Proceedings of the 5th International Conference on Materials Chemistry and Environmental Engineering
DOI: 10.54254/2755-2721/2025.29781

Research on Performance of Wind, PV, Thermal and Hydrogen Energy Storage Combined Power Grid System

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Abstract. With the continuous growth of world energy demand and the rapid development of energy storage technology, adding energy storage systems to power systems to improve energy utilization efficiency and reduce energy waste caused by sustainable energy volatility will be a common form in the future. Optimizing energy scheduling is the key to improving system efficiency and economy. This paper proposes a wind, PV, thermal and hydrogen energy storage combined power grid system based on hydrogen energy storage technology. By considering constraints such as system power balance, sustainable energy output power, and energy storage system operation balance, a mathematical model is established and solved with the minimum operating cost as the objective function. Finally, the load and sustainable energy potential data of each California region are used to verify the superiority of the system proposed in this paper.

Keywords: Joint Grid System, Objective Function, Constraints, Hydrogen energy storage system, Model Optimization

1. Introduction

As science, technology, and industrialization continue to advance, humanity's energy demand is steadily increasing. A large amount of energy supply has become one of the necessary factors for the progress of human society. In 2023, the utility-scale power generation in the United States will be about 417.8 billion kWh, of which about 60% will come from fossil fuels and 21% from renewable energy [1]. Although traditional fossil fuels have brought huge economic growth and benefits to the energy industry chain, the excessive exploitation and use of traditional energy has led to various environmental issues, including air pollution, greenhouse gas effects, and acid rain. Data sets from various scientific institutions show that from 1850 to 2025, the global average surface temperature has risen by nearly 1.5°C, causing great damage to the original ecological environment. At the same time, it is precisely because of the sharp increase in greenhouse gases that, as of now, 3.3 to 3.6 billion people live in extreme climates [2]. Therefore, the use of renewable energy has become a topic of close attention around the world and is hailed as the only way for mankind to move towards a green future. Since the 20th century, enhancing the efficiency of renewable energy utilization and strengthening basic application research of renewable energy have become the tone for most countries to formulate energy policies. For example, the "dual carbon" goals of "carbon neutrality" and "carbon peak" have started my country's energy revolution from fossil energy to new clean energy.

However, renewable energy sources suffer from significant intermittency and volatility compared to traditional fossil fuels, which poses challenges in terms of peak management and frequency regulation. In addition, under large-scale grid connection conditions, as a result of considerable variations in time and space coupled with unpredictable fluctuations in wind and PV power, along with the limited capacity of conventional thermal power supporting systems, the regulatory capacity of the integrated power grid may be insufficient, increasing the This reduces the risk of wind and light abandonment, which consequently undermines the reliability and stability of the power grid [3]. Thus, energy storage systems are crucial for the advancement and efficient use of renewable energy. Through its charging and discharging cycles, the energy storage system is capable of leveling power peaks and troughs caused by wind and PV power generation, effectively achieving balanced storage of power and energy in the power system, thus significantly reducing waste in the development of renewable energy. electrical phenomena [4]. For example, Ou Yang et al. integrated wind power and energy storage systems extensively into the grid and investigated methods to optimize power supply balance by using nonlinear optimization models and calculus methods [5]; Li et al. proposed a method that takes into account both technology and economics. A unique peak-shaving optimization control method for zinc-bromine flow battery (ZBB) energy storage alleviates the power grid's wind curtailment problem and maintains good peak-shaving economics of the system throughout its life cycle [6]; Guo et al. improved the volatility, intermittency and unpredictability of the system during the operation of the microgrid by incorporating a battery energy storage system (BESS) into the microgrid [7]; Xu et al. Based on the charging infrastructure planning of Dapeng New District in Shenzhen, wind, PV, and multiple energy complementary units were installed across three charging sites to enhance the sustainability of the energy system, ensure stable grid operation, and support the advancement of green industries [8]... Although photovoltaic and wind power generation usually use efficient battery energy storage systems, their storage capacity limitations and low energy density still limit their continued development and widespread application. In contrast, hydrogen is regarded as an effective energy storage solution because of its high energy density and its capability for stable, long-term storage. Compared with batteries, hydrogen energy storage has obvious advantages in energy density, long-term storage reliability, and large-scale energy storage feasibility. It is especially suitable for large-scale and long-term energy balance needs, thus demonstrating its role in renewable energy integration. It has broad application prospects [9].

The hydrogen energy storage system mainly consists of a storage part and an electrolysis part. At present, hydrogen storage is mainly divided into three ways: compressed gas, liquid and solid. Compressed gas storage is to store hydrogen under high pressure in steel or composite gas cylinders, with a common pressure range of 6000-10000 psi [10]. This method is relatively mature and widely used in industry, transportation and energy [11]. The main types of high-pressure gas hydrogen storage tank materials used as the storage part are type III and type IV tanks. Type III tanks are composed of metal linings wrapped in composite materials and are suitable for mobile transportation. Type IV tanks use plastic linings and are completely wrapped in composite materials, which reduces corrosion to the tank body [12]. Li J et al. are exploring the integration of organic metal frameworks (MOFs) and nanomaterials as new materials into the production of storage tanks

DOI: 10.54254/2755-2721/2025.29781

to improve storage capacity, structural strength and corrosion resistance [13]. In the electrolysis part, proton exchange membrane (PEM) electrolysis has become a promising sustainable energy hydrogen production technology, especially when combined with renewable energy sources such as photovoltaic and wind power. Arunachalam, M., & Han, D. S. studied the use of PEM electrolysis to optimize the volatility of PV radiation for grid regulation [14]. The study showed that PEM electrolysis has the characteristics of fast response time and strong ability to handle fluctuating loads [15]. The principle of PEM electrolysis is relatively simple. Only protons are allowed to pass through the reaction while blocking electrons. Therefore, when applying an electric current, it can promote the decomposition of water molecules into hydrogen and oxygen. This reaction is called hydrogen evolution reaction. Platinum-based catalysts are usually used in hydrogen evolution reaction, but due to the high cost of platinum, researchers are working to reduce the content of platinum in the catalyst to reduce costs while maintaining the reaction rate. Wang T et al. explored the use of iridium-based catalysts as an alternative to platinum-based catalysts, which found a balance between catalytic activity, stability and cost under the acidic conditions of PEM cells [16].

Based on this, there are many cases in this field where hydrogen energy storage systems are applied to sustainable energy optimization. For example, Jin and Cheng et al. combined wind power, photovoltaics and hydrogen energy storage devices to form a comprehensive power generation system, and conducted in-depth analysis in terms of system application type, capacity configuration and control optimization, further promoting the technological progress and engineering application of a wind and PV hybrid power generation system combined with hydrogen energy storage [17]; Liu also proactively enhanced the existing wind and photovoltaic complementary systems by introducing hydrogen energy generation units, combining them into an "open" system for new renewable energy manufacturing and production [18]; Xu et al. analyzed the benefits of hydrogen energy storage in comparison to other energy storage methods, expounded the requirements of emerging power systems for hydrogen energy, and established an application framework for hydrogen storage within the 'source-grid-load' structure of these new systems [19].

This study aims to alleviate the energy waste and instability of renewable energy generation in the process involving wind and PV power generation, enhancing the efficiency of renewable energy use within the power grid, balance user load requirements and enhance the system's economic efficiency. It connects traditional thermal, wind, PV power generation, and hydrogen storage units into the grid and establishes a mathematical model for an integrated wind, PV, thermal, hydrogen, and energy storage power grid system. The model takes minimizing the system operation cost as the objective function, and the main costs considered include the generation costs for wind and PV farms, electrolyzer expenses, hydrogen storage costs, and operational costs of fuel cells. At the same time, power balance constraints, wind and photovoltaic power generation constraints, and energy storage system operation constraints are established to ensure the stability and economy of the system. In terms of power balance, the charge and discharge processes of thermal power generation, wind power generation, photovoltaic power generation, and hydrogen energy storage systems are comprehensively dispatched to ensure that the load demand is met; in terms of energy storage, the maximum storage capacity of hydrogen, the power range of electrolyzers, and the discharge efficiency of fuel cells are mainly considered. This study solved the established model in MATLAB, using load data and wind and photovoltaic power generation potential in California, USA as input, and compared and analyzed the energy waste and system performance with and without hydrogen energy storage systems to verify the optimization effect of the model.

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2. Composition of wind, PV, thermal, hydrogen and energy storage combined power grid system

Figure 1 demonstrates the overall structure of the system. The system proposed in this paper generally includes power grid, power generation system, hydrogen energy storage system and loads at all levels. The power grid is composed of power transmission equipment, which is responsible for the transmission of electricity; the power generation system includes thermal power plants, wind power plants and PV power plants, which are responsible for the generation of electricity; the composition of hydrogen energy storage system includes electrolytic cells, high-pressure hydrogen storage tanks and hydrogen fuel cells, and the load collects and stores the system's excess electricity for use by the power grid when there is a power shortage; the load is a factory or a residence, which is the user of the system's electricity.

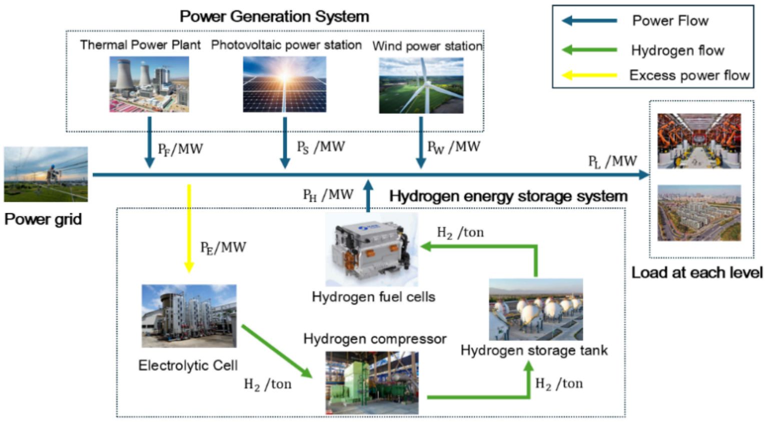

Figure 1. Wind, PV, thermal, hydrogen and energy storage hybrid power grid system

In the wind, PV, thermal, hydrogen and energy storage hybrid power grid system, the power generation system generates electricity and transmits it to the power grid, which transmits the electricity to various levels of loads. While the output of electricity is higher than the load demand, the power grid will transmit the excess electricity to the electrolyze in the energy storage system for electrolysis to produce hydrogen. The generated hydrogen enters the gas tank through the compressor for storage. While the power output of the power system is lower than the load demand, the hydrogen in the high-pressure hydrogen storage tank will be transported to the fuel cell for power generation to make up for the lack of electricity demand.

When the system is running, thermal power generation will serve as the base load, and its output power will be a constant value, in order to meet the large load demand determined in the system; while PV energy, wind energy and fuel cell power generation will serve as peak load regulation to meet the load demand that fluctuates over time. On the fundament of meeting the power balance, the system will reasonably plan the scale and output of each system to achieve economic operation. On the other hand, the hydrogen energy storage system can also effectively solve the fluctuations caused by the integration of PV energy and wind energy into the power grid, thereby improving the utilization efficiency of sustainable energy and ensuring the economy and stability of the wind, PV, thermal and hydrogen energy storage combined power grid system.

3. Mathematical models of the system components

To compare the overall performance changes of the system after the introduction of energy storage unit, this section will establish mathematical models for the system with and without hydrogen energy storage equipment respectively.

3.1. Objective function

In the energy system, economic indicators are undoubtedly the most important, so keeping the system running at the lowest cost is the objective function of this system. Therefore, the objective function mainly considers the cost of photovoltaic and wind farms, the cost of electrolyzes, the cost of high-pressure hydrogen storage tanks, and the cost of power generation of fuel cells.

3.1.1. Photovoltaic and wind power generation costs

The cost of photovoltaic and wind power generation is affected by many factors, such as investment and construction, operation and maintenance, life cycle, and scrapping and recycling. Therefore, this paper uses the levelized cost of electricity (LCOE) for cost calculation. LCOE represents the cost-effectiveness of the power system and can be used to compare energy alternatives and possible power system solutions [20]. LCOE estimation is based on the ratio from the present value of the total life cycle cost to the present value of the total life cycle energy generation [21]. Therefore, it is also called the cost per kilowatt-hour, that is, the cost required to generate 1kwh of electricity. The calculation formula is as follows:

$$LCOE = \frac{TLCC}{TLEG} = \frac{\sum_{t=0}^{T} \frac{C_t}{(1+i)^t}}{\sum_{t=0}^{T} \frac{E_t}{(1+i)^t}} \tag{1}$$

In the formula, C_t is the cost at the tth moment; E_t is the power generation at the tth moment; i is the discount rate; and T is the total lifespan. With the help of formula 2.1, the cost per kilowatt-hour of wind power and PV power generation can be calculated. Therefore, the cost of the two power generation modes at a certain moment can be calculated by the following formula:

$$\begin{cases} C_{W\,t} = C_{W\,L} \times P_{W\,To} \times CF_{W.t} \times t \\ C_{S\,t} = C_{S\,L} \times P_{S\,To} \times CF_{S.t} \times t \end{cases} \tag{2}$$

In the formula, $C_{W\,t}$, $C_{S\,t}$ are the costs of wind power and photovoltaic power generation at time t; $C_{W\,L}$, $C_{S\,L}$ are the costs per kilowatt-hour of wind power and photovoltaic power generation; $P_{W\,To}$, $P_{S\,To}$ are the overall installed capacities of wind power and photovoltaic power generation; $CF_{W.t}$, $CF_{S.t}$ are the capacity coefficients for PV and wind energy production at the moment t; t is the time interval of this period.

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3.1.2. Cost of hydrogen energy storage systems

The cost of the hydrogen energy storage system includes the cost of the electrolytic cell, the cost of hydrogen storage, and the operating cost of the fuel cell. In the system, the electricity consumed by the electrolytic cell during operation is the excess electricity in the power grid, so there is no need to pay electricity costs; and the raw material hydrogen of the fuel cell during operation is generated within the system, so there is no need to pay raw material costs. The cost model of each part of the energy storage system is shown in the following formula:

$$\begin{cases} C_{H_2\,C\,t} = P_{in\,t} \times c_C \times t \\ C_{H_2\,S\,t} = V_{H_2\,t} \times c_S \times t \\ C_{H_2\,F\,t} = P_{out\,t} \times c_F \times t \end{cases} \tag{3}$$

In the formula, $C_{H_2C\,t}$, $C_{H_2S\,t}$, $C_{H_2F\,t}$ are the prices of the electrolytic cell, hydrogen storage and fuel cell respectively; $P_{in\,t}$ is the power of the electrolytic cell when it is absorbing extra power from the power grid at time t; V_{H_2t} is the storage capacity of hydrogen at time t; $P_{out\,t}$ is the power of the hydrogen fuel cell at time t. c_C, c_S, c_F are cost coefficients. Therefore, the total cost of the hydrogen energy storage system at time t is:

$$C_{H_2\,To\,t} = C_{H_2\,C\,t} + C_{H_2\,S\,t} + C_{H_2\,F\,t} \tag{4}$$

3.1.3. Economic objective function

The economic objective function aims to make the system run at the minimum cost. In the system proposed in this paper, thermal power generation is the base load and will not change over time, so its cost is fixed and will not change over time, and does not need to be reflected in the function. In the original system, only the cost of wind power and photovoltaic power needs to be considered, so the objective function is:

$$minC_{To} = \sum_{t=0}^{T} (C_{W\,t} + C_{S\,t}) \tag{5}$$

After adding the hydrogen energy storage system, the cost of this part also needs to be calculated, so the objective function becomes:

$$minC_{To} = \sum_{t=0}^{T} (C_{W\,t} + C_{S\,t} + C_{H_2\,To\,t}) \tag{6}$$

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3.2. Constraints

3.2.1. Power balance constraints

For the original system:

$$P_{load\,t} \leq P_{F\,t} + P_{W\,t} + P_{S\,t} \tag{7}$$

After the introduction of the hydrogen energy storage system:

$$P_{load\,t} + P_{in\,t} \leq P_{F\,t} + P_{W\,t} + P_{S\,t} + P_{out\,t} \tag{8}$$

Where, $\mathrm{P}_{\mathrm{load\ t}}$ is the load demand of the system at time t; $\mathrm{P}_{\mathrm{F\ t}}$ is the output power of thermal power generation at time t; $\mathrm{P}_{\mathrm{W\ t}}$ and $\mathrm{P}_{\mathrm{S\ t}}$ are the output powers of wind power and PV power generation at time t respectively.

3.2.2. Wind and PV power constraints

$$\begin{cases} 0 \leq P_{W\,t} \leq P_{W\,t,max} \\ 0 \leq P_{S\,t} \leq P_{S\,t,max} \end{cases} \tag{9}$$

3.2.3. Energy storage system constraints

When the system is in the energy storage state:

$$\begin{cases} V_{H_2\,t} \leq V_{H_2\,max} \\ P_{H_2\,C\,min} \leq P_{in\,t} \leq P_{H_2\,C\,max} \\ V_{H_2\,t} = \frac{P_{in\,t} \times t}{2 \times F \times U} \end{cases} \tag{10}$$

In the formula, $\mathrm{V}_{\mathrm{H_2max}}$ the maximum hydrogen storage capacity of the system; $\mathrm{P}_{\mathrm{H_2C\ min}}$ and $\mathrm{P}_{\mathrm{H_2C\ max}}$ are the minimum starting power and maximum consumption power of the electrolytic cell; F is the Faraday constant; and U is the electrolytic cell voltage.

When the system is in discharge state:

$$\begin{cases} V_{H_2\,u\,t} \leq V_{H_2\,t} \\ P_{out\,t} = \eta \times \frac{V_{H_2\,u\,t} \times \Delta G}{t} \end{cases} \tag{11}$$

In the formula, $\mathrm{V}_{\mathrm{H_2u\ t}}$ is the amount of hydrogen used in the hydrogen fuel cell; η is the efficiency of the fuel cell; ΔG is the Gibbs free energy of hydrogen in the fuel cell.

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4. Solution of the model

Figure 2 shows the model solution process. This paper uses the load conditions and wind and photovoltaic potential in California as the input data of the model, and combines the mathematical model proposed in Section 3 to solve the calculation in MATLAB. The energy waste under the two system models and the use of the hydrogen energy storage system in the optimization system are analyzed.

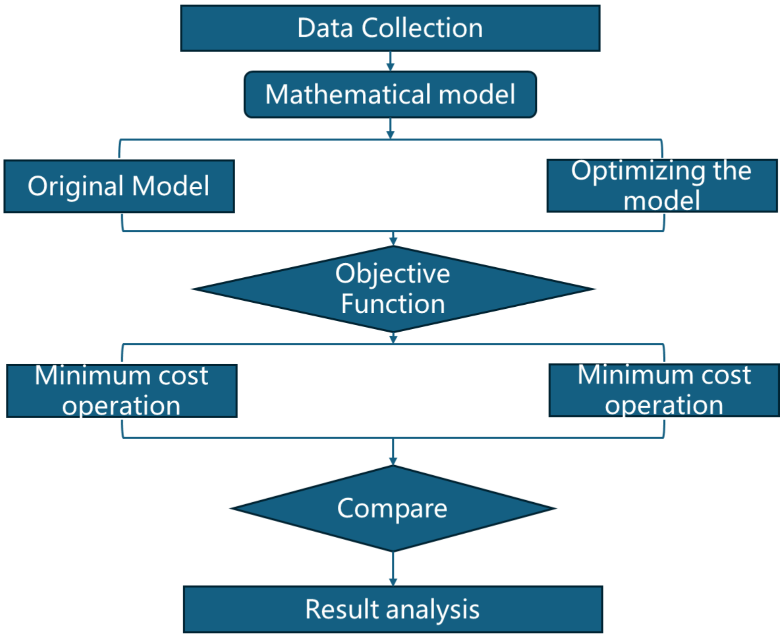

Figure 2. Model solving process

Figure 3 shows the load demand in California in 2019. The U.S. Energy Information Administration (EIA) provided the data [22]. The figure shows the load power of the region every hour. From the fitting curve, the peak load in the region occurs between May and September.

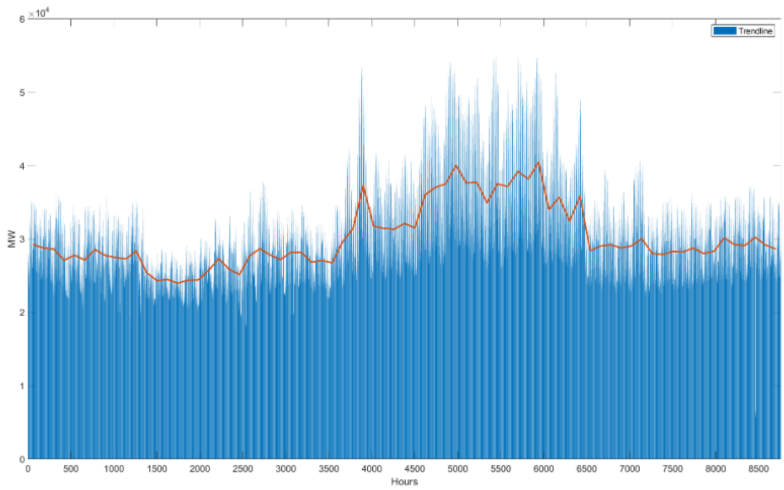

Figure 3. Load in California in 2019

Figure 4 shows the wind and photovoltaic potential in California. The data comes from Renewables, and the figure reflects the capacity factors of wind and photovoltaic power generation

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in the region every hour in 2019 [23]. The capacity factor can express the power generation potential at that time. From the fitting curve, it can be seen that the power generation potential of PV energy is relatively stable throughout the year, and is only lower at the beginning and end of the year. However, it can be seen from the bar chart that its potential is intermittent, that is, PV energy cannot generate electricity at night. The power generation potential of wind energy fluctuates greatly throughout the year, with two peaks at the beginning of the year and one peak at the end of the year. The wind energy potential is lower from May to August.

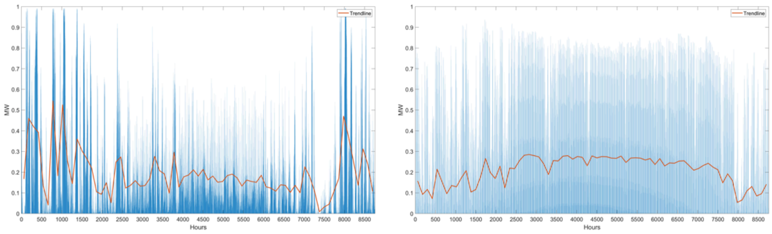

Figure 4. Annual potential of wind power and photovoltaic power generation (a) Wind power (b) Photovoltaic power

On the other hand, to ensure the economy of the system, cost data also needs to be input into the model, as shown in the following table:

Table 1. Cost of each part of the system

Name	Cost ($ per MW)
Wind power	70[24]
Photovoltaic power	247[24]
Electrolytic Cell	60
Hydrogen storage	400($ per tone)
Fuel cells	70

This data can be fed into the MATLAB code that solves the problem, which is shown in the Appendix.

5. Results analysis

5.1. Energy waste

According to data from EIA, the average hourly power of the California region in 2019 was 30,000 MW. In this section, the output of thermal power generation is set to 25,000 MW to meet five-sixths of the average load power demand, and the various parameters of the system with and without hydrogen energy storage are observed. Figure 5 shows the energy waste of the two systems, and Figure 6 shows the storage of hydrogen:

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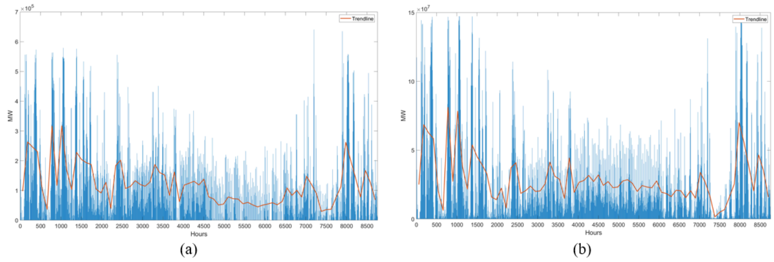

Figure 5. System energy waste (a) optimized system (b) original system

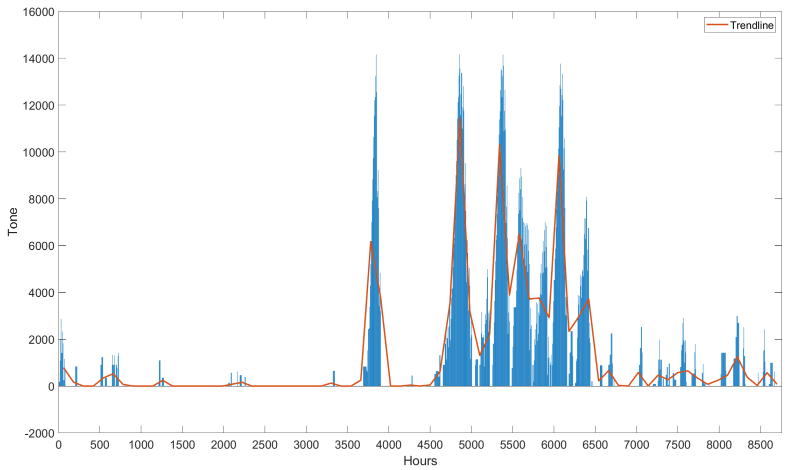

Figure 6. Hydrogen storage situation

The figure shows that after the hydrogen energy storage technology was introduced, the system's energy waste has drastically decreased. Energy waste is mostly concentrated at the start and end of the year in both systems. From the storage of hydrogen, it can be seen that the energy storage system is concentrated in the time period from May to September. This is also the reason why energy waste is low during this period. Combined with the data in Section 4, due to the high potential of wind power generation at the beginning and end of the year, the high output of the power generation system can meet the load demand. Additionally, the cost of storing hydrogen is considerable, therefore under the conditions of the economic objective function, the system will not decide to store hydrogen for an extended period of time during a period of high production capacity. The energy storage system begins to function during the mid-year period of May through September, when the overall load demand rises and peaks. During this period, the energy storage system will choose to store hydrogen at a time when the load demand is relatively low and the potential of wind and photovoltaic power generation is high, and use fuel cell power generation to compensate for the power demand of the grid at the load peak. Table 2 shows the cost and power station scale of the two systems.

Table 2. System parameter comparison

	PV	Wind	Cost
Original system	1.7652e+05MW	2.48e+07MW	1.7804e+09$
Optimize the system	3.3237e+04MW	9.7187e+04MW	2.9416e+07$

DOI: 10.54254/2755-2721/2025.29781

The optimized system is better than the original system both in terms of installed capacity of photovoltaic and wind energy and the total cost of the system. When the energy storage system is added to the system, the excess energy is utilized, so even if the installed capacity of wind and photovoltaic energy is reduced, the peak demand of the load can be met. On the other hand, the electricity and hydrogen required for the operation of the energy storage system are generated internally by the system without paying additional costs, which is much lower than the cost of building more wind power plants and photovoltaic power plants. Therefore, it is also a more economical way to use hydrogen energy storage systems to reduce the mismatch between production capacity and demand to meet load demand. In general, energy storage systems help improve the efficiency of wind and photovoltaic power generation and reduce the total cost of the system.

5.2. Different thermal power load conditions

In the previous section, this article compared the performance changes of the entire power system after the introduction of the hydrogen energy storage system and concluded that the utilization efficiency of sustainable energy such as PV and wind energy can be increased. This part will alter the model's thermal power production output power and examine the effects on the system in order to better investigate the rules. This section analyzes the performance changes of the system when the thermal power output is reduced from 25000MW to 15000MW in steps of 1000MW. Figure 7 shows the energy waste of the system under different thermal output conditions, and Figure 8 shows the storage of hydrogen:

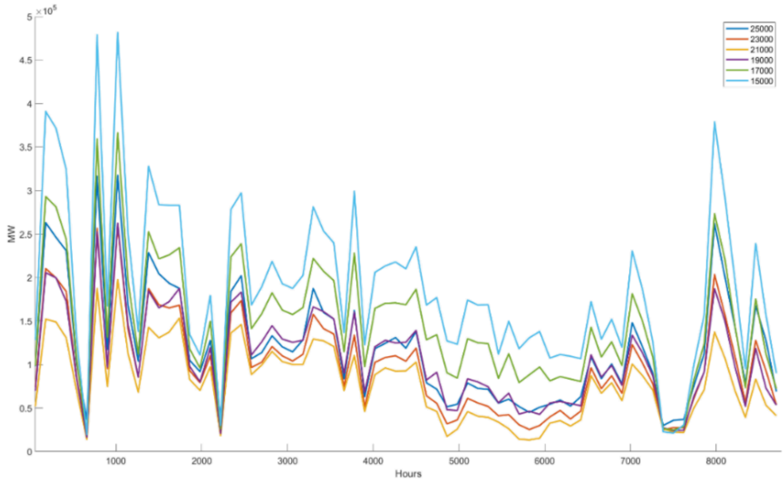

Figure 7. Energy waste at different power outputs of thermal power generation

DOI: 10.54254/2755-2721/2025.29781

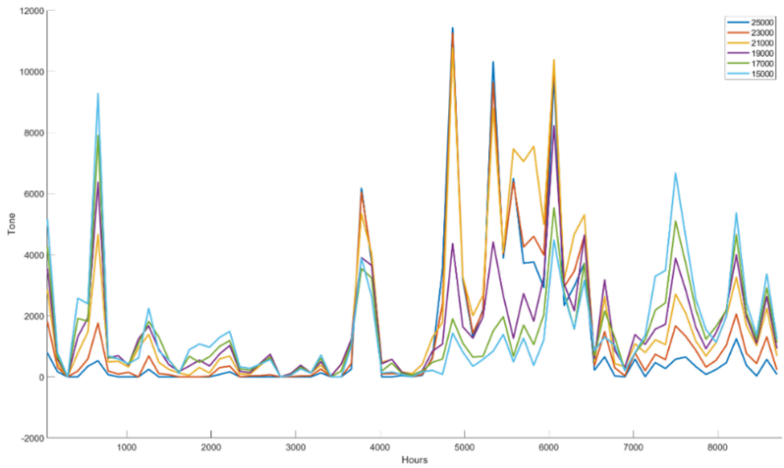

Figure 8. Hydrogen storage at different power outputs of thermal power generation

From the above two figures, it can be seen that when the thermal output is high, the energy waste of the system is relatively low. This is because the thermal load meets most of the load requirements of the system. The installed capacity of sustainable energy is relatively small, so the impact of energy waste caused by its volatility is relatively small. However, as the thermal output decreases, the energy waste of the system does not gradually increase but first decreases and then increases. This shows that when the scale of sustainable energy is expanded, the utilization rate of the hydrogen energy storage system is improved, and the energy waste problem is effectively alleviated. It can also be seen from Figure 8 that the storage capacity of hydrogen is increasing. However, when the thermal load is lower than 21000MW, energy waste begins to increase. At this time, the load demand borne by sustainable energy is too large and the storage cost of hydrogen is also high. In this case, as shown in Figure 8, not too much excess energy will be converted into hydrogen for storage. The utilization rate of the hydrogen energy storage system also decreases. Therefore, under the economic objective function, the regulation of energy utilization by hydrogen energy storage is limited, and when the thermal load is too low, the effect is not ideal.

6. Conclusion

This paper aims to solve the problem of fluctuation of sustainable energy such as wind power and photovoltaic power generation, and establishes a wind-PV-fired-hydrogen energy storage combined power grid system. The mathematical model is established based on the load, photovoltaic and wind power generation potential in California, USA. The following conclusions are drawn from the research and analysis:

1) After the hydrogen energy storage system is added to the power grid system, its main working range is concentrated in the high-load period. Overall performance may lower system costs and increase wind and PV power generation's utilization efficiency. However, given the conditions of the economic objective function, the system will not decide to store hydrogen for an extended period of time owing to the significant expense of doing so. Therefore, during the peak period of the power generation system's production capacity, the energy storage system's operating frequency is low and energy waste is also more serious.

2) When the thermal load is above a certain ratio, as the thermal output decreases, the utilization rate of the hydrogen energy storage system increases, and the energy utilization efficiency increases. However, when the thermal load is lower than a certain value, due to the operation under the

DOI: 10.54254/2755-2721/2025.29781

economic objective function and the need for sustainable energy to meet a large amount of load demand, the utilization rate of the hydrogen energy storage system will decrease, and the energy utilization efficiency of the system will also decrease accordingly.

Acknowledgement

Bowen Lyu, Zhengxi Li , Zixi Zhu , YangZheQi Li , Chengxuan Li contributed equally to this work and should be considered co-first authors.

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Appendix

Original system:

```
clc
clear all
%% Overall supply and demand
% Get hourly wind data, which is capacity factor
OriginalWindPowerData = readmatrix("WindPowerData8760h.xlsx");
OriginalnPeriods = size(OriginalWindPowerData,1);
OriginalPVData = readmatrix("PVPowerData8760h.xlsx");
OriginalPowerDemandData = readmatrix("PowerDemandData8760h.xlsx");
nPeriods = 1460; % number of hours

WindPowerData = zeros(1, nPeriods);
PVData = zeros(1, nPeriods);
PowerDemandData = zeros(1, nPeriods);

for i=1:nPeriods
 WindPowerData(i) = sum(OriginalWindPowerData(((i-1)*6+1):(i*6)));
 PVData(i) = sum(OriginalPVData(((i-1)*6+1):(i*6)));
 PowerDemandData(i) = sum(OriginalPowerDemandData(((i-1)*6+1):(i*6)));
end

% Plot the wind power data
figure; % Create a new figure for Wind Power Data
bar(WindPowerData, 0.5)
xlim([1, nPeriods])
xlabel('Hour')
ylabel('Capacity Factor')
title('Hourly Wind Power Capacity Factor')

% Plot the PV power data
figure; % Create a new figure for PV Data
bar(PVData, 0.5)
xlim([1, nPeriods])
xlabel('Hour')
ylabel('Capacity Factor')
title('Hourly PV Power Capacity Factor')

figure
bar(PowerDemandData,.5)
xlim([1,nPeriods])
xlabel('PowerDemandData: MW')
```

```
%% parameters
%economics
AnnualisedCAPEXWind = 70; %million $ per MW
AnnualisedCAPEXPV = 247; %million $ per MW

ThermalPowerInput = 25000; %MW, this level is to be adjusted to see its impact

%% Decision variables

%capacities of technical components
CapacityWindPower = optimvar('CapacityWindPower','LowerBound',0);
CapacityPVPower = optimvar('CapacityPVPower','LowerBound',0);
RenewablePoweroutput = optimvar('RenewablePoweroutput',nPeriods,'LowerBound',0);
WastedPower = optimvar('WastedPower',nPeriods,'LowerBound',0);

%% Linear Constraints
%wind power balance
Renewablepowersupplycons = RenewablePoweroutput(:) == WindPowerData(:)*CapacityWindPower+PVData(:)*CapacityPVPower;
Overallpowerbalancecons = RenewablePoweroutput(:) + ThermalPowerInput*6 == PowerDemandData(:) + WastedPower(:);

TotalCost =AnnualisedCAPEXPV *CapacityPVPower + AnnualisedCAPEXWind *CapacityWindPower ;

H2SystemOpt = optimproblem('ObjectiveSense','minimize');
H2SystemOpt.Objective = TotalCost;  %成本最小优化
H2SystemOpt.Constraints.Renewablepowersupplycons = Renewablepowersupplycons;
H2SystemOpt.Constraints.Overallpowerbalancecons = Overallpowerbalancecons;

% To save space, suppress iterative display.

options = optimoptions('linprog','Display','iter');
```

```
%%
% Solve the problem.

[H2SystemOptsol,fval,exitflag,output] = solve(H2SystemOpt,'options',options);
%% Examine the Solution

total_cost = fval
CapacityWindPower = H2SystemOptsol.CapacityWindPower
CapacityPVPower = H2SystemOptsol.CapacityPVPower


% Plot the solution as a function of time.



figure
bar(H2SystemOptsol.WastedPower,.5,'g')
ylabel('MW')
title('WastedPower','FontWeight','bold')
```

Optimize the system:

DOI: 10.54254/2755-2721/2025.29781

```matlab
%% Optimal Design of a H2 Supply System: Problem-Based
clc
clear all
%% Overall supply and demand
% Get hourly wind data, which is capacity factor
OriginalWindPowerData = readmatrix("WindPowerData8760h.xlsx");
OriginalnPeriods = size(OriginalWindPowerData,1);
OriginalPVData = readmatrix("PVPowerData8760h.xlsx");
OriginalPowerDemandData = readmatrix("PowerDemandData8760h.xlsx");

nPeriods = 1460; % number of hours

WindPowerData = zeros(1, nPeriods);
PVData = zeros(1, nPeriods);
PowerDemandData = zeros(1, nPeriods);

for i=1:nPeriods
 WindPowerData(i) = mean(OriginalWindPowerData(((i-1)*6+1):(i*6)));
 PVData(i) = mean(OriginalPVData(((i-1)*6+1):(i*6)));
 PowerDemandData(i) = sum(OriginalPowerDemandData(((i-1)*6+1):(i*6)));
end

% Plot the wind power data
figure; % Create a new figure for Wind Power Data
%bar(WindPowerData, 0.5)
xlim([1, nPeriods])
xlabel('Hour')
ylabel('Capacity Factor')
title('Hourly Wind Power Capacity Factor')

% Plot the PV power data
figure; % Create a new figure for PV Data
%bar(PVData, 0.5)
xlim([1, nPeriods])
xlabel('Hour')
ylabel('Capacity Factor')
title('Hourly PV Power Capacity Factor')

figure
%bar(PowerDemandData,.5)
xlim([1,nPeriods])
xlabel('PowerDemandData: MW')
title('Hourly Power Demand')
```

```matlab
%% parameters
%economics
AnnualisedCAPEXWind = 70; %million $ per MW
AnnualisedCAPEXPV = 247; %million $ per MW
AnnualisedCAPEXEly = 60; %million $ per MW
AnnualisedCAPEXH2Storage = 380; %million $ per tonne
AnnualisedCAPEXSOFC = 70; %million $ per MW


%technical
EfficiencyEly = 0.75; %on the LHV basis
H2LHV = 120; %MJ/kg
H2CompressionEnergy = 0.1; %MJ/kg, not used in this sample code
EfficiencySOFC = 0.6; %on the LHV basis
ThermalPowerInput =15000; %MW, this level is to be adjusted to see its impact
%% Decision variables

%capacities of technical components
CapacityWindPower = optimvar('CapacityWindPower','LowerBound',0);
CapacityPVPower = optimvar('CapacityPVPower','LowerBound',0);
CapacityElectrolyser = optimvar('CapacityElectrolyser','LowerBound',0);
CapacitySOFC = optimvar('CapacitySOFC','LowerBound',0);

CapacityH2StorageValley = optimvar('CapacityH2StorageValley','upperBound',0);
CapacityH2StoragePeak = optimvar('CapacityH2StoragePeak','LowerBound',0);
%Enery flows
RenewablePoweroutput = optimvar('RenewablePoweroutput',nPeriods,'LowerBound',0);
WastedPower = optimvar('WastedPower',nPeriods,'LowerBound',0);
PowerInputToElectrolyser = optimvar('PowerInputToElectrolyser',nPeriods,'LowerBound',0);
PowerOutputFromSOFC = optimvar('PowerOutputFromSOFC',nPeriods,'LowerBound',0);
H2StorageLevel = optimvar('H2StorageLevel',nPeriods,'LowerBound',0);
```

```matlab
%% Linear Constraints
%wind power balance
Renewablepowersupplycons = RenewablePoweroutput(:) == WindPowerData(:)*CapacityWindPower*6+PVData(:)*CapacityPVPower*6;
Overallpowerbalancecons = RenewablePoweroutput(:) - PowerInputToElectrolyser(:) + PowerOutputFromSOFC(:) + ThermalPowerInput*6 == PowerDemandData(:) + WastedPower(:);
%H2 balance
H2OutputFromElectrolyser = PowerInputToElectrolyser.*EfficiencyEly/H2LHV*3600/1000;
H2InputToSOFC = PowerOutputFromSOFC./EfficiencySOFC/H2LHV*3600/1000;

TotalH2ProductionOverOptimisationPeