
Article

Coordinated Optimization Operation Strategy for Hybrid Hydrogen Production System Considering Dynamic Characteristics and State Transition of Electrolyzers

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Abstract

Against the backdrop of the global low-carbon energy transition, the volatility of photovoltaic (PV) output has been found to significantly affect the safe and stable operation of hydrogen production systems. To ensure efficient hydrogen production while enhancing system safety, a coordinated optimal operation strategy is proposed for a hybrid hydrogen production system that accounts for the dynamic characteristics and state transitions of electrolyzers. By leveraging the power-efficiency curves and historical operating time of electrolyzers, together with a state tracking and feedback mechanism, the proposed strategy is able to capture state transition processes and the real-time operational status of electrolyzers. Subsequently, by accounting for the operating characteristics of different electrolyzers and dividing reasonable power intervals, the optimal power allocation among hybrid electrolyzers is achieved. A comparative analysis of four different schemes was conducted via simulation experiments, and the results demonstrate that compared with a single electrolyzer hydrogen production system, the hybrid system achieves a better trade-off between efficiency and economic performance while effectively enhancing PV absorption capacity. Furthermore, relative to a traditional operation strategy, the proposed strategy increases hydrogen production capacity, efficiency, and profit by 25.75%, 8.90%, and 36.00%, respectively, while reducing the unit hydrogen production cost by 23.13%.

Keywords: hybrid hydrogen production; electrolyzer; dynamic characteristics; state transition; power allocation

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1. Introduction

With the sustained growth in global energy demand and the increasing severity of climate change impacts, the low-carbon transition of the energy structure has been widely recognized as a global consensus. In this context, hydrogen energy has been identified as a promising clean energy carrier, owing to its high energy density, excellent storage performance, and wide availability, with significant potential to mitigate these challenges and facilitate the optimization of future energy systems [1–3].

Regarding studies on electro-hydrogen coupling, multi-form energy storage involving electricity, heat, and hydrogen was investigated in [4], and an optimal dispatch strategy was proposed for an integrated energy system incorporating electricity, heat, gas, and hydrogen; this strategy was shown to effectively enhance the absorption capacity of wind and photovoltaic (PV) power. In [5], a segmented fuzzy efficiency improvement control strategy with modular optimization of the electrolyzer array was proposed to ensure the safe operation of electrolyzers while enhancing hydrogen production efficiency. Building on this work, a system optimal operation strategy was developed in [6] to account for the characteristics; through regulating the internal power allocation of the electrolyzer array, the utilization rate of the hydrogen production system was improved. In [7], a hydrogen production system control strategy was designed based on a hydrogen production efficiency model of proton exchange membrane electrolyzers (PEMELs), using the particle swarm optimization (PSO) algorithm, resulting in increased hydrogen production output and economic benefits. All these studies employ dispatch strategies centered on a single type of electrolyzer, either alkaline electrolyzers (AELs) or PEMELs. Among these two electrolyzer types, alkaline water electrolysis technology exhibits the highest maturity and lowest cost; however, AELs suffer from low electrolysis efficiency and slow dynamic response, whereas PEMELs offer superior performance at the expense of high investment costs. Other water electrolysis hydrogen production technologies remain confined to the laboratory research and development stage and have yet to enter practical application [8,9]. Adopting a single electrolytic hydrogen production approach therefore limits the overall performance and economic benefits of hydrogen energy storage systems.

The coupled application of AELs and PEMELs enables the complementary utilization of their respective dynamic characteristics, thereby significantly enhancing the system's dynamic regulation performance. This has been recognized as one of the key future development trends in electrolytic hydrogen production within integrated energy systems [10,11]. However, the realization of efficient synergy between these two electrolyzer types, in order to fully exploit the cost advantage of AELs and the rapid response capability of PEMELs, remains a significant research challenge. In [12], an optimal power control technology and capacity configuration method for hybrid hydrogen production systems was developed to ensure system stability. In [13], an optimal control strategy was proposed for photovoltaic-storage coupled hydrogen production systems, considering factors such as the power fluctuation rate of hybrid electrolyzers and the photovoltaic curtailment rate; this strategy was shown to improve system operation performance. In [14], an optimal system dispatch method was proposed that accounts for the dynamic safety constraints of electrolyzers, thereby ensuring their safe operation. In [15,16], a coordinated operation strategy for multi-type electrolyzers was developed, incorporating the dynamic performance and start-stop constraints of different electrolyzers; this strategy significantly enhances renewable energy absorption and system economic performance. While these studies achieve complementary advantages through coordinated control of different electrolyzers, they overlook the fact that power fluctuations subject electrolyzers to long-term fluctuating operation, resulting in frequent start-stop cycles for certain units and thereby impairing the overall system service life. In [17], a hydrogen production scheme was proposed that coordinates electrolyzer operation mode allocation with day-ahead energy storage planning, thereby effectively mitigating electrolyzer power fluctuations. In [18], a model of electrolyzer load operation characteristics was established to balance electrolyzer operation. In [19], an optimal dispatch scheme was proposed for electricity-hydrogen-heat integrated energy systems, considering the coordinated operation of multiple electrolyzers under different operating states; this scheme was shown to mitigate electrolyzer service life degradation. In [20], an electrolyzer model incorporating variable load

response characteristics was established, resulting in a reduced electrolyzer start–stop frequency. Although these studies balance the operational statuses of individual electrolyzers and extend system service life through system-level optimization, the synergistic effects among different electrolyzers are not explicitly considered.

In summary, existing studies have not simultaneously accounted for the differences in dynamic characteristics between AELs and PEMELs and the need to balance electrolyzer operational statuses, thereby limiting the achievement of both high efficiency and safety in system hydrogen production. To address this limitation, this paper makes the following contributions, and a brief comparison with the scheduling strategies proposed in References [15–20] is provided in Table 1.

- (1) A model of the AEL-PEMEL hybrid hydrogen production system is established, including a photovoltaic unit model and hybrid electrolyzer models that characterize power characteristics, hydrogen production, and state transitions, thereby providing a foundation for the subsequent design of the system's optimal control strategy.
- (2) An optimal control strategy is developed by integrating the electrolyzer state tracking and feedback mechanism with an interval-based power allocation method, in accordance with the differences in dynamic characteristics and state transition features of electrolyzers, thereby ensuring safe and stable system operation while achieving high-efficiency hydrogen production.
- (3) The feasibility and economic efficiency of the proposed strategy are verified through simulation analysis of four comparative schemes under different typical-day scenarios.

Table 1. Comparison of hydrogen production system scheduling strategies.

Ref.	Electrolyzer Type	Electrolyzer State Modeling	Optimization Objectives	Measures for Mitigating Lifetime Degradation
[15]	Coordinated operation of AEL and PEMEL	Start-up delay considered, without explicit subdivision of start-up states	Minimization of annual investment and of operation and maintenance costs, as well as wind and photovoltaic curtailment rates	Rotational operation strategy to avoid prolonged shutdown.
[16]	Coordinated operation of AEL and PEMEL	Temperature–power coupling considered, without explicit subdivision of start-up states	Minimization of total system operating cost	Modular control strategy to avoid concentrated degradation.
[17]	Single AEL	Five electrolyzer operating modes are defined (variable-load operation/overload operation/hot standby/cold start-up/shutdown)	Minimization of unit hydrogen production cost and wind and photovoltaic curtailment rates	Energy storage buffering to smooth power fluctuations.
[18]	Single AEL	Five electrolyzer operating statuses are defined (overload/rated/optimal/minimum safe/fluctuating)	Extension of electrolyzer service life	Static array rotation to balance operating states.
[19]	Single AEL	Four electrolyzer operating conditions are defined (rated/fluctuating/standby/shutdown)	Minimization of total system operating cost	Combined operation strategy to reduce the proportion of fluctuating operating conditions.
[20]	Single AEL	Five electrolyzer operating modes are defined (variable-	Minimization of total system operating cost	Limitation of the durations of overload, cold standby, and shutdown to reduce electrolyzer start–stop frequency.

This paper	Coordinated operation of AEL and PEMEL	load operation/overload operation/low-load operation/cold standby/shutdown)		
		Seven electrolyzer operating statuses are defined (low-load/variable-load/overload/hot start-up/cold start-up/standby/shutdown), with modeling based on the differences in dynamic characteristics between AEL and PEMEL	Minimization of unit hydrogen production cost and photovoltaic curtailment rate	(1) Real-time dynamic rotation and balancing of electrolyzer operating states based on a state tracking and feedback mechanism. (2) State-dependent constraints on the durations of overload, cold standby, and shutdown for individual electrolyzers, differentiated according to the dynamic characteristics of AEL and PEMEL.

2. Structural Analysis and Modeling of the AEL-PEMEL Hybrid Hydrogen Production System

2.1. AEL-PEMEL Hybrid Hydrogen Production System Structure

The photovoltaic electrolysis hydrogen production system, in which photovoltaic devices are directly coupled with electrolyzers, enables the direct conversion of solar energy into hydrogen fuel and is regarded as a core technological pathway for renewable energy conversion and storage [21]. To mitigate the adverse effects induced by the volatility of photovoltaic power generation and to ensure the efficiency and economic performance of the hydrogen production system, a coordinated operation mode of AELs and PEMELs is adopted, and the structure of the AEL-PEMEL hybrid hydrogen production system is illustrated in Figure 1. The system is powered by photovoltaic units, in which the AEL group and PEMEL group operate in a coordinated manner as hydrogen production units, while a dedicated hydrogen production power supply provides stable direct current for them.

