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Modeling and economic optimization scheduling strategy of wind-solar-storage coupled off-grid hydrogen production system

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ABSTRACT

Due to the common intermittent characteristics of wind power generation and photovoltaic power generation and the complementary characteristics of power generation periods, the rational design of the operation energy scheduling strategy of the renewable energy hydrogen production system equipped with energy storage batteries is necessary and economical.

In this paper, firstly, the off-grid DC bus architecture is optimally selected based on the study of the wind-solar storage coupled hydrogen production system, and the system model is established in Matlab/simulink environment. Secondly, considering the constraints such as equipment power leveling and service life, combined with the study of system optimization scheduling strategy, an economic optimization scheduling model is established with the goal of maximizing system revenue. Finally, we set up different working conditions for simulation analysis to verify the effectiveness and feasibility of the Simulink model and the economic optimization scheduling strategy of the wind-solar storage coupled off-grid hydrogen production system. This paper aims to provide ideas and methods for energy transition and renewable energy hydrogen production system to reduce costs and increase efficiency.

Keywords: Wind-solar storage, hydrogen production from renewable energy, off-grid, energy scheduling.

NONMENCLATURE

Abbreviations	
O&M	Operation and Maintenance
PV	Photovoltaic
SOC	State of charge

1. INTRODUCTION

In 2015, countries around the world signed the Paris Agreement to address global climate change, requiring greenhouse gases in this century to achieve the agreement's goal of "net zero emissions", the use of fossil fuels must be significantly reduced in the next few decades, the global energy system to put forward the demand for energy transformation.

Hydrogen energy is becoming a key alternative for practicing energy revolution strategies and achieving carbon neutrality. Hydrogen energy is green, clean, renewable, and broad-source, and has become an important way to implement low-carbon transition in the new era [1-3].

At present, the relevant research content of wind-solar storage coupled hydrogen system is relatively extensive, but most of them are aimed at achieving the two goals of improving energy conversion efficiency and pursuing system economic benefits. The domestic research on hydrogen production technology started relatively late but the research contributes to the demonstration project of hydrogen production account for much of the research on domestic renewable energy hydrogen production technology and its off-grid architecture of wind-solar storage coupled hydrogen production system is not much, mainly from the perspective of system economic feasibility and control strategy to analyze and optimize the hydrogen production technology. Foreign studies on off-grid hydrogen production coupled with wind-solar storage aim at ensuring the economic feasibility of the system and optimizing the efficiency of hydrogen production, mainly from the perspective of hydrogen production, focusing on aspects such as how to use wind photovoltaic power to meet the hydrogen production requirements and the utilization path of the resulting hydrogen.

By analyzing the current research on wind-solar storage coupled off-grid hydrogen production system, the thesis carries out mathematical modeling of the wind-solar storage coupled off-grid hydrogen production system, conducts research on its economic optimization scheduling strategy and establishes a scheduling model to maximize system revenue. The rest of this paper is organized as follows: The system architecture selection is given in the section 2. An economic optimization scheduling strategy using a scheduling model aimed at maximizing revenue is established in section 3, and the system and its scheduling model are simulated and analyzed under different working conditions

2. SYSTEM ARCHITECTURE SELECTION

2.1 Description of system components

The main components of the wind-solar coupled hydrogen system include wind power generation unit, photovoltaic power generation unit, energy storage unit (e.g. battery, hydrogen storage tank), electrolyzer, power electronic converter (e.g. DC/AC converter, etc.), and depending on the actual situation, other micro sources (e.g. diesel generator, fuel cell), loads (e.g. charging pile), etc. Each component of the system is coupled and connected in a certain topology through the power electronic converter to form a complete system

The power generated from wind/photovoltaic can be used directly for load demand or transferred to hydrogen or stored in the storage unit, and its storage size depends on the intermittency level of solar or wind power. When the wind power and PV output at the power generation end is equal to the power demanded at the load end, there will be no excess power or power shortage; when the wind power and PV output at the power generation end is greater than the power demanded at the load end, the electricity can be converted to hydrogen energy through the electrolyzer hydrogen production unit to absorb the excess power of the system, or the excess power can be absorbed by the energy storage unit and stored in the form of electricity; when the wind power and PV output at the power generation end is lower than the power demanded at the load end, the energy storage When the wind power and PV output at the power generation end is lower than the power demand at the load end, the energy storage unit will release energy to make up the shortage of system power [4].

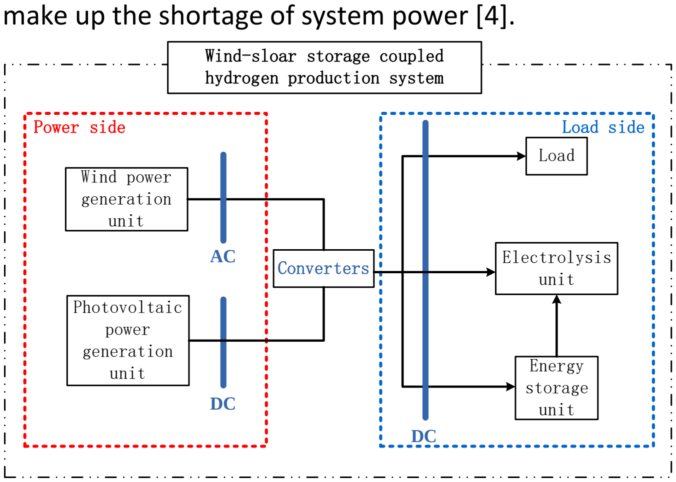

Fig. 1 System structure composition

2.2 System architecture analysis

The wind-sloar coupled hydrogen system is divided into two modes of grid-connected operation and off-grid operation according to whether it is connected to the grid or not. Based on this, the system can be divided into grid-connected AC bus architecture (Fig.2), grid-connected DC bus architecture (Fig. 3), off-grid AC bus architecture(Fig. 4), and off-grid DC bus architecture(Fig. 5) according to the system bus form.

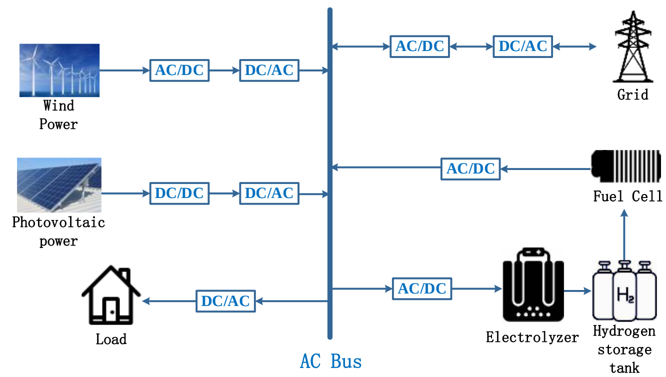

Fig. 2 Grid-connected AC bus architecture

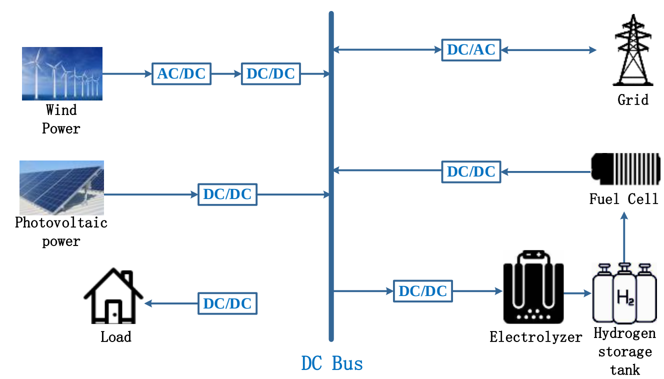

Fig. 3 Grid-connected DC bus architecture

For grid-connected operation mode, the system does not need to install energy storage cells, which can save investment and maintenance costs, and the excess energy of the system can be connected to the grid. When the grid needs peak regulation, it can access the fuel cell power generation unit to form an adjustable margin to meet the system demand. The electrolysis tank can obtain electricity from both micro-source and grid to meet the demand of hydrogen production and ensure the quality of hydrogen gas. However, the system causes harmonic pollution to the grid due to the large number of power electronics in the system. Harmonic distortions can be mitigated by using appropriate filters and PWM switching converters [5]. In addition, there is a risk of impedance mismatch between microgrids and large grids, which can easily cause inter-grid zone oscillations [6].

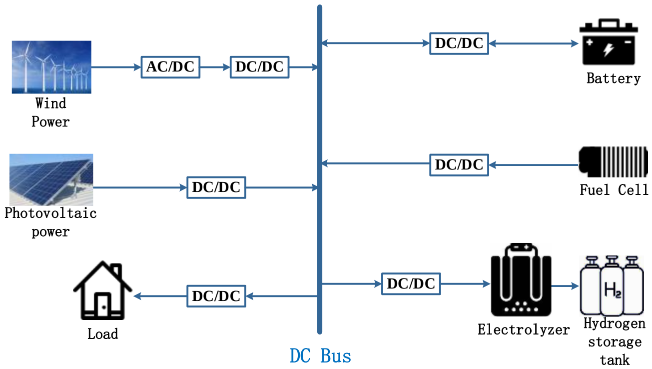

Fig. 4 Off-grid AC bus architecture

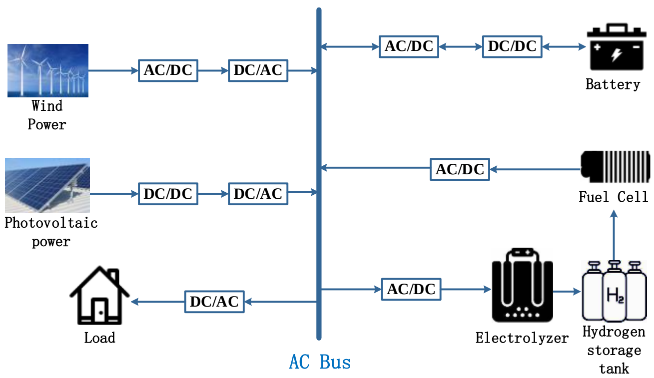

Fig. 5 Off-grid DC bus architecture

For off-grid operation mode, the system is not restricted by the geographical area, and can be installed and used wherever there is wind and light, which has strong practicality and is very suitable for remote areas without grid, isolated islands, and areas with frequent power outages. It can supply power nearby without long-distance transmission, reduce energy loss, easy to install and use, and easy to maintain. However, it needs to be equipped with batteries for leveling out bus voltage power imbalance, providing bus voltage support and improving the quality of hydrogen production. The maintenance difficulty of the storage unit and the 3-5 years life cycle of the storage battery will increase the system cost.

2.3 System optimization architecture selection

If the system uses AC bus, the system design can be based on the mature technology of AC large grid, and the equipment to meet various power requirements in the system is easy to procure. The disadvantage is that the system needs a large number of AC/DC and DC/AC converters, which will not only make the system cost higher, but also make the system less efficient. If the system uses a DC bus, the DC bus does not have to be stabilized and synchronized at a constant frequency while coupling different generation sources. The off-grid DC bus architecture system reduces a large number of AC/DC and DC/AC links and maximizes energy extraction from solar and wind power using fewer power electronic converters, making the system simple and highly efficient in conversion.

Based on the analysis of four types of landscape storage coupled hydrogen system architectures, off-grid operation mode requires the configuration of energy storage units to level out the problem of public DC bus power imbalance, but in the case of possible increase in investment and maintenance costs, the off-grid operation mode is less restricted than the grid-connected operation mode, and does not generate harmonic pollution to the public grid and cause grid oscillation. In off-grid operation mode, the DC bus system architecture uses fewer conversion links than the AC bus system, saving the DC/AC conversion links of wind turbines and photovoltaic units and the AC/DC conversion links of the front-end of electrolytic cells, without reactive power and frequency regulation problems. In view of this, the off-grid DC bus architecture is selected in the paper.

After selecting a simple and efficient off-grid DC bus architecture, a dynamic model of the system with the dynamic characteristics of the device was developed in Matlab/Simulink to simulate the power generation, battery power and hydrogen demand power to facilitate the verification of the feasibility of the economic optimization scheduling strategy later on.

3. ECONOMIC OPTIMAL SCHEDULING STRATEGY

In order to achieve optimal energy management and economic scheduling of the off-grid hydrogen production system coupled with the wind-solar storage, this section takes into account the revenue from hydrogen sales, the cost of wind power generation, the cost of photovoltaic power generation, the cost of energy storage batteries, and the cost of hydrogen production in the electrolyzer (the cost of each unit includes depreciation cost and maintenance cost) under the premise of ensuring that the system meets the demand for hydrogen production [7] to achieve the goal of maximizing the operational revenue of the off-grid hydrogen production system coupled with the wind-solar storage.

