_{1,k}}{(1+i)^n} \tag{22}$$

$$x_{1,k}=\begin{cases}1 & n=N_k^{rep}\\ 0 & n\ne N_k^{rep}\end{cases} \tag{23}$$

$$N_k^{rep}=N_k\cdot x_{2,k}+1 \tag{24}$$

$$x_{2,k} = 1 \sim \left[\frac{N_s}{l_k} - 1 \right] \quad (25)$$

C_k^{inv}, C_k^{om}, and C_k^{rep} are the total investment cost, O&M cost, and replacement cost of each module, respectively, N_s and l_k are the project life and module life, respectively, and N_k^{rep} is the year of module replacement.

III. B. 3) Constraints

Based on the hydrogen load magnitude of the system, the number or capacity constraints of the source and storage units are initially determined and can be expressed as follows:

$$0 < N_{WT} \le N_{WT}^{\max} \quad (26)$$

$$0 < N_{BESS} \le N_{BESS}^{\max} \quad (27)$$

$$0 < C_{HST} < C_{HST}^{\max} \quad (28)$$

N_{WT} and N_{BESS} are the number of turbines and lithium batteries installed, and C_{HST} is the rated capacity of the hydrogen storage tank. The $N_{WT}^{\max}$, $N_{BESS}^{\max}$ and $C_{HST}^{\max}$ are the maximum number of installations or the maximum capacity of the corresponding units.

The output power of each module is also limited by its capacity constraint as follows:

$$0 < P_{WT}(t) < P_{WT}^{\max} \quad (29)$$

$$-R_{BESS} \times C_{BESS} \le P_{BESS}^{\mathrm{dis}}(t) \le 0 \quad (30)$$

$$0 \le P_{BESS}^{\mathrm{ch}}(t) \le R_{BESS} \times C_{BESS} \quad (31)$$

$$P_{SOEC}^{\min} \le P_{SOEC}(t) \le P_{SOEC}^{\max} \quad (32)$$

R_{BESS} is the battery charge/discharge multiplier.

In order to guarantee the charging and discharging capacity of hydrogen storage tanks and lithium batteries, the following constraints are imposed on their storage states, respectively:

$$SOC_{BESS}^{\min} \le SOC_{BESS}(t) \le SOC_{BESS}^{\max} \quad (33)$$

$$SOC_{HST}^{\min} \le SOC_{HST}(t) \le SOC_{HST}^{\max} \quad (34)$$

where $SOC_{BESS}^{\min}$ and $SOC_{BESS}^{\max}$ are the minimum and maximum values of the battery's charge state, respectively, and $SOC_{HST}^{\min}$ and $SOC_{HST}^{\max}$ are the hydrogen storage state's minimum and maximum values.

In addition, the power balance is also the cornerstone of the stability of the SOEC system, which can be expressed as:

$$P_{PV}(t) + P_{WT}(t) + P_{BESS}(t) = P_{SOEC}(t) + P_{grid}(t) \quad (35)$$

P_{grid} is the excess power delivered by the system to the higher grid.

III. C. Solution methods

III. C. 1) Genetic algorithms

Genetic algorithms are heuristic algorithms that mimic the evolution of organisms through heredity, in addition to mimicking the principle of survival of the fittest in the theory of evolution, they also mimic the crossover and mutation operations that occur when genetic information is reproduced. In solving the optimization problem, the problem is abstracted into a code as if into the form of a gene chromosome in biological genetics, with genes in different positions controlling different characteristics of the organism. Then through the principle of selection, crossover and mutation operation in genetics, the chromosome is evolved to keep the genes with high adaptability inherited to the next generation, and the genes with low adaptability are eliminated.

(1) Population initialization

In the process of population initialization, it is necessary to set the maximum number of evolutionary generations of the population L, the crossover probability P_c, the mutation probability P_m, and to generate P individuals as the initial population $P(0)$ in a randomized manner.

(2) Chromosome coding

Abstracting the problem parameters into an encoding, a chromosome encoding can represent the solution of the problem. The encoding method has an important impact on the speed and accuracy of the problem solution, common integer encoding, binary encoding, Gray code encoding, symbolic encoding and so on. In this paper, binary coding method is used.

(3) Adaptation function

Different types of problems have different optimization objectives, that is, there are different forms of objective function, usually directly using the objective function or using its deformation as the fitness function, through the fitness function to get the individual fitness. Using the boundary construction method:

The problem of finding the maximum value of the objective function, such as Eq:

$$F(f(x))=\begin{cases} f(x)+C_{\min}, & f(x)+C_{\min}<0 \\ 0, & f(x)+C_{\min}\geq 0 \end{cases} \tag{36}$$

where $C_{\min}$ is an appropriate relatively small value, which can be a pre-specified number, at which point the value is static. It can also be the smallest objective function value in the current population generation of the evolution, and this value is dynamically changing.

The problem of finding the minimum value of the objective function, as in Eq:

$$F(f(x))=\begin{cases} -f(x)+C_{\max}, & f(x)-C_{\max}<0 \\ 0, & f(x)-C_{\max}\geq 0 \end{cases} \tag{37}$$

where $C_{\max}$ is an appropriate relatively large value, which can be either a pre-specified static number or the largest objective function value in the evolutionary current generation, which also changes dynamically.

(4) Selection operation

In the selection operation process, individuals with high fitness will have a higher probability of being selected for inheritance into the next generation of the population to participate in the subsequent genetic process. Commonly used selection operations include roulette algorithm, sorted selection method, seed selection method and so on. Roulette is a proportional selection algorithm in which a roulette wheel is divided into sectors of different sizes, corresponding to different items. When the roulette wheel spins and stops, the item that the fingers are pointing at is the selected item. The process of using the roulette algorithm is as follows:

Step 1: Calculate the fitness of each individual and sum up the fitness of the group:

$$\sum_{i=1}^{N} F_i \tag{38}$$

where F_i denotes the fitness of the i th individual and N is the total number of individuals.

Step 2: The proportion of the individual's fitness to the overall fitness is calculated as the probability P_i that the individual will be passed on to the next generation:

$$P_i=\frac{F_i}{\sum_{i=1}^{N} F_i} \tag{39}$$

(5) Crossover operation

The crossover operation can generate new individuals, is to prevent the algorithm "early maturity" of the important links. Common crossover operations include single-point crossover, multi-point crossover, order crossover and so on. The specific process of single-point crossover is as follows:

Step 1: Pair the individuals in the population, then there is no greater than $\frac{N}{2}$ the largest integer group of individuals for crossover operation.

Step 2: A randomly selected gene locus, which is the crossover point. If the chromosome length is n , there are a total of $(n-1)$ crossover points to choose from.

Step 3: Using P_c as the crossover probability, the two parts of the chromosomes of the two individuals are exchanged at the crossover point to obtain a new chromosome.

(6) Mutation operation

Mutation operation is also an important part of generating new individuals, when the diversity of the population is reduced, the crossover operation is difficult to improve the diversity of the population again, so the crossover operation can make the algorithm jump out of the local optimal solution. The specific process of genomic mutation is as follows:

Step 1: Select individuals to participate in the mutation operation based on the mutation probability P_m.

Step 2: Determine the mutation point. The gene locus of the mutation can be fixed, or the mutation point can be determined by using a random number. The mutated gene can use inverse operation or other rules to mutate the gene to get a new gene. A new individual is obtained from the gene after completing the mutation operation.

(7) Basic Process

The general steps of the genetic algorithm are as follows:

Step 1: Population initialization, randomly generate P individuals as the initial population.

Step 2: Calculate the fitness value of each individual of the population and perform fitness evaluation.

Step 3: Judge whether the end condition is satisfied, if so, output the optimal solution and end the operation, otherwise continue to execute the next step.

Step 4: Perform the selection operation according to the selection operator to produce the next generation of population, the population size is still P.

Step 5: Perform crossover operation with crossover probability P_c.

Step 6: Perform variation operation with variation probability P_m.

Step 7: Perform the operation of Step 2 again for the newly generated population.

III. C. 2) Improved genetic algorithms

In traditional genetic algorithms, fixed parameters are sometimes used for the crossover probability and variance probability of a solution, resulting in the crossover probability and variance probability remaining constant throughout the iteration process, which makes the algorithm's performance not good enough. In this chapter, a nonlinear way of probability change based on the iteration process is designed. Firstly, the parameter I is defined as shown in Equation (40):

$$I = \frac{gen-1}{Gen-1} \tag{40}$$

where, gen -current iteration number, Gen -total iteration number.

Thus, the parameter I can represent the iteration process, the closer I is to 0, the closer the iteration is to the starting point. The closer I is to 1, the closer the iteration is to the end.

On this basis, the nonlinear crossover probability and variance probability are designed as shown in equations (41), (42):

$$P_{crossover} = P_{crossover}^{\min} + \left(P_{crossover}^{\max} - P_{crossover}^{\min}\right) \times \left(1 - \left(\frac{gen-1}{Gen-1}\right)^4\right) \tag{41}$$

$$P_{mutation} = P_{mutation}^{\min} + \left(P_{mutation}^{\max} - P_{mutation}^{\min}\right) \times \left(1 - \left(\frac{gen-1}{Gen-1}\right)^4\right) \tag{42}$$

Under this design, at the beginning of the iteration, the crossover and mutation probabilities are close to their respective maximum values, in which case the individuals in the population have a higher probability of participating in the crossover and mutation, which means that the algorithm searches for feasible solutions in a wider range. Near the end of the iteration, the crossover probability and mutation probability will rapidly decrease to their respective minimum values, in which case the probability of individuals being affected by crossover and mutation will become smaller, and the optimal solution is more likely to be retained in the algorithm, thus realizing the protection of the better solution.

IV. Algorithm performance testing and case analysis

IV. A. Algorithm Performance Testing

IV. A. 1) Evaluation indicators

Evaluating the search results of a multi-objective optimization algorithm needs to consider the diversity, balance, and coverage of the solution set. Therefore, this paper adopts spatial evaluation method and generation distance as the evaluation index of the algorithm.

(1) Spatial evaluation method (SP)

A kind of spatial evaluation index applicable to two-dimensional objective function is used to evaluate the uniformity of the distribution of the solutions in the Pareto solution set, which is based on the principle of comparing the distribution of the results by comparing the distances between consecutive solutions. A larger value of SP indicates that the solutions are more dispersed, and a smaller value of SP indicates that the solutions are more densely and uniformly distributed. The value of SP is in the range of 0 to 1, and its calculation formula is shown in Eqs.(43) to Eqs.(45):

$$SP = \frac{1}{|S|-1}\sum_{i=1}^{|S|-1}(d_i - \bar{d}) \tag{43}$$

$$d_i = \left\| F(x^i) - F(x^{i+1}) \right\| \tag{44}$$

$$\bar{d} = \frac{d_i}{|S|-1} \tag{45}$$

where d_i - Euclidean distance between two consecutive solutions, $\bar{d}$ - average of all d_i, $|S|$ - size of Pareto boundary.

Since the spatial evaluation method only considers the homogeneity of the solution set but not the extensiveness of the solution set, it is usually necessary to combine other indicators for comprehensive evaluation when using SP as an evaluation index.

(2) Generation distance (GD)

Generation distance (GD) is a kind of index for evaluating the convergence of the optimization algorithm, which is based on the principle of comparing the distance between the Pareto frontier solution searched by the optimization algorithm and the real Pareto frontier solution. The smaller the value of GD is, the closer the searched Pareto solution set is to the real Pareto frontier solution. Its calculation formula is shown in Equation (46) and Equation (47):

$$GD = \frac{1}{|S|}\sqrt{\sum_{i=1}^{|S|} d_i^2} \tag{46}$$

$$d_i = \min \left\| F(x^i) - F(p) \right\| \tag{47}$$

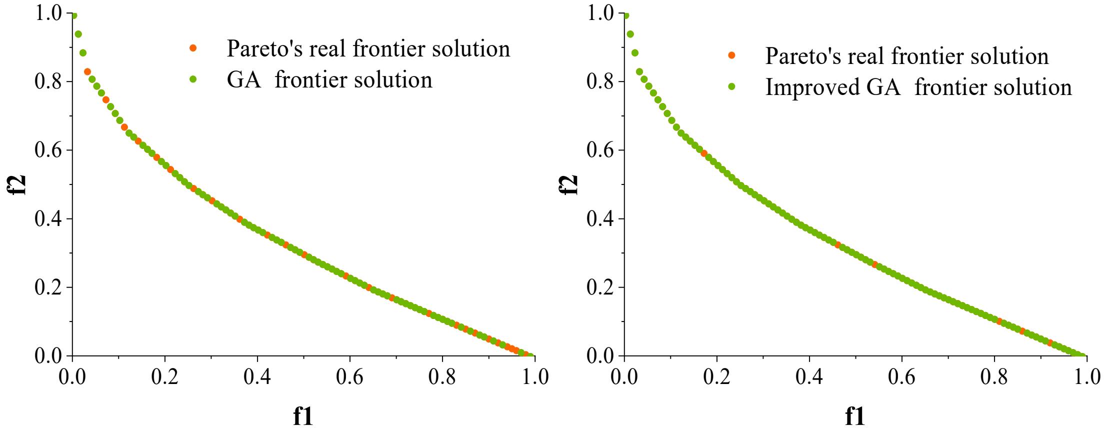
where d_i - the Euclidean distance between x^i and the nearest reference point p on the true Pareto solution set P.

IV. A. 2) Test results

In this paper, ZDT test functions (ZDT1~ZDT3) are used, and the objective functions of this series of test functions are all double objective functions, which have the same dimension as the objective function of the scheduling optimization model of the off-grid wind power hydrogen production system in this paper. Comparing the traditional genetic algorithm with the improved genetic algorithm in this paper, the optimization results of ZDT1~ZDT3 are shown in Fig. 2~Fig. 4, in which the orange point is the Pareto true frontier solution and the green point is the Pareto frontier solution obtained by the algorithm search. The optimization results of the improved genetic algorithm overlap more with the set of true Pareto solutions and their distribution is more uniform. The genetic optimization algorithms before and after the improvement are used for 25 runs for ZDT1, ZDT2, and ZDT3, respectively, and the evaluation indexes of the functions are recorded and the average of the 25 results is calculated. The evaluation results of the test functions are shown in Table 1. The improved genetic algorithm performs better in the evaluation metrics SP and GD, and its SP value is less than 0.0055 and GD value is less than 0.0040 for the three test functions, which is obviously smaller than the traditional genetic algorithm, which means that the improved genetic algorithm has better search ability in the space with higher convergence speed, and it can better cover the Pareto frontiers and maintain the diversity of the Pareto solution set.

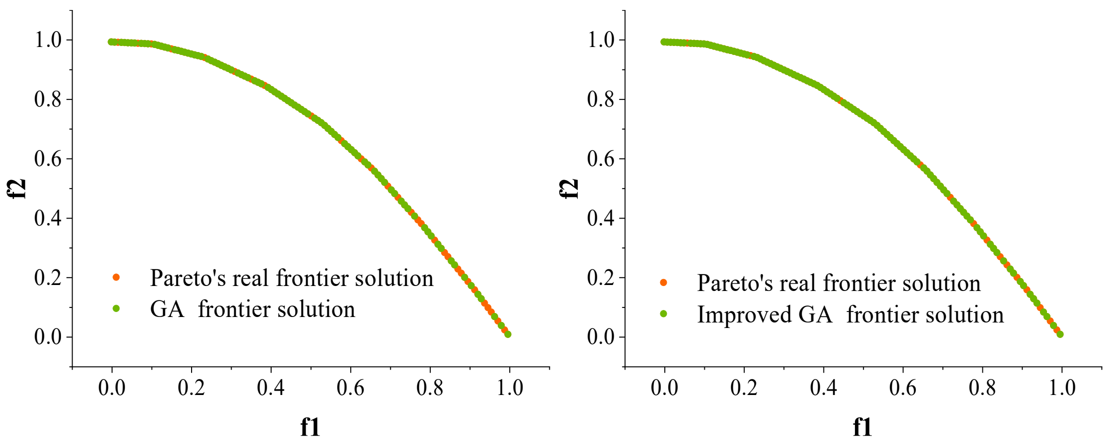
Table 1: Test function assessment result

Evaluation index	GA	Improved GA
ZDT1		
SP	0.0063	0.0042
GD	0.0041	0.0023
ZDT2		
SP	0.0095	0.0053
GD	0.0067	0.0036
ZDT3		
SP	0.0075	0.0045
GD	0.0022	0.0012



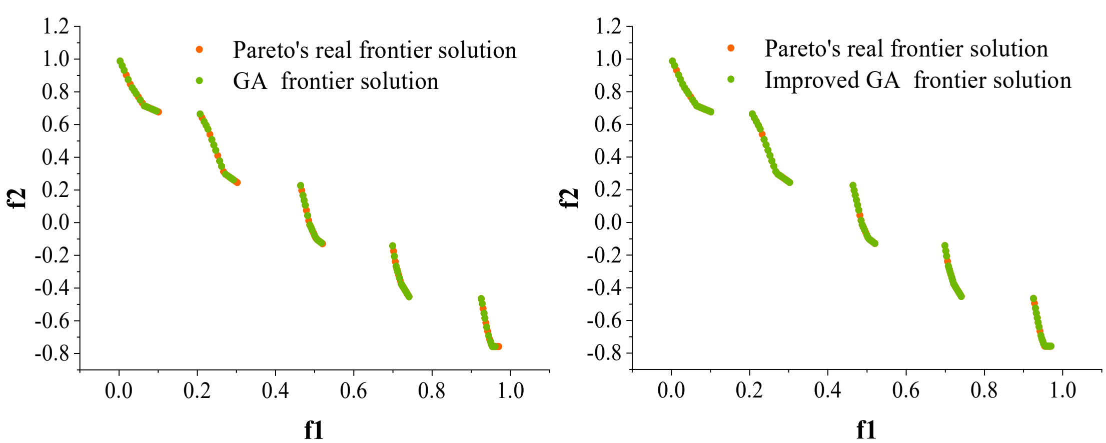
(a)GA (b)Improved GA

Figure 2: ZDT1 optimization results



(a)GA (b)Improved GA

Figure 3: ZDT2 optimization results



(a)GA (b)Improved GA

Figure 4: ZDT3 optimization results

IV. B. Analysis of examples

In this section, the wind speed data of a sea area is used as an example for the arithmetic analysis, the wind speed data is obtained from the NASAMERRA-2 meteorological database, and the arithmetic analysis is realized based on Matlab R2022a.

IV. B. 1) Comparison of simulation results

Using the improved genetic algorithm to simulate and solve the off-grid wind power hydrogen production system, four planning schemes are obtained, and the comparison of the simulation configuration results is shown in Table 2. The configuration results of the collector system of the wind farms in the four scenarios all adopt large-capacity wind turbines with rated capacity greater than 10 MW for network profitability, which is in line with the current development trend of expanding stand-alone capacity of wind power projects, and to some extent illustrates the practicability of the capacity planning model.

Among them, Scenarios 2 and 4 require a higher collector voltage level, with a collector voltage of more than 50MW. It is inferred that because the PEM electrolyzer has a wider operating range, it has a stronger ability to convert electricity to hydrogen, and at the same time, the collector voltage level has a smaller impact on the investment return, and if a higher collector voltage level is adopted, it can reduce the topology loss and increase the power input into the electrolyzer, which can enhance the hydrogen production and improve the profitability of the system. This will increase the hydrogen production and improve the profitability of the system.

Meanwhile, from the results of the capacity configuration of the electrolyzer and the hydrogen storage tank, it can be seen that as the capacity of the electrolyzer rises, the capacity of the hydrogen storage tank also rises, because a higher capacity of the electrolyzer can generate more hydrogen, and therefore requires more sufficient space for hydrogen storage, which explains to some extent the rationality of the capacity planning model.

Table2: Comparison of simulation configuration results

	Monolithic typhoon rated capacity/MW	Collector voltage/kV	Electrolytic cell rated capacity/MV	Hydrogen tank capacity/ ton
Solution 1	12	34	61	103.78
Solution 2	13	55	42.45	98.27
Solution 3	11	48	65.58	110.26
Solution 4	14	59	46.14	100.87

Hydrogen supply and economic comparison of the simulation configuration results are shown in Table 3. The hydrogen supply missing probability LHSP of the four scenarios is lower than 10%, and the levelized hydrogen cost LCOH is 22.84~28.27 yuan, which basically has the market competition conditions, and to a certain extent proves the effectiveness of the scheduling control model of the off-grid wind power hydrogen production system. Among the four scenarios, Scenario 3 has the lowest levelized hydrogen cost and the second lowest probability of missing hydrogen supply, which are 22.84 yuan and 4.53%, respectively, and thus has the best profitability performance and is most suitable for the development of wind power.

Table 3: Comparison of hydrogen supply and economy

	Annual hydrogen flow/ton	LHSP/%	LCOH/yuan	Initial investment cost/100 million yuan
Solution 1	4621.09	7.28	24.99	6.71
Solution 2	5015.45	3.72	28.27	8.01
Solution 3	4716.53	4.53	22.84	6.93
Solution 4	5089.14	5.28	26.91	8.17

IV. B. 2) Sensitivity analysis

Sensitivity analysis is an important part of the system planning process, which is used to reflect the impact of changes in certain model parameters on the target output of the system. The composition of the off-grid wind power hydrogen production system is relatively simple, and it is necessary to explore the impact of the important parameters in the model on the system hydrogen supply and the cost of hydrogen production. The off-grid wind power hydrogen production and storage system is mainly composed of three parts: the wind farm collector system, the hydrogen production platform, and the hydrogen storage and transportation system, and the WTGs, the electrolyzer hydrogen production equipment, and the high-pressure gaseous hydrogen storage tanks are the important components in the system cost structure. Therefore, in this section, the three model parameters of wind turbine cost, electrolyzer cost, and hydrogen storage tank cost are selected to analyze the probability of missing hydrogen supply and the levelized hydrogen cost of the system using Scenario 3 as an example, and the results of the sensitivity analysis are shown in Fig. 5.

The interval variation range of turbine cost, electrolyzer cost, and hydrogen storage cost is [-45%, 45%], and the system's LHSPs in this variation interval are all below 18%, and the LCOH is between 18 to 34 yuan, with strong hydrogen supply performance and investment robustness. The effect of the electrolyzer cost on the LHSP is more significant, which becomes more obvious as the price of the electrolyzer cost decreases, while the fan cost has a more pronounced effect on the LHSP in the [0, 45%] interval, and the hydrogen storage tank cost has a less significant effect on the LHSP. The degree of change in LCOH shows that the effect of fan cost is more pronounced, followed by electrolyzer cost, and hydrogen storage tank cost has the lowest effect.

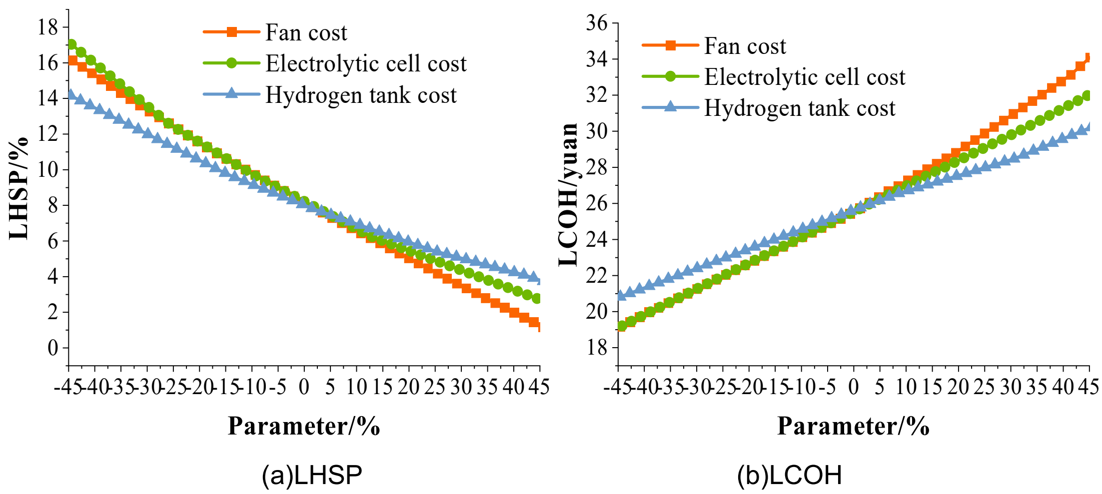


Figure 5: The results of sensitivity analysis

V. Conclusion

The study of scheduling optimization of off-grid wind power hydrogen production system shows that considering the degradation characteristics of battery and electrolyzer has a significant impact on the system configuration and economy. By constructing a complete system model and introducing an improved genetic algorithm, an effective balance between hydrogen supply reliability and economy is realized. The algorithm test results show that the SP and GD values of the improved genetic algorithm on the ZDT1 test function are 0.0042 and 0.0023, which are 33.3% and 43.9% lower than those of the traditional genetic algorithm, respectively, which verifies the superiority of the proposed method in terms of uniformity and convergence of the solution. An example analysis based on wind speed data in a sea area yields four feasible configuration schemes, among which the optimal scheme is able to control the probability of hydrogen supply shortage within 4.53%, reduce the cost of levelized hydrogen to 22.84 yuan/kg, and produce 4716.53 tons of hydrogen per year with an initial investment cost of 693 million yuan. The sensitivity analysis further reveals that the electrolyzer cost has the most significant impact on the reliability of hydrogen supply, while the fan cost is the dominant factor affecting the levelized hydrogen cost. The system consistently maintains strong investment robustness over the parameter variation interval of [-45%,45%]. This study provides technical support for the optimal configuration and efficient scheduling of wind power hydrogen generation system under off-grid conditions, which is of great practical significance to promote the large-scale application and economic development of hydrogen energy.

Author Contributions

Conceptualization, Z.L.; methodology, E.Z.; software, E.Z.; validation, E.Z.; formal analysis, X.X.; investigation, E.Z.; resources, Y.D.; data curation, E.Z.; writing—original draft preparation, E.Z.; writing—review and editing, X.C.; visualization, X.C.; supervision, C.Q.; project administration, Y.D.; funding acquisition, Z.L. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflict of interest.

Disclaimer/Publisher's Note

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