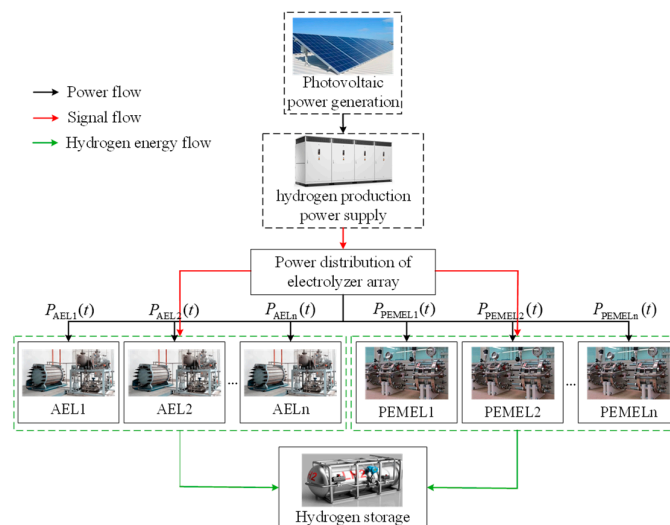


Figure 1. Structure of AEL-PEMEL hybrid hydrogen production system.

2.2. Photovoltaic Unit Model

The core components of photovoltaic units consist of multiple solar cells connected in series or parallel. Considering their power output characteristics, the output power of photovoltaic units can be expressed as:

$$P_{pv} = U_{pv} I_{sc} \left[1 - C_1 \left(e^{\frac{U_{pv}}{C_2 U_{oc}}} - 1 \right) \right] \quad (1)$$

where P_{pv} is the output power of photovoltaic units; U_{pv} is the output voltage of photovoltaic units; I_{sc} is the short-circuit current; U_{oc} is the open-circuit voltage; C_1 and C_2 are the parameters of the photovoltaic unit models.

The photovoltaic unit model parameters C_1 and C_2 can be expressed as:

$$\begin{cases} C_1 = \left(1 - \frac{I_{mp}}{I_{sc}} \right) e^{\frac{-U_{mp}}{C_2 U_{oc}}} \\ C_2 = \left(\frac{U_{mp}}{U_{oc}} - 1 \right) \left[\ln \left(1 - \frac{I_{mp}}{I_{sc}} \right) \right]^{-1} \end{cases} \quad (2)$$

where I_{mp} is the current at the maximum power point; and U_{mp} is the voltage at the maximum power point.

2.3. Hybrid Electrolyzer Model

The hybrid electrolyzer model is composed of an AEL group and a PEMEL group. An AEL is technically mature and cost-effective but exhibits limited adaptability to volatile power sources, whereas a PEMEL features a rapid dynamic response that can effectively accommodate power supply fluctuations, albeit at a higher investment cost. Therefore, priority is given to ensuring the safe and stable operation of AELs. On this basis, power fluctuations are accommodated by PEMELs, thereby enabling the complementary utilization of the two electrolyzer types.

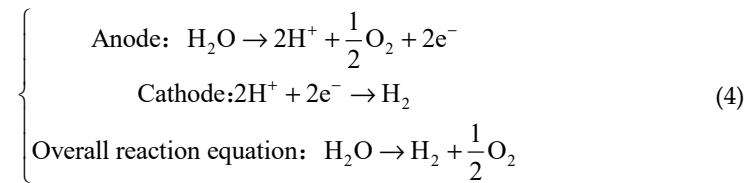
2.3.1. Electrolyzer Power Characteristic Model

The operating power of an AEL P_{AEL} is expressed as [22,23]:

$$P_{AEL} = \left\{ s \ln \left(\frac{I_{AEL} \left(k_1 + \frac{k_2}{T_{AEL}} + \frac{k_3}{T_{AEL}^2} \right)}{A} \right) + 1 + U_0 + \frac{I_{AEL} (r_1 + r_2 T_{AEL})}{A} \right\} I_{AEL} \quad (3)$$

where I_{AEL} is the input current of an AEL; U_0 is the output voltage of an AEL; T_{AEL} is the temperature of an AEL; r_1 , r_2 , k_1 , k_2 , and k_3 are the empirical coefficients of the AEL power model; A is the effective electrolysis area of an AEL; and s is the overvoltage coefficient of an AEL.

A PEMEL is mainly composed of an anode, a cathode, and a polymer proton exchange membrane layer, and its chemical equation is expressed as follows:



The operating power of a PEMEL P_{PEMEL} is expressed as [24]:

$$P_{\text{PEMEL}} = [U_{\text{ocv}} + U_{\text{act}} + U_{\text{ohm}} + U_{\text{diff}}] \cdot I_{\text{PEMEL}} \quad (5)$$

where I_{PEMEL} is the operating current of a PEMEL; U_{ocv} is the open-circuit voltage of a PEMEL; U_{act} is the activation voltage of a PEMEL; U_{ohm} is the ohmic overvoltage generated by the internal resistance of a PEMEL; and U_{diff} is the diffusion voltage of a PEMEL.

The open-circuit voltage of a PEMEL U_{ocv} is expressed as:

$$U_{\text{ocv}} = 1.229 - 0.0009(T_{\text{PEMEL}} - 298) + \frac{RT_{\text{PEMEL}}}{2F} \ln \left(\frac{P_{\text{H}_2} \sqrt{P_{\text{O}_2}}}{P_{\text{H}_2\text{O}}} \right) \quad (6)$$

where R is the universal gas constant, with a value of 8.3144 J/(mol·K); T_{PEMEL} is the temperature of a PEMEL; P_{H_2} , P_{O_2} , and $P_{\text{H}_2\text{O}}$ are the partial pressures of hydrogen, oxygen, and water; and F is the Faraday constant.

The activation voltage of a PEMEL U_{act} is expressed as:

$$U_{\text{act}} = \left(\frac{RT_{\text{PEMEL}}}{\alpha_a F} + \frac{RT_{\text{PEMEL}}}{\alpha_c F} \right) \arcsin \left(\frac{i_{\text{PEMEL}}}{2i_{\text{an0}}} \right) \quad (7)$$

where α_a and α_c are the charge transfer coefficients of the anode and cathode; i_{PEMEL} is the current density of a PEMEL; and i_{an0} is the exchange current density of the anode.

The ohmic overvoltage generated by the internal resistance of a PEMEL U_{ohm} is expressed as:

$$U_{\text{ohm}} = \frac{\delta i_{\text{PEMEL}}}{\sigma} + \frac{\rho l i_{\text{PEMEL}}}{A_{\text{CS}}} \quad (8)$$

where δ is the thickness of the PEMEL membrane electrode assembly; σ is the ionic conductivity of a PEMEL; ρ is the electronic material resistivity of a PEMEL; l is the electronic path length; and A_{CS} is the cross-sectional area of the PEMEL conductor.

The diffusion voltage of a PEMEL U_{diff} is expressed as:

$$U_{\text{diff}} = \frac{RT_a}{4F} \ln \left(\frac{x_{\text{O}_2,\text{m}}}{x_{\text{O}_2,\text{e}}} \right) + \frac{RT_c}{2F} \ln \left(\frac{x_{\text{H}_2,\text{m}}}{x_{\text{H}_2,\text{e}}} \right) \quad (9)$$

where T_a and T_c are the temperatures of the anode and cathode; $x_{\text{O}_2,\text{m}}$ and $x_{\text{O}_2,\text{e}}$ are the mole fractions of oxygen in the gas channel and on the electrode surface; and $x_{\text{H}_2,\text{m}}$ and $x_{\text{H}_2,\text{e}}$ are the mole fractions of hydrogen in the gas channel and on the electrode surface.

2.3.2. Electrolyzer Hydrogen Production Model

The hydrogen production rates n_{H_2} and hydrogen production efficiencies η_{el} of AELs and PEMELs can all be expressed as follows:

$$\begin{cases} n_{H_2} = \frac{\eta_F N_{el} I_{el}}{zF} \\ \eta_{el} = \frac{n_{H_2} \Delta G_{el}}{P_{el}} \end{cases} \quad (10)$$

where N_{el} is the number of electrolyzers; η_F is the Faraday efficiency of the electrolyzer; ΔG_{el} is the Gibbs free energy change; z is the number of electrons transferred during the reaction; I_{el} is the total electrolysis current of the electrolyzer; and P_{el} is the total hydrogen production power of the electrolyzer.

As can be seen from the power-efficiency curves of AELs and PEMELs shown in Figure 2, when the input power of an AEL is low, its hydrogen production efficiency increases markedly as the input power rises; it reaches the maximum efficiency of approximately 75% at a per-unit input power of about 0.25, after which it gradually declines. For PEMELs, the maximum hydrogen production efficiency of approximately 80% is achieved at a per-unit input power of about 0.1, after which the efficiency gradually decreases [25,26]. Based on these observations, to improve the overall operating efficiency of the system, it is necessary to allocate the input power of each electrolyzer in a rational manner according to the actual operating conditions.

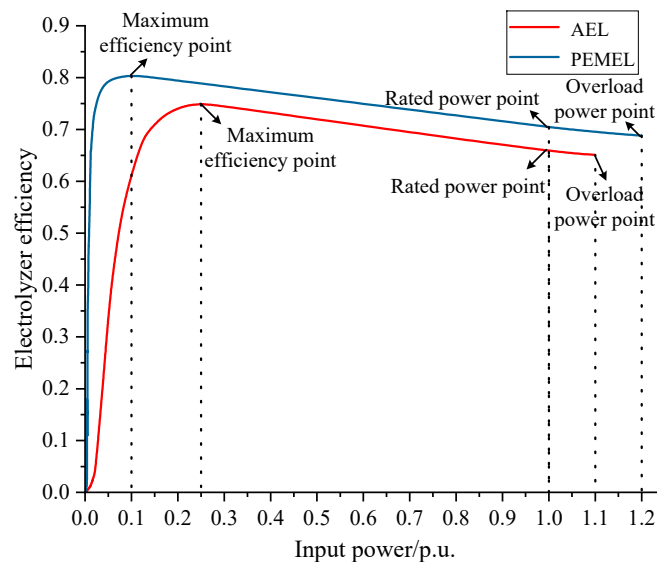


Figure 2. The power-efficiency curves of AEL and PEMEL.

2.3.3. The State Transition Model of the Electrolyzer

According to the operating characteristics of electrolyzers, their operational statuses can be classified into shutdown, cold start, standby, hot start, and operating states, with the operating state further subdivided into overload, variable-load, and low-load states. To better identify the real-time operational statuses of electrolyzers, variables S and R are used to distinguish them. T_s denotes the cold start response time, T_R denotes the hot start response time, and $T_{reserve}$ denotes the maximum duration of the standby state. The state transition process of the electrolyzer is illustrated in Figure 3, with the corresponding definitions provided below.

- (1) Shutdown state ($S = -1$, $R = T_R$): the electrolyzer shuts down.
- (2) Cold start state ($0 \leq S < T_s$, $R = T_R$): to activate an electrolyzer in the shutdown state, it is necessary to re-enter the operating state through the cold start state; at this time,

- R remains unchanged, and S changes from -1 to 0 . The cold start response time is relatively long. If the cold start response time of the electrolyzer T_S has not yet been met at the next moment, then $S(t+1) = S(t) + 1$ until $S(t) = T_S - 1$. Therefore, when the electrolyzer is in the cold start state, the value of variable S is $0 \leq S < T_S$.
- (3) Standby state ($S = T_S$, $0 \leq R < T_R$): the electrolyzer stops operating. When the standby state reaches its maximum duration $R(t) = T_{\text{reserve}}$, the electrolyzer exits the standby state and enters the shutdown state.
- (4) Hot start state ($S = T_S$, $0 \leq R < T_R$): to activate an electrolyzer in the standby state, it is necessary to re-enter the operating state through the hot start state; at this time, S remains unchanged, and R changes from -1 to 0 . If the hot start response time of the electrolyzer T_R has not yet been met at the next moment, then $R(t+1) = R(t) + 1$ until $R(t) = T_R - 1$. Therefore, when the electrolyzer is in the hot start state, the value of variable R is $0 \leq R < T_R$.
- (5) Operating state ($S = T_S$, $R = T_R$): the operating power range of the electrolyzer is $P_{\text{el_min}} \leq P_{\text{el}} \leq P_{\text{el_max}}$. When $P_{\text{el}} = P_{\text{el_min}}$, the electrolyzer is in the low load state; when $P_{\text{el_min}} < P_{\text{el}} < P_{\text{el_max}}$, the electrolyzer is in the variable load state; when $P_{\text{el}} = P_{\text{el_max}}$, the electrolyzer is in the overload state. To ensure the safe operation of the system, overload operation of the electrolyzer should be avoided as much as possible so as to extend the overall service life of the system.

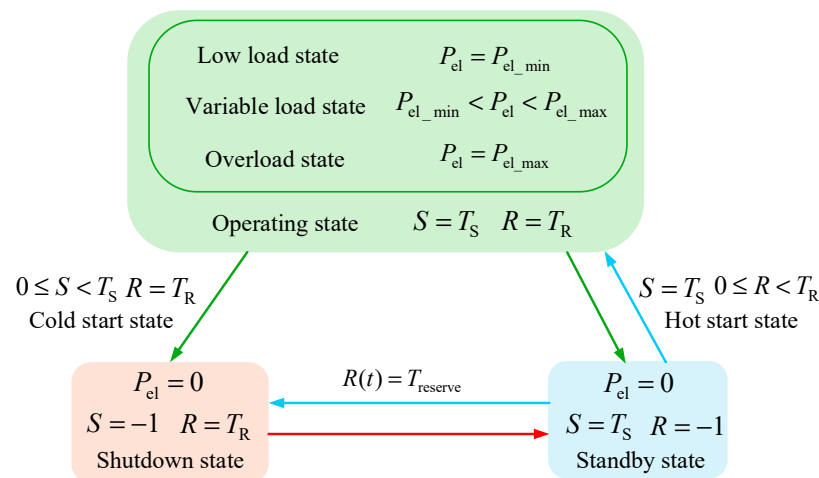


Figure 3. The state transition diagram of the electrolyzer.

3. Cooperative Optimal Operational Strategy for the Hybrid Hydrogen Production System

To fully exploit the cost advantage of an AEL and the rapid response capability of a PEMEL, while accounting for differences in their dynamic characteristics, a hybrid hydrogen production mode combining AELs and PEMELs is adopted, which enhances hydrogen production efficiency, mitigates photovoltaic power volatility, and ensures system safety and economic performance simultaneously. The main parameters of AELs and PEMELs are compared in Table 2.

Table 2. The main parameters of AELs and PEMELs.

Parameter	AEL	PEMEL
Power modulation range/%	20–110	5–120
Hot start response time/s	200	10
Cold start response time/s	3600	300
Maximum ramp rate/(%/s)	8	25
Maximum duration of over-load operation/h	1	2
Acquisition cost/(CNY/kW)	3000	8000
Operation and maintenance cost/(CNY/kW)	160	480

To accommodate photovoltaic power output while minimizing frequent start-up and shutdown of electrolyzers and prolonged fluctuating operation, the operating time allocated to each electrolyzer in different states should be reasonably distributed. This section introduces an electrolyzer state tracking and feedback mechanism and proposes an optimal control strategy for hybrid electrolyzers in which the historical operating duration of each state is considered to achieve balanced state operation. Meanwhile, the dynamic characteristics of different electrolyzers are taken into account, and power intervals are partitioned to reduce overall operational risk.

3.1. Electrolyzer State Tracking and Feedback Mechanism

As indicated in Section 2.3.3, the operational statuses of the electrolyzer include operating, hot start, cold start, standby, and shutdown states. By accurately recording the real-time operational status of each electrolyzer and uniformly storing key information, including the current state, historical states, and historical state durations, the status information is fed back in real time to the power allocation strategy. Specifically, within a single transition cycle, priority is given to allocating the operating state, standby state, and shutdown state to the electrolyzers with the shortest duration in that state. Meanwhile, electrolyzers that have already undergone state transitions in the previous cycle are prevented from repeated transitions. This approach avoids overuse, prolonged idleness, and excessive state switching of individual electrolyzers, thereby ensuring safe and stable system operation and extending the overall service life. Additionally, the electrolyzer status information is updated at each time step upon completion of state transition and power allocation.

If an electrolyzer is in the operating state, hot start (completed) state, or cold start (completed) state at the current moment (t), the following rules apply based on the power allocation results after status information feedback: if the input power $P_{el} > 0$, the electrolyzer shall be in the operating state; if the input power $P_{el} = 0$, the electrolyzer shall be in the standby state. This is illustrated in Cases 1–6 of Table 3.

If an electrolyzer is in the hot start (incomplete) state or cold start (incomplete) state at the current moment (t), i.e., the response time for hot start T_R or cold start T_S has not yet been reached, the hot start state or cold start state shall be kept unchanged. This is shown in Cases 7 and 8 of Table 3.

If an electrolyzer is in the standby state at the current moment (t), since hot start requires a certain response time T_R , it is necessary to determine whether the electrolyzer will be in the hot start state, standby state, or shutdown state at the next moment ($t+1$) based on the photovoltaic power $P_{PV}(t+T_R)$ at time $(t+T_R)$, as well as by comprehensively considering the historical operating durations of each state of the electrolyzer and

whether the maximum duration of the standby state has T_{reserve} been reached. This is illustrated in Cases 9–11 of Table 3.

If an electrolyzer is in the shutdown state at the current moment (t), since cold start requires a certain response time T_s , it is necessary to determine whether the electrolyzer will be in the cold start state or shutdown state at the next moment ($t+1$) based on the photovoltaic power $P_{\text{PV}}(t+T_s)$ at time $(t+T_s)$, as well as by comprehensively considering the historical operating durations of each state of the electrolyzer. This is illustrated in Cases 12–13 of Table 3.

Based on the principle of “priority activation of the electrolyzer with the shortest historical state duration and priority shutdown of the electrolyzer with the longest historical state duration”, the system is operated according to the following rules: when the photovoltaic output increases at time $t+\Delta t$, the system shall, based on the statistics of historical operating state durations, give priority to activating the electrolyzer with the shortest historical operating state duration, switching it from the shutdown state to the cold start state or from the standby state to the hot start state; when the photovoltaic output decreases at time $t+\Delta t$, the system shall, based on the aforementioned statistics, give priority to switching the electrolyzer with the longest historical operating state duration from the operating state to the standby state. Furthermore, given that electrolyzers are only allowed to operate in overload conditions for short durations, the input power of each electrolyzer is dynamically allocated to ensure balanced overload operating durations, thereby preventing prolonged overload operation of individual units and mitigating system service life degradation.

In summary, the state transitions of individual electrolyzers are accomplished through the electrolyzer state tracking and feedback mechanism. This mechanism enables the operational statuses of electrolyzers to be adjusted according to input power and historical operating conditions, thereby enhancing overall system performance while maintaining high hydrogen production efficiency.

Table 3. Summary of electrolyzer state transitions.

Operational Status at Time (t)	Operational Status at Time ($t+1$)	Case
Operating state: $S(t) = T_s$, $R(t) = T_R$	$P_{\text{el}}(t+1) > 0$: operating state, $S(t+1) = T_s$, $R(t+1) = T_R$	1
	$P_{\text{el}}(t+1) = 0$: standby state, $S(t+1) = T_s$, $R(t+1) = -1$	2
Hot start (completed) state: $S(t) = T_s$, $R(t) = T_R - 1$	$P_{\text{el}}(t+1) > 0$: operating state, $S(t+1) = T_s$, $R(t+1) = T_R$	3
	$P_{\text{el}}(t+1) = 0$: standby state, $S(t+1) = T_s$, $R(t+1) = -1$	4
Cold start (completed) state: $S(t) = T_s - 1$, $R(t) = T_R$	$P_{\text{el}}(t+1) > 0$: operating state, $S(t+1) = T_s$, $R(t+1) = T_R$	5
	$P_{\text{el}}(t+1) = 0$: standby state, $S(t+1) = T_s$, $R(t+1) = -1$	6
Hot start (incomplete) state: $S(t) = T_s$, $0 \leq R(t) < T_R - 1$	Hot start state: $S(t+1) = T_s$, $R(t+1) = R(t) + 1$	7

Cold start (incomplete) state: $0 \leq S(t) < T_S - 1, R(t) = T_R$	Cold start state: $S(t+1) = S(t) + 1,$ $R(t+1) = T_R$	8
	Hot start state: $S(t+1) = T_S,$ $R(t+1) = R(t) + 1$	9
Standby state: $S(t) = T_S,$ $R(t) = -1$	Standby state: $S(t+1) = T_S,$ $R(t+1) = -1$	10
	Shutdown state: $S(t+1) = -1,$ $R(t+1) = T_R$	11
	Cold start state: $S(t+1) = S(t) + 1,$ $R(t+1) = T_R$	12
Shutdown state: $S(t) = -1,$ $R(t) = T_R$	Shutdown state: $S(t+1) = -1,$ $R(t+1) = T_R$	13

3.2. Hybrid Electrolyzer Power Allocation Method

The traditional electrolyzer power allocation method allocates input power sequentially, enabling electrolyzers to operate at the rated power in a prioritized order. This method does not account for the dynamic characteristics of electrolyzers, resulting in suboptimal hydrogen production efficiency. Furthermore, under insufficient photovoltaic power conditions, this approach tends to cause continuous operation of some electrolyzers while others remain idle, leading to significant disparities in service life degradation and posing a risk to safe and stable system operation.

Therefore, a power allocation method considering the dynamic characteristics of hybrid electrolyzers is proposed. Based on the power-efficiency relationships of AELs and PEMELs illustrated in Figure 2, efficient system operation is achieved through power interval division and dynamic adjustment of electrolyzer power allocation. Let P_{total} be the total input power, P_{H_2} be the total hydrogen production power of the electrolyzers, $P_{\text{ael_e}}$ be the rated power of an AEL, $P_{\text{ael_min}}$ be the underload power of an AEL ($P_{\text{ael_min}} = 0.2P_{\text{ael_e}}$), $P_{\text{ael_max}}$ be the overload power of an AEL ($P_{\text{ael_max}} = 1.1P_{\text{ael_e}}$), $P_{\text{ael_h}}$ be the power for operation at maximum efficiency of an AEL, $P_{\text{ael_in}}$ be the average input power of an AEL, $P_{\text{ael_H}_2}$ be the hydrogen production power of an AEL, $P_{\text{pemel_e}}$ be the rated power of a PEMEL, $P_{\text{pemel_min}}$ be the underload power of a PEMEL ($P_{\text{pemel_min}} = 0.05P_{\text{pemel_e}}$), $P_{\text{pemel_max}}$ be the overload power of a PEMEL ($P_{\text{pemel_max}} = 1.2P_{\text{pemel_e}}$), $P_{\text{pemel_h}}$ be the power for operation at maximum efficiency of a PEMEL, $P_{\text{pemel_in}}$ be the average input power of PEMEL, and $P_{\text{pemel_H}_2}$ be the hydrogen production power of a PEMEL. The interval-based power allocation scheme for the electrolyzers is illustrated in Figure 4, and the specific division method is described as follows:

- (1) When $P_{\text{ael_in}} < P_{\text{ael_min}}$ or $P_{\text{pemel_in}} < P_{\text{pemel_min}}$, all electrolyzers are in non-operating states.
- (2) When $P_{\text{ael_in}} = P_{\text{ael_min}}$ or $P_{\text{pemel_in}} = P_{\text{pemel_min}}$, all electrolyzers are in underload operating states.
- (3) When $P_{\text{ael_min}} < P_{\text{ael_in}} < P_{\text{ael_h}}$ or $P_{\text{pemel_min}} < P_{\text{pemel_in}} < P_{\text{pemel_h}}$, the electrolyzers operate at the power for operation at maximum efficiency with priority. Taking an AEL

- as an example, the first a electrolyzers operate at P_{ael_h} ($a \in [1, n]$, where n is the total number of AELs), and the remaining electrolyzers are in non-operating states.
- (4) When $P_{ael_in} = P_{ael_h}$ or $P_{pemel_in} = P_{pemel_h}$, all electrolyzers operate at the power for operation at maximum efficiency.
 - (5) When $P_{ael_h} < P_{ael_in} < P_{ael_e}$ or $P_{pemel_h} < P_{pemel_in} < P_{pemel_e}$, a portion of the electrolyzers are allocated to operate at the rated power, and the remaining electrolyzers operate at the power for operation at maximum efficiency. Taking an AEL as an example, the first a electrolyzers operate at P_{ael_e} ($a \in [1, n]$), and the remaining b electrolyzers operate at P_{ael_h} ($b \in [n - a, n]$).
 - (6) When $P_{ael_in} = P_{ael_e}$ or $P_{pemel_in} = P_{pemel_max}$, all electrolyzers operate at the rated power.
 - (7) When $P_{ael_e} < P_{ael_in} < P_{ael_max}$ or $P_{pemel_e} < P_{pemel_in} < P_{pemel_max}$, a portion of the electrolyzers are allocated to operate at the overload power, and the remaining electrolyzers operate at the rated power. Taking an AEL as an example, the first a electrolyzers operate at P_{ael_max} ($a \in [1, n]$), and the remaining b electrolyzers operate at P_{ael_e} ($b \in [n - a, n]$).
 - (8) When $P_{ael_in} = P_{ael_max}$ or $P_{pemel_in} = P_{pemel_max}$, all electrolyzers are in overload operating states.

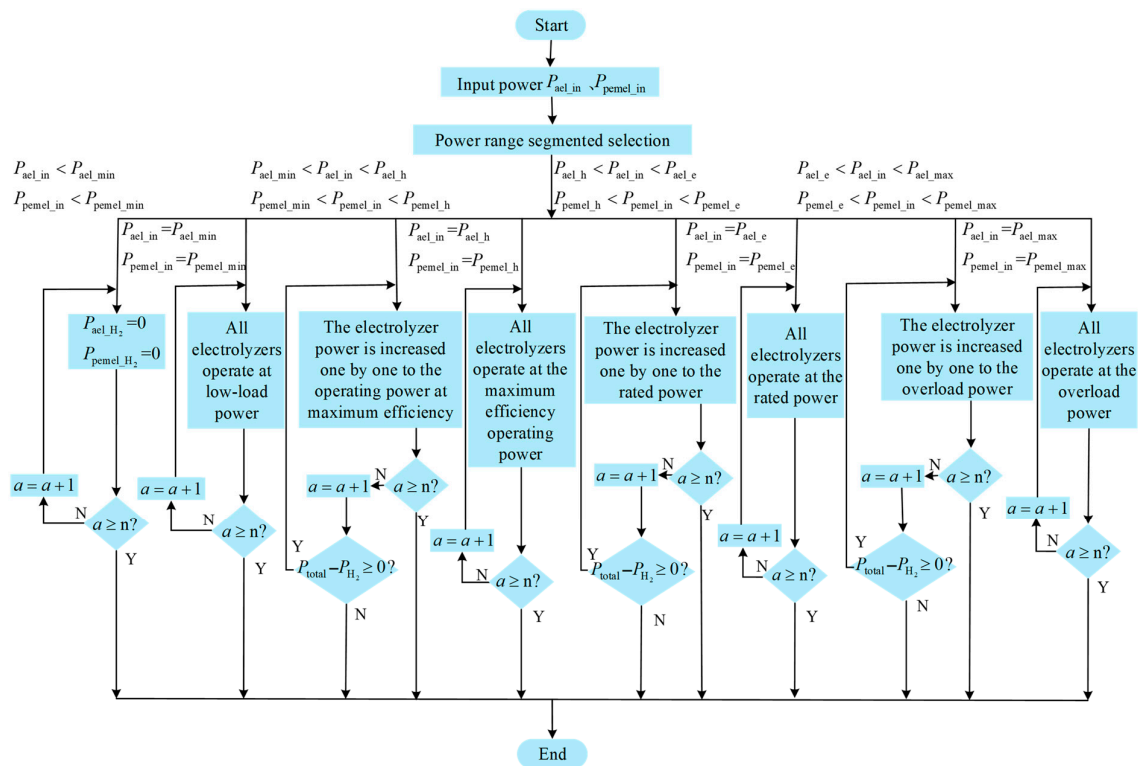


Figure 4. Schematic diagram of interval power allocation for electrolyzers.