3.1 Economic optimization scheduling model

To ensure that the system operates with maximum revenue, the objective function being established is

$$\max F = \sum_{t=1}^{24} \left(R_{H_2} - C_{fix} - C_{dep}\right) \tag{1}$$

where the hydrogen sales revenue R_{H_2}, total system operation and maintenance costs C_{fix}, total system depreciation cost C_{dep} are defined as

$$R_{H_2} = S_{H_2} \cdot N_{H_2}(t) \cdot \rho_{H_2} \quad (2)$$

$$C_{fix} = \sum_{i=1}^{4} k_i \cdot P_i(t) \quad (3)$$

$$C_{dep} = \sum_{i=1}^{4} \frac{C_{ins,i} \cdot f_{i,cr}}{8760 \cdot c_i \cdot P_{i,rated}} P_i(t) \quad (4)$$

$$f_{i,cr} = \frac{r_i(1+r_i)^{n_i}}{(1+r_i)^{n_i} - 1} \quad (5)$$

where S_{H_2} is hydrogen sales price; $N_{H_2}(t)$ is volume of hydrogen production at time t; ρ_{H_2} is hydrogen density (0.089g/L); k_i is O&M cost factor for category i equipment; $P_i(t)$ is power of category i equipment at time t; $C_{ins,i}$ is construction cost of category i equipment; $f_{i,cr}$ is recovery factor for category i equipment; c_i is capacity factor of category i equipment (ratio of annual average power generation to annual theoretical power generation); $P_{i,rated}$ is rated power of category i equipment; r_i is depreciation rate of category i equipment; n_i is Service life of category i equipment.

The constraints of the scheduling model include:

a. Power balance constraint

$$P_{wind} + P_{pv} + P_{bat} = P_{el} \quad (6)$$

where P_{wind} is wind power; P_{pv} is photovoltaic power; P_{bat} is battery charging and discharging power, and when $P_{bat}> 0$, the energy storage unit discharges; when $P_{bat} < 0$, the energy storage unit charges; P_{el} is hydrogen production demand power(Electrolyzer power).

b. Equipment operating constraints

$$\begin{cases} 0 \le P_{wind}(t) \le P_{1,max} \\ 0 \le P_{pv}(t) \le P_{2,max} \\ 0 \le |P_{bat}(t)| \le P_{3,max} \\ 0 \le P_{el}(t) \le P_{4,max} \end{cases} \quad (7)$$

where $P_{1,max}$, $P_{2,max}$, $P_{3,max}$, $P_{4,max}$ are the maximum values of the power of the wind power unit, the photovoltaic power unit, the energy storage unit, and the electrolyzer hydrogen production unit, respectively. To describe the state requirements for the absorption/release of electrical energy from the energy storage unit, the constraint set on the operation of the energy storage unit is

$$\mathrm{SOC}_{\min} \le \mathrm{SOC}_t \le \mathrm{SOC}_{\max} \quad (8)$$

where SOC_t is the charge level of the energy storage unit at time t. $\mathrm{SOC}_{\min}$, $\mathrm{SOC}_{\max}$ refer to the minimum and maximum values of the charge level allowed by the energy storage device, respectively.

3.2 Economic optimal scheduling strategy

The input power of the electrolyzer hydrogen production unit in off-grid operation mode depends entirely on the wind power output, photovoltaic power output and energy storage battery charging and discharging power, and the cost of restarting and stopping the electrolyzer is large. The paper focuses on the optimal scheduling under resource availability and system reliability and its scheduling flow is shown in Fig.6. In view of this, with a guaranteed continuous operation of the electrolyzer throughout the day (24 hours), the system has the following main operating conditions depending on weather conditions and storage battery charge:

Case 1: In weak wind and no light, the wind power is fed into the electrolyzer to produce hydrogen, and the energy storage battery absorbs/releases electricity equal to the difference between the wind power and the hydrogen demand of the electrolyzer under the constraint of prohibiting excessive charging and discharging.

Case 2: In strong wind and low light conditions, wind power and photovoltaic power are jointly fed into the electrolyzer to produce hydrogen, and the energy storage battery absorbs/releases electricity equal to the difference between the wind/photovoltaic power and the hydrogen production demand of the electrolyzer under the constraint of prohibiting excessive charging and discharging.

Case 3: In strong wind and light conditions, wind power and photovoltaic power generation are jointly fed into the electrolyzer to produce hydrogen, and under the constraint of prohibiting excessive charging and discharging of the energy storage battery, the electricity equivalent to the difference between the output of the wind/photovoltaic power generation unit and the hydrogen production demand of the electrolyzer is absorbed/released.

Case 4: In strong wind without light, the wind power is fed into the electrolyzer to produce hydrogen, and the energy storage battery absorbs/releases electricity equal to the difference between the wind power and the hydrogen production demand of the electrolyzer under the constraint of prohibiting excessive charging and discharging.

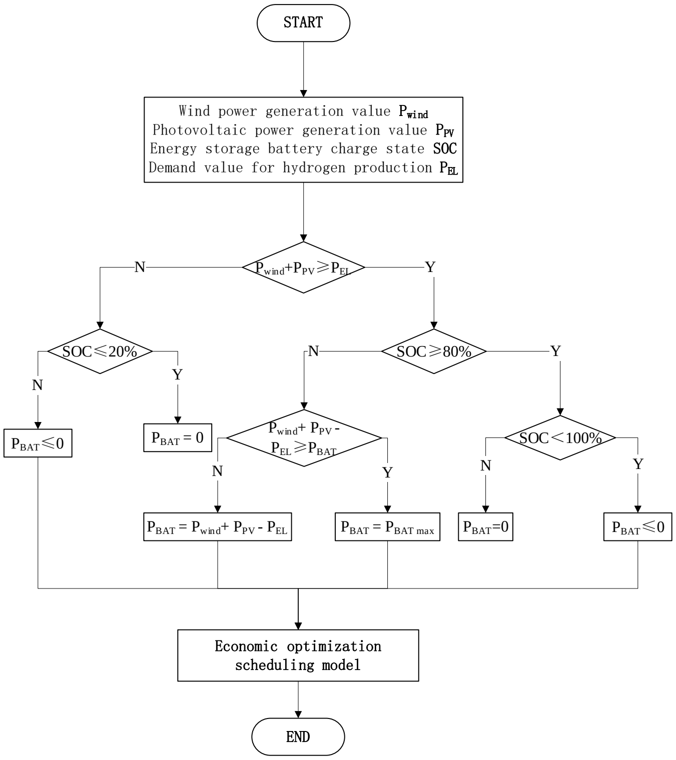

Fig. 6 Scheduling flow

4. SIMULATION AND RESULTS

4.1 Case simulation

In order to verify the effectiveness and feasibility of the model of the off-grid hydrogen production system coupled with wind-solar storage and its economic optimal scheduling strategy, the paper selects the average wind speed variation (m/s) and the average light intensity variation (W/m^2) at different times of the day (24 hours) under typical wind-solar conditions (ambient temperature 25°C) in a region of Chongqing in summer as the input data of the wind/photovoltaic power generation unit in the model of the off-grid hydrogen production system coupled with wind-solar storage.

Table 1

Economic optimal scheduling model parameters

		Wind power	PV power	Battery	Electrolyzer
$P_{i,rated}$	kW	1500	3000	300	4500
$C_{ins,i}$	¥/ kW	1500	1900	2	1666
ki	¥/ kWh	0.005	0.015	0.011	0.05
r_i	%	5	5	6.5	6
n_i	Years	20	20	10	20

During 0:00-6:00 hours, there is no light in the system environment and the average wind speed is weak, so the input power of the electrolyzer depends only on the wind power and the energy storage battery power. During 12:00-15:00, the average ambient light intensity increases to the rated light intensity but the average wind speed is constant, and the power output of PV power generation increases, which makes the power of electrolyzer hydrogen production unit increase; during 15:00-19:00, the average light intensity decreases, and the power input to electrolyzer decreases, after 19:00, the light intensity decreases to 0, and the system operates only by the power output of wind power generation unit to produce hydrogen.

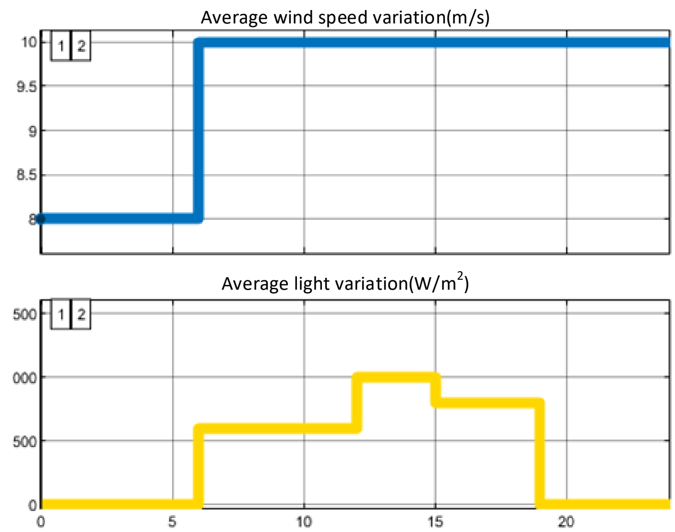

Fig. 7 Average wind speed variation and average light intensity variation in different time periods during 24 hours

The Simulink system model is run in Matlab/simulink simulation environment, and programmed to collect wind power $P_{wind}(t)$, photovoltaic power $P_{pv}(t)$, energy storage battery charge/discharge power $P_{bat}(t)$, electrolyzer hydrogen production power $P_{el}(t)$ at each time of 24 hours a day. The data obtained from the system model are input into the economic optimization scheduling model in the command window of Matlab simulation software to obtain the daily scheduling and daily net revenue results of the off-grid hydrogen production system coupled with the wind speed and light intensity, and the net revenue changes with the electrolyzer power. The peak value is 4.4×104 m3 and 98,000 yuan respectively, and the scheduling corresponds to the demand for hydrogen production in the electrolyzer of about 4MW, the output power of the wind power generation unit is 1.38MW, and the output power of the photovoltaic power generation unit is 2.43MW.

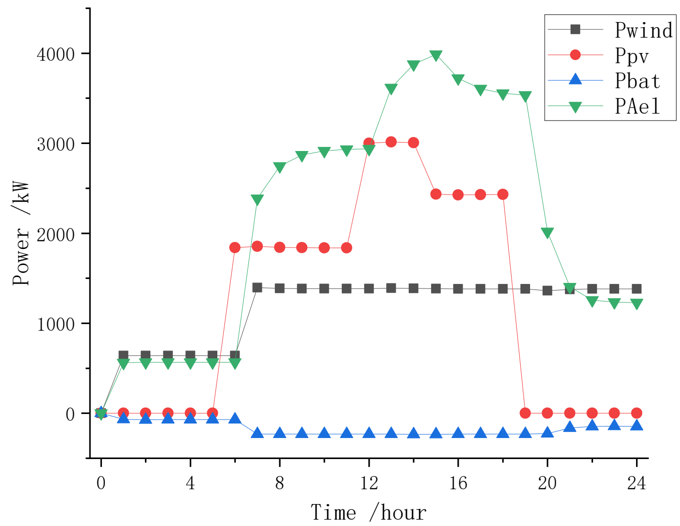

Fig. 8 Wind-solar storage coupled off-grid hydrogen production system power results

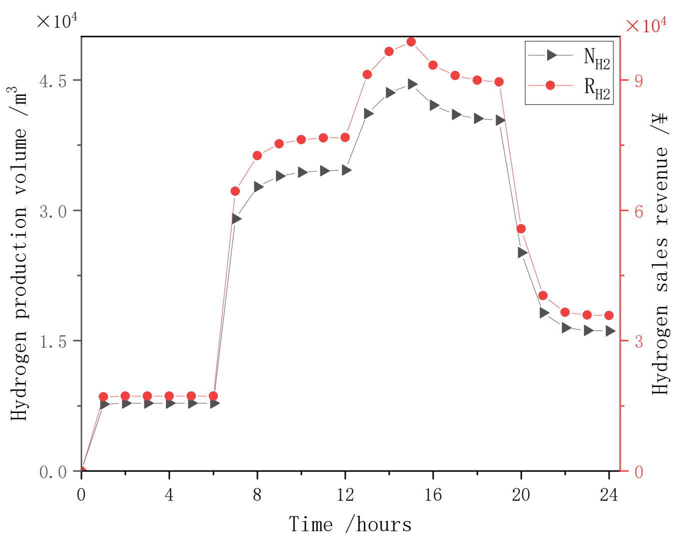

Fig. 9 Hydrogen production and net benefit results

4.2 Sensitivity analysis

For the economic scheduling strategy of adjusting the demand for hydrogen production and storage charging/discharging according to the wind-solar energy input under different working conditions, there will be different decision-making attitudes in the actual expert decision making. In view of this, the power levels of different hydrogen production demands are 1~4, and the economic scheduling strategies for different working conditions are:

G_1(Weak wind without light, battery charging/ discharging, hydrogen production demand 1);

G_2(Strong wind without light, battery charging/ discharging, hydrogen production demand 2);

G_3(Strong wind with weak light, battery charging/ discharging, hydrogen production demand 3);

G_4(Strong wind with strong light, battery charging/ discharging, hydrogen production demand 4).

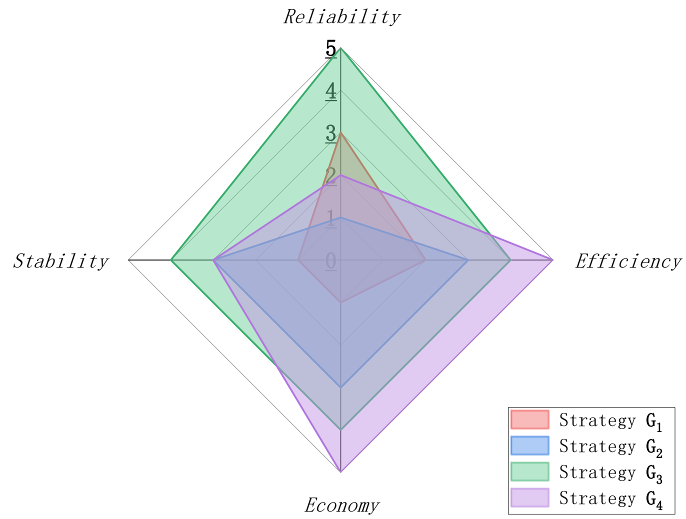

Fig. 10 Scheduling strategy sensitivity analysis radar chart

Table 2

Scheduling strategy evaluation

	G_1	G_2	G_3	G_4
Q_1	3	1	5	2
Q_2	1	3	4	3
Q_3	1	3	4	5
Q_4	2	3	4	5

The evaluation indexes set for the energy scheduling strategy of the off-grid hydrogen production system coupled with wind-solar storage are reliability, stability, economy and efficiency analysis, and the corresponding evaluation values are Q_1, Q_2, Q_3 and Q_4, based on which the scheduling strategy evaluation table shown in Table 2 is obtained and the sensitivity analysis based on the table data is shown in Figure.10. It can be seen from the radar diagram that the scheduling strategies G_1 and G_2 do not show good economy and reliability in the lightless and windy conditions, and although the scheduling strategies of strong wind and strong light can bring more benefits to the system under the conditions of high efficiency and high demand for hydrogen production, the negative impact on the system equipment under such conditions must be considered. In summary, the optimal scheduling strategy under strong wind and low light conditions has shown its stability, reliability and high efficiency while ensuring the economy.

5. CONCLUSION

Under the environment of energy strategy reform and layout development of various countries facing energy problems, renewable energy is gradually becoming an inevitable option to replace fossil energy. Meanwhile, hydrogen energy as an ideal energy carrier also provides solutions to the world energy transformation. The combination of renewable energy generation technology and hydrogen energy utilization puts more requirements on the reliability, effectiveness and economy of the coupled hydrogen production system of wind-solar storage.

The research objectives of the thesis are to establish a reliable model of the dynamic characteristics of the equipment of the off-grid hydrogen production system coupled with wind-solar storage, and to simulate and analyze the feasible strategies for the economic optimization and scheduling of the system under different working conditions, so as to study the application of wind and storage power generation technology, electrolytic tank hydrogen production technology and the operation and scheduling of MW-class wind and storage coupled hydrogen production system. The main work accomplished in the thesis is as follows:

(1) Based on the description of the composition and operation mechanism of the hydrogen production system coupled with wind-solar storage, four different system architectures are studied and analyzed, and the off-grid DC bus system architecture is optimally selected based on the system efficiency and reliability.

(2) The energy scheduling strategy applicable to the off-grid hydrogen production system coupled with wind-solar storage is studied and analyzed, and an economic scheduling model is established after establishing the economic optimization objective of the system to maximize revenue.

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