3.3. Optimal Power Allocation Model for Hybrid Hydrogen Production System

3.3.1. Objective Function

The photovoltaic curtailment rate of the hybrid hydrogen production system β and its unit hydrogen production cost C are taken as the evaluation objectives.

$$\left\{ \begin{array}{l} \beta = \frac{\sum_{t=1}^T (P_{pv_t} - P_{el_t})}{\sum_{t=1}^T P_{pv_t}} \\ C = \frac{C_{buy} + \sum_{x=1}^H C_{r_x}}{\sum_{x=1}^H V_{el_x}} \end{array} \right. \quad (11)$$

where P_{pv_t} is the output power of the photovoltaic unit at time t ; P_{el_t} is the system hydrogen production power at time t ; T is the total operation duration of the system; C_{buy} is the equipment purchase cost; C_{r_x} is the equipment operation and maintenance cost in the x -th year; V_{el_x} is the total hydrogen production volume in the x -th year; and H is the full life cycle of the equipment.

3.3.2. Constraints

(1) Power balance constraint:

$$P_{ael_t} + P_{pemel_t} + P_{curt_t} = P_{pv_t} \quad (12)$$

where P_{ael_t} is the output power of the AEL at time t ; P_{pemel_t} is the output power of the PEMEL at time t ; and P_{curt_t} is the photovoltaic curtailment power of the system at time t .

(2) Photovoltaic unit output power constraint:

$$0 \leq P_{pv_t} \leq P_{pv_max} \quad (13)$$

where P_{pv_max} is the upper limit of the output power of the photovoltaic unit.

(3) AEL fluctuating power constraint:

$$P_{ael_min} \leq P_{ael_t} \leq 1.1P_{ael_e} \quad (14)$$

$$P_{ael_t} - P_{ael_t-1} \leq r_{ael}\Delta t \quad (15)$$

where r_{ael} is the maximum ramping rate of the AEL.

(4) PEMEL fluctuating power constraint:

$$P_{pemel_min} \leq P_{pemel_t} \leq 1.2P_{pemel_e} \quad (16)$$

$$P_{pemel_t} - P_{pemel_t-1} \leq r_{pemel}\Delta t \quad (17)$$

where r_{pemel} is the maximum ramping rate of the PEMEL.

(5) AEL and PEMEL overload operation time constraint:

$$\left\{ \begin{array}{l} 0 \leq T_{ael_max,i} \leq T_{ael_max} \\ 0 \leq T_{pemel_max,k} \leq T_{pemel_max} \end{array} \right. \quad (18)$$

where $T_{ael_max,i}$ is the overload operation time of the i -th AEL; $T_{pemel_max,k}$ is the overload operation time of the k -th PEMEL; T_{ael_max} is the maximum continuous overload

operation time of the AEL; and $T_{\text{pemel_max}}$ is the maximum continuous overload operation time of the PEMEL.

3.3.3. Model Solution Strategy

In the hybrid hydrogen production system integrating AELs and PEMELs, significant differences exist between the two technologies in terms of equipment cost and hydrogen production performance. To fully exploit their respective advantages, this paper aims to improve system economic efficiency, ensure effective utilization of electrical energy, and enhance photovoltaic power absorption capacity. Therefore, the photovoltaic curtailment rate β and unit hydrogen production cost C are adopted as objective functions, and the total power is rationally allocated between the AEL and PEMEL units. Common algorithms for multi-objective optimization problems include the genetic algorithm (GA), differential evolution (DE), the non-dominated sorting genetic algorithm II (NSGA-II), and multi-objective particle swarm optimization (MOPSO). In this study, the MOPSO algorithm is employed because based on the swarm collaborative evolution mechanism of PSO, it exhibits fast convergence, a limited number of parameters, and no requirement for individual encoding. Moreover, it effectively overcomes the limitations of other algorithms, such as the premature convergence of GA, the parameter sensitivity of DE, and the complex implementation of NSGA-II, thereby demonstrating superior applicability. The particle population size is set to 100, and the maximum number of iterations is set to 150. The update formulas for the velocity and position of the i -th particle at the $(k+1)$ -th iteration are as follows:

$$\begin{cases} v_i^{k+1} = \omega v_i^k + c_1 r_1 (p_{\text{pbest}}^k - p_i^k) + c_2 r_2 (p_{\text{gbest}}^k - p_i^k) \\ p_i^{k+1} = p_i^k + v_i^{k+1} \end{cases} \quad (19)$$

where ω is the inertia weight, which is dynamically adjusted within the interval [0.4, 0.9]; v_i^k is the velocity of particle i at the k -th iteration; p_i^k is the position of particle i at the k -th iteration; c_1 and c_2 are the individual and global learning factors, respectively; r_1 and r_2 are random numbers uniformly distributed within the interval [0, 1]; p_{pbest}^k is the individual best position at the k -th iteration; and p_{gbest}^k is the global best position at the k -th iteration.

For multi-objective optimization problems, the solutions obtained through algorithmic computation are typically expressed as a set of non-dominated Pareto-optimal solutions. To mitigate the influence of subjective factors on scheduling rationality, the entropy weight method is employed to determine the weights of each objective for the Pareto frontier solutions. A smaller entropy value of an objective function indicates a higher degree of data dispersion and, consequently, a larger corresponding weight. Based on the obtained weights, the comprehensive score of each Pareto frontier solution is calculated, providing a quantitative basis for the optimal selection of scheduling schemes. The specific procedures of the entropy weight method are summarized as follows:

To prevent the presence of zero-valued elements during the normalization process, a displacement term δ is introduced to all data, and its calculation is provided as follows:

$$y_{ij} = \frac{\max x_j - x_{ij}}{\max x_j - \min x_j} + \delta \quad i = 1, \dots, n, j = 1, \dots, m \quad (20)$$

$$\delta = 0.01(\max x_j - \min x_j) \quad (21)$$

where y_{ij} is the normalized value; x_{ij} is the value of the j -th objective function for solution i ; and $\max x_j$ and $\min x_j$ are the maximum and minimum values of the j -th objective function among all solutions, respectively.

The proportion of the j -th objective function for solution i is expressed as:

$$p_{ij} = \frac{y_{ij}}{\sum_{j=1}^m y_{ij}} \quad (22)$$

The entropy value of the j -th objective function e_j is expressed as:

$$e_j = -k \sum_{j=1}^m p_{ij} \ln p_{ij}, \quad e_j \geq 0 \quad (23)$$

$$k = \frac{1}{\ln m}, \quad k > 0 \quad (24)$$

The weight of each objective w_j is expressed as:

$$w_j = \frac{1 - e_j}{\sum_{j=1}^n (1 - e_j)} \quad (25)$$

The comprehensive score of each solution s_i is expressed as:

$$s_i = \sum_{j=1}^n (w_j x_{ij}) \quad (26)$$

The solution procedure of the MOPSO optimization algorithm is illustrated in Figure 5.

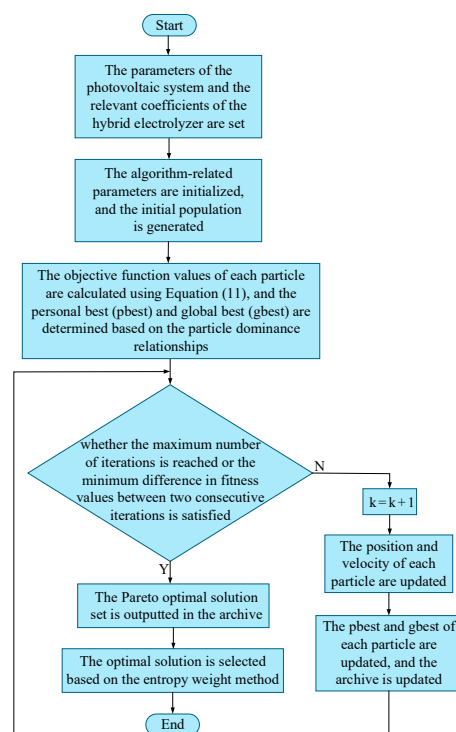


Figure 5. MOPSO optimization algorithm solution process.

4. Results of the Experiment

4.1. Experimental Parameters Description

To validate the effectiveness of the proposed method, MATLAB R2018b is used with the YALMIP toolbox to call the CPLEX commercial solver, and the system is configured with an Intel i7-14650HX CPU and 16 GB of RAM. The photovoltaic unit is configured with a capacity of 1 MW, and the hybrid electrolyzer has a capacity of 450 kW, with a 2:1 capacity ratio between AELs and PEMELs. For the control group, both single AELs and single PEMELs are configured with a capacity of 450 kW. Considering the different response times of AELs and PEMELs, with PEMELs exhibiting rapid response characteristics and a hot start-up time of only 10 s, this paper selects a dispatching cycle of 10 h and a sampling time interval of 10 s. The initial state of all electrolyzers is set to standby, and the hydrogen selling price is set at 35 CNY/kg [27].

The photovoltaic unit model established in Section 2.2 (Equations (1) and (2)) describes the photovoltaic cell's photoelectric conversion characteristics at a mechanistic level, ensuring that the selected typical daily curves align with the physical characteristics of photovoltaic output. The photovoltaic unit output power curves for three typical days, each spanning the time period from 8:00 to 18:00 in a certain region, are randomly selected, as shown in Figure 6.

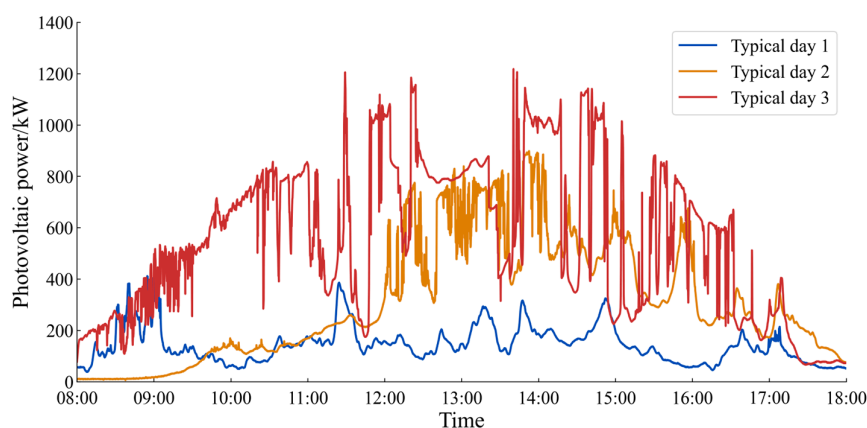


Figure 6. Typical-day photovoltaic output power curve.

This paper presents four different electrolyzer control schemes for comparative experiments and analyzes the optimization effect of the proposed scheme from multiple perspectives.

Scheme 1: configured with AELs exclusively for hydrogen production, introducing the electrolyzer state tracking and feedback mechanism, and incorporating the interval power allocation method.

Scheme 2: configured with PEMELs exclusively for hydrogen production, introducing the electrolyzer state tracking and feedback mechanism, and incorporating the interval power allocation method.

Scheme 3: configured with both AELs and PEMELs for hybrid hydrogen production, adopting the traditional electrolyzer power allocation method, without the use of the electrolyzer state tracking and feedback mechanism or the interval power allocation method.

Scheme 4: configured with both AELs and PEMELs for hybrid hydrogen production, adopting the optimized operation strategy proposed in this paper, introducing the electrolyzer state tracking and feedback mechanism, and incorporating the interval power allocation method and the MOPSO optimization algorithm.

4.2. Analysis of Results of Comparing Different Schemes

The results for hydrogen production volume, efficiency, and photovoltaic curtailment rate during the dispatching cycles of three typical days under different schemes are shown in Table 4. From the analysis of the comparison results, Scheme 4 achieves a maximum increase of 57.88% in hydrogen production volume compared to Scheme 1 and 25.75% compared to Scheme 3; for hydrogen production efficiency, Scheme 4 achieves a maximum increase of 24.87% compared to Scheme 1 and 8.90% compared to Scheme 3; for photovoltaic curtailment rate, Scheme 4 achieves a maximum decrease of 10.99% compared to Scheme 1, 2.96% compared to Scheme 2, and 9.01% compared to Scheme 3.

In summary, the operation strategy proposed in this paper results in slightly lower hydrogen production efficiency and volume compared to the single-PEMEL scheme, but significantly higher values compared to the single-AEL scheme. This is because compared to an AEL, a PEMEL not only exhibits higher hydrogen production efficiency but also has superior capabilities in handling fluctuating power. Both the proposed operation strategy and the traditional strategy employ a coordinated operation mode of AELs and PEMELs. However, the traditional strategy prioritizes AEL activation, which is limited by AELs' slow dynamic response and long cold/hot start-up times. Specifically, electrolyzers remain idle during the start-up phase, and all are required to operate at rated power, failing to dynamically match photovoltaic output fluctuations. This results in low energy utilization efficiency and significant photovoltaic curtailment. In contrast, the proposed strategy operates as follows: under stable and high-peak photovoltaic output conditions, an AEL is prioritized to take advantage of its low cost and high steady-state efficiency. Simultaneously, state tracking is employed to maintain its high-efficiency range, preventing energy loss due to AELs' long cold start-up time in the traditional strategy. During output ramp-up, ramp-down phases, and periods of frequent fluctuations, PEMELs' fast response capability mitigates output fluctuations, preventing photovoltaic curtailment caused by fixed rated power operation in the traditional strategy. When overall photovoltaic output is low, a PEMEL is prioritized for low-load operation, avoiding AEL idleness due to its high start-up threshold and improving energy utilization efficiency. Therefore, the optimized strategy proposed in this paper demonstrates significant superiority over the traditional strategy in hydrogen production performance.

Table 4. Hydrogen production comparison of each typical day under different schemes.

Parameter	Typical Day 1				Typical Day 2				Typical Day 3			
	Scheme 1	Scheme 2	Scheme 3	Scheme 4	Scheme 1	Scheme 2	Scheme 3	Scheme 4	Scheme 1	Scheme 2	Scheme 3	Scheme 4
Hydrogen production volume/kg-year ⁻¹	3668.32	5312.04	4362.12	5142.43	2822.61	4524.78	3543.65	4456.42	4129.01	5765.37	4712.04	5456.85
Hydrogen production efficiency/%	37.43	63.98	54.24	62.30	32.14	55.23	42.30	51.20	35.66	61.07	47.14	55.48
Photovoltaic curtailment rate/%	9.98	1.56	8.27	0.03	11.26	3.23	9.28	0.27	10.79	2.55	8.56	0.18

To further assess the economic impact of the proposed operation strategy on the hybrid hydrogen production system of AELs and PEMELs, the results for unit hydrogen production cost and hydrogen production revenue during the dispatching cycles of three typical days under different schemes are shown in Table 5. From the comparison results,

Scheme 4 achieves a maximum reduction of 46.58% in unit hydrogen production cost compared to Scheme 2 and 23.13% compared to Scheme 3; in terms of hydrogen production revenue, Scheme 4 achieves a maximum increase of 51.31% compared to Scheme 1, 36.18% compared to Scheme 2, and 36.00% compared to Scheme 3.

In summary, due to the significant differences between AELs and PEMELs—where an AEL has a lower cost but inferior hydrogen production capability, and a PEMEL exhibits fast response characteristics but a higher cost—the single-AEL scheme has the lowest unit hydrogen production cost, while the single-PEMEL scheme has the highest. In contrast, the scheme which combines AELs and PEMELs capitalizes on the complementary advantages of both electrolyzer technologies, thereby ensuring both high efficiency and economic performance in hydrogen production. As shown in Table 5, compared to the traditional operation strategy, the strategy proposed in this paper significantly improves the system's hydrogen production revenue. This is because the proposed strategy fully accounts for the dynamic characteristics and state transitions of electrolyzers. Under stable and high-peak photovoltaic output conditions, it maximizes the economies of scale for AELs and minimizes excessive start–stop losses for PEMELs. When photovoltaic output is low, it avoids the cost waste caused by AEL idleness, prevents the overuse or idleness of certain electrolyzers, and ensures optimal utilization of photovoltaic output.

Table 5. Economic comparison of each typical day under different schemes.

Parameter	Typical Day 1				Typical Day 2				Typical Day 3			
	Scheme 1	Scheme 2	Scheme 3	Scheme 4	Scheme 1	Scheme 2	Scheme 3	Scheme 4	Scheme 1	Scheme 2	Scheme 3	Scheme 4
	1	2	3	4	1	2	3	4	1	2	3	4
Unit hydrogen production cost/CNY·kg ^{−1}	8.57	16.26	11.47	8.95	10.76	18.21	13.54	11.77	7.61	15.37	10.68	8.21
Hydrogen production revenue/10 ⁴ CNY	9.70	9.95	10.26	13.40	6.84	7.60	7.61	10.35	11.31	11.32	11.46	14.62

Through the previously discussed hydrogen production and economic comparisons for each typical day under different schemes, it has been verified that the optimized operation strategy for the AEL-PEMEL hybrid hydrogen production system proposed in this paper effectively absorbs photovoltaic output, improves energy utilization efficiency, nearly eliminates photovoltaic curtailment, and significantly increases the system's hydrogen production revenue while ensuring high-efficiency hydrogen production.

4.3. Analysis of Electrolyzer Operational Statuses

As an example, the operational status distribution of the electrolyzers under each scheme during the dispatching cycle for Typical Day 1 is shown in Figures 7–10. The analysis of the figures shows that due to the longer hot start-up response time of an AEL compared to a PEMEL, an AEL remains in a non-operational state for a significantly longer duration, which leads to a higher level of photovoltaic curtailment. In contrast, a PEMEL has a wider power modulation range than an AEL, allowing it to effectively handle fluctuating power, maintain its operational state more stably, and reduce efficiency losses during non-operational periods. Furthermore, because Schemes 1, 2, and 4 incorporate the electrolyzer state tracking and feedback mechanism, they better balance the operational durations of each electrolyzer across different states compared to Scheme 3. Balanced operation reduces the frequency of start–stop cycles, overload duration, and current/voltage fluctuations in electrolyzers. These factors have been shown to be positively correlated with the lifetime degradation of electrolyzers, thereby effectively preventing lifetime loss

due to the over-operation of individual electrolyzers [28]. However, the current constraints only set thresholds based on operational safety, without establishing a quantitative relationship with the physical degradation mechanisms of electrolyzers, such as membrane electrode aging and bipolar plate corrosion. This limits the ability to accurately quantify the contribution of this strategy to extending the electrolyzers' lifetime.

By adopting a hybrid hydrogen production configuration combining AELs and PEMELs, the system leverages the advantages of different electrolyzer types and ensures more stable overall operation through intelligent scheduling of operational states, thereby avoiding the adaptability limitations associated with single-type electrolyzers. Compared to Scheme 3, the operational status switching frequency of the electrolyzers in Scheme 4 is significantly reduced. This reduction not only minimizes energy losses caused by switching and extends the electrolyzers' lifespan but also improves photovoltaic output absorption, enhances hydrogen production efficiency, and increases the overall utilization rate of equipment.

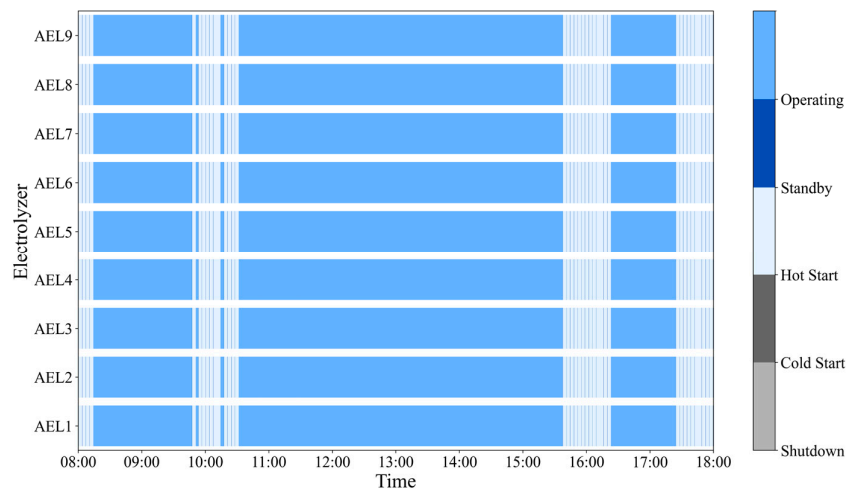


Figure 7. Operational status distribution of electrolyzers under Scheme 1.

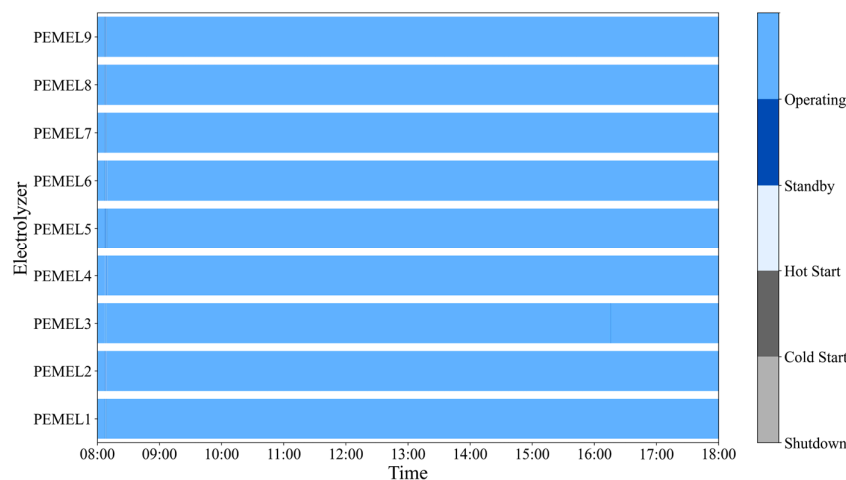


Figure 8. Operational status distribution of electrolyzers under Scheme 2.

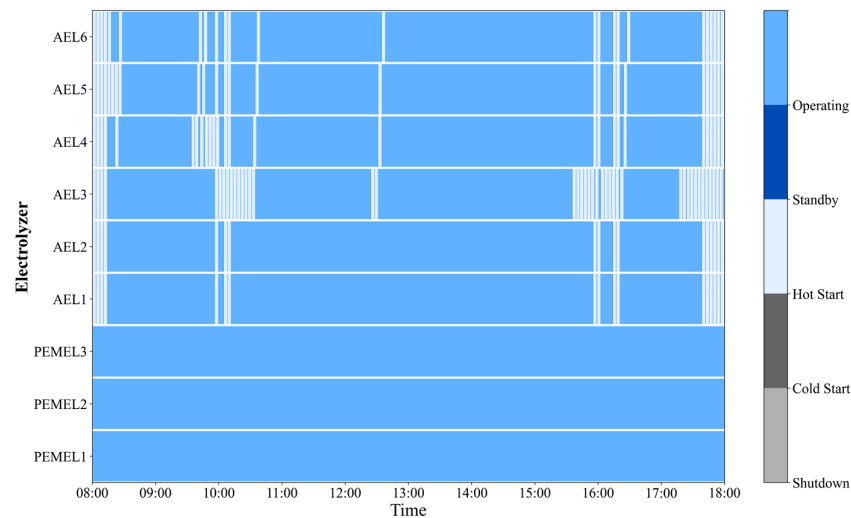


Figure 9. Operational status distribution of electrolyzers under Scheme 3.

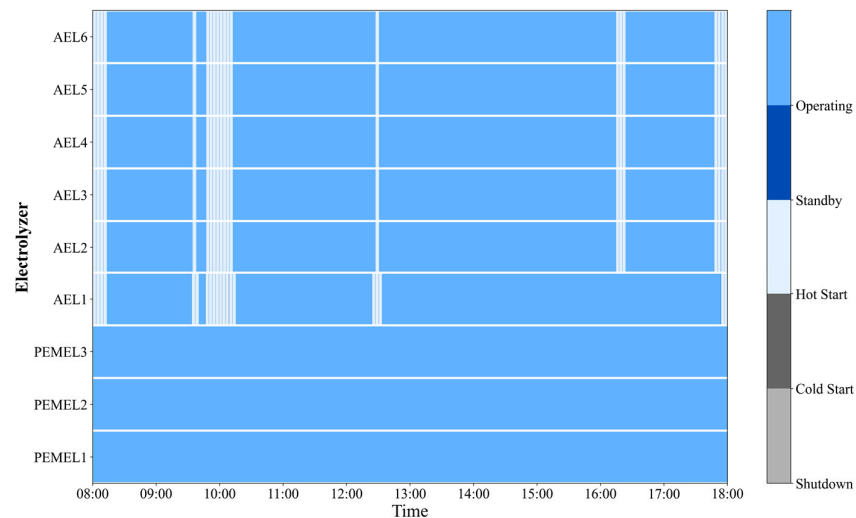


Figure 10. Operational status distribution of electrolyzers under Scheme 4.

4.4. Analysis of Electrolyzer Capacity Ratio

The impact on performance of varying the PEMEL proportion in the hybrid electrolyzer system is shown in Figure 11. As the proportion of PEMELs increases, the system's hydrogen production volume exhibits a continuous growth trend. This is primarily due to the faster response speed and wider dynamic regulation range of PEMELs compared to AELs, which enhances the system's adaptability to renewable energy fluctuations, thereby increasing overall hydrogen production capacity. However, the system's hydrogen production revenue shows an initial increase followed by a decrease, with maximum revenue achieved when the AEL-to-PEMEL capacity ratio is approximately 2:1. This occurs because at this ratio, the low-cost advantage of AELs and the high-efficiency regulation capability of PEMELs are fully coordinated, effectively controlling the electrolyzers' operating costs and ensuring efficient hydrogen production through flexible capacity regulation.

Therefore, rational planning of the electrolyzer capacity ratio can significantly enhance the system's hydrogen production capacity and economic efficiency, while ensuring the safe and stable operation of the system.

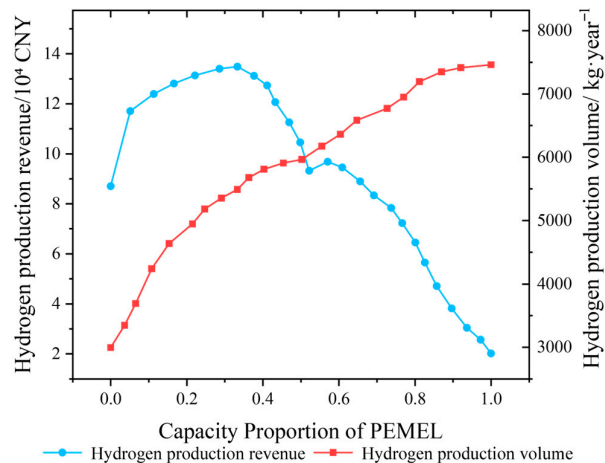


Figure 11. The impact of different capacity ratios.

5. Conclusions

Considering the dynamic characteristics and state transitions of electrolyzers, this paper proposes a coordinated optimal operation strategy for the hybrid hydrogen production system, effectively leveraging the low-cost advantage of AELs and the fast-response characteristic of PEMELs. The main conclusions drawn from the case study analysis are as follows:

- (1) Compared to the single-AEL hydrogen production system, the hybrid electrolyzer hydrogen production system proposed in this paper has resulted in increases of 57.88%, 24.87%, and 51.31% in hydrogen production volume, efficiency, and revenue, respectively. In contrast, compared to the single-PEMEL hydrogen production system, it has reduced the unit hydrogen production cost by 46.58% and increased hydrogen production revenue by 36.18%, thereby confirming that the application of hybrid electrolyzers can effectively enhance the adaptability and economy of the system.
- (2) By introducing the electrolyzer state tracking and feedback mechanism, fully accounting for the cumulative duration of electrolyzers in different operational statuses, and rationally arranging the power allocation scheme for each electrolyzer, dynamic balance in the operational durations of electrolyzers can be achieved. This not only prevents lifetime loss due to the over-operation of individual electrolyzers but also ensures the safe and stable operation of the system.
- (3) By adopting the electrolyzer interval power allocation method proposed in this paper, hydrogen production volume, efficiency, and revenue have increased by 25.75%, 8.90%, and 36.00%, respectively, compared to the traditional electrolyzer power allocation method, while the unit hydrogen production cost has decreased by 23.13%. This not only significantly improves the system's photovoltaic absorption capacity, achieving nearly zero photovoltaic curtailment and ensuring the rational allocation of power in the hydrogen production system, but also ensures the safe and economic operation of the system, thereby verifying the effectiveness of the coordinated optimal operation strategy for the hybrid hydrogen production system proposed in this paper.

Future research will advance in the following four dimensions.

Full-Lifecycle Reliability Assessment of the System

A full-lifecycle reliability model for the hybrid hydrogen production system will be developed by incorporating long-term influencing factors such as electrolyzer state-switching fatigue, interannual fluctuations in photovoltaic output, and equipment aging

attenuation. This model will quantify the long-term effects of the strategy on electrolyzer lifespan degradation and system operation and maintenance costs, thus ensuring performance stability over prolonged operational periods.

Construction of an Intelligent Sensing-Control Collaborative Architecture

A sensing network for monitoring the electrolyzer operational status, based on the Internet of Things (IoT) and edge computing, will be established to enable real-time data collection and edge-side analysis of photovoltaic output, hydrogen production efficiency, and electrolyzer operating conditions. By incorporating reinforcement learning algorithms, this framework will iteratively optimize state scheduling and power allocation strategies, thereby enhancing the system's adaptive regulation capabilities.

Benefit Quantification Analysis in Green Power-to-Hydrogen Scenarios

In industrial green hydrogen application scenarios (e.g., refining, metallurgy), the economic benefits of the proposed strategy in terms of hydrogen production cost, equipment lifespan, and photovoltaic absorption rate will be evaluated. Additionally, the carbon emission reduction effect of the strategy, facilitated by improved green power absorption, will be quantified to elucidate its industrial application value under the “dual-carbon” goals.

Application-Oriented Research Under Differentiated Scenarios

Application-oriented research under differentiated scenarios is conducted, with a focus on investigating the impacts of heterogeneous climatic conditions, power grid operating conditions, and operational modes on scheduling strategies, optimizing scenario-adaptive schemes, and providing robust technical support for the large-scale deployment and application of the proposed strategy.

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References

1. Wang, S.; Kong, L.; Cai, G.; Yan, H.; Han, Z.; Liu, C.; Wan, Y.; Yang, S.; Wang, X. Current Status, Challenges and Prospects of Key Application Technologies for Hydrogen Storage in Power System. *Proc. CSEE* **2023**, *43*, 6660–6681.
2. National Development and Reform Commission; National Energy Administration. *Medium- and Long-Term Plan for the Development of the Hydrogen Energy Industry (2021–2035)*; National Development and Reform Commission: Beijing, China; National Energy Administration: Beijing, China, 2022.
3. Liu, X.; Liu, J.; Zhou, Z.; Han, W.; Wang, G.; Li, W. Current progress and future development trends of green hydrogen production technologies based on new energy. *Mod. Chem. Ind.* **2025**, *45*, 33–39. <https://doi.org/10.16606/j.cnki.issn0253-4320.2025.07.007>.
4. Deng, Y.; Li, C.; Shao, C.; Zhang, Q. Stochastic optimal scheduling of integrated electric-heat-gas-hydrogen energy system. *Acta Energetica Sin.* **2023**, *44*, 522–529.
5. Niu, M.; Hong, Z.; Li, B.; Li, X. Optimal control strategy of wind power to hydrogen system considering electrolyzer efficiency improvement. *Acta Energetica Sin.* **2023**, *44*, 366–376.

6. Li, H.; Yuan, Y.; Tong, L. Optimised control strategy for wind power hydrogen generation system considering hydrogen production efficiency. *Acta Energiæ Solaris Sin.* **2025**, *46*, 154–164. <https://doi.org/10.19912/j.0254-0096.tynxb.2024-1037>.
7. Zhang, X.; Ge, Y.; Yao, H.; Yuan, T. Operation control strategy of hydrogen production electrolytic cell based on particle swarm optimization algorithm. *Therm. Power Gener.* **2023**, *52*, 115–122.
8. Song, W.; Xie, L.; Zhang, L.; Bian, Y.; Hu, C.; Liu, Y. Bi-level capacity planning of microgrid considering multi-mode electrolyzer operation strategy for hydrogen production. *Smart Power* **2025**, *53*, 44–53. <https://doi.org/10.20204/j.sp.2025.10007>.
9. Sun, H.; Wu, W.; Chen, L.; Xing, Z. Review on the Development of New Energy Electrolytic Water Hydrogen Production Technology. *J. Power Supply* **2024**, 1–18. Available online: <https://link.cnki.net/urlid/12.1420.TM.20240123.1730.002> (accessed on 25 January 2026).
10. Ge, S.; Yang, Z.; Bai, J.; Ding, Y.; Wen, J.; Li, X. Development Status and Prospect of Hydrogen Production Technology by Renewable Energy and Its Main Equipment. *J. Taiyuan Univ. Technol.* **2024**, *55*, 759–787.
11. Lin, J.; Cheng, X.; Qiu, Y.; Chi, Y.; Song, Y. A Review of Structure Configuration, Integration, Operation and Key Technologies of Renewable Energy Power to Hydrogen System. *High Volt. Eng.* **2025**, *51*, 2078–2095. <https://doi.org/10.13336/j.1003-6520.hve.20242046>.
12. Li, J.; Zhao, W.; Liang, Z.; Miao, H.; Yuan, X. Power distribution technology based on hybrid-electrolyzer hydrogen production system. *Autom. Electr. Power Syst.* **2024**, *48*, 9–18.
13. Liang, Z.; Wang, L.; Li, J. Nash equilibrium based optimal control method for hydrogen production system with photovoltaic-storage coupling. *Autom. Electr. Power Syst.* **2025**, *49*, 125–134.
14. Zhang, H.; Fan, F.; Song, K.; Jiang, J.; Sun, C.; Zhou, J.; Wang, Z.; Xue, R. Day-ahead scheduling of microgrid considering safety constraints of hybrid electrolyzers. *Clean Coal Technol.* **2025**, *31*, 62–71. <https://doi.org/10.13226/j.issn.1006-6772.BB24122701>.
15. Zhang, F.; Li, P.; Zhou, Z. Research on the optimal configuration of off-grid hydrogen production systems considering the synergistic effects of multi-type electrolytic cell modules. *J. Nanjing Univ. Inf. Sci. Technol.* **2025**, 1–16. Available online: <https://link.cnki.net/urlid/32.1801.n.20251023.1441.001> (accessed on 25 January 2026).
16. Duan, L.; Jia, Y.; Huang, L.; Cao, Z. Optimisation strategy for an integrate electric-hydrogen-thermal energy system with multiple types of electrolyser modules. *J. Shanghai Jiaotong Univ.* **2025**, 1–17. Available online: <https://link.cnki.net/urlid/31.1466.U.20250529.1424.008> (accessed on 25 January 2026).
17. Li, Q.; Han, Y.; Bai, Z.; Han, Y.; Zheng, B. Coordination operation strategy and capacity optimization of off-grid wind-solar hybrid hydrogen production system. *Proc. CSEE* **2024**, *44*, 8136–8146.
18. Zhu, Y.; Liu, Y.; Wang, Z.; Wu, H.; Hui, X. Optimized rotation strategy of electrolyzer arrays in renewable energy hydrogen production system. *Acta Energiæ Solaris Sin.* **2025**, *46*, 530–540. <https://doi.org/10.19912/j.0254-0096.tynxb.2024-0423>.
19. Chen, Z.; Zhang, Y.; Zhu, S.; Xie, S. Optimal Scheduling of Electricity-hydrogen-heat Integrated Energy System Considering Combined Operation of Multi-electrolyzers Under Multiple Conditions. *Power Syst. Technol.* **2025**, *49*, 542–551.
20. Lin, Q.; Meng, C.; Huang, R.; Liu, R.; Wang, W. Optimized scheduling of integrated energy systems on islands considering refined utilization of hydrogen energy. *J. Fuhou Univ. (Nat. Sci. Ed.)* **2025**, *53*, 671–678.
21. Wang, S.; Chen, X.; Ren, L.; Chen, C.; Wang, L.; Wang, Q.; Fan, J.; Chen, J. Progress and prospects of photovoltaics-driven water electrolysis for green hydrogen production. *Mod. Chem. Ind.* **2025**, *45*, 68–72+78. <https://doi.org/10.16606/j.cnki.issn0253-4320.2025.02.014>.
22. Yang, Z.; Tian, X.; Wu, W.; Yuan, T. Optimal capacity configuration of wind-hydrogen-hcng coupled network considering combined electrolyzer operation. *Autom. Electr. Power Syst.* **2023**, *47*, 76–85.
23. Ding, J.; Fang, X.; Song, Y.; Zheng, C.; Tang, X.; Yao, W. Conception of electricity and hydrogen integrated energy network for renewable energy transmission in western China under background of carbon neutralization. *Autom. Electr. Power Syst.* **2021**, *45*, 1–9.
24. Li, Z.; Zhao, Y.; Wu, P.; Chang, Y.; Zhao, S. Low-carbon dispatching strategy of integrated energy system with coordination of green hydrogen and blue hydrogen based on fine modeling of hydrogen production equipment. *Power Syst. Technol.* **2024**, *48*, 2317–2326.
25. Han, P.; Xu, X.; Wang, H.; Yan, Z. Operational Efficiency Enhancement of Multi-Stack Proton Exchange Membrane Electrolyzer Systems with Power-Temperature Adaptive Control. *Trans. China Electrotech. Soc.* **2024**, *39*, 2236–2248.
26. Zhang, W.; Zhou, J.; Li, M.; Xu, G.; Dong, W.; Liu, W. Optimization Strategy of Wind and Solar Hydrogen Production Alkaline-PEM Hybrid Electrolyzers Cluster Considering Energy Consumption Characteristics. *Power Syst. Technol.* **2025**, *49*, 63–72.

27. Guo, F.; Xu, G.; Wang, X.; Zhang, Y.; Xu, C.; Wang, Y. A planning method for stand-alone wind-solar hydrogen storage system based on 8760 hours production simulation. *Power Syst. Technol.* **2024**, *48*, 2227–2235.
28. Dou, Z.; Kong, W.; Jiang, K.; Li, J.; Wei, Y.; Zhang, C. Collaborative Control Technology for Electric Hydrogen Coupling System Cluster. *Power Gener. Technol.* **2025**, 1–14. Available online: <https://link.cnki.net/urlid/33.1405.TK.20251103.0848.002> (accessed on 25 January 2026).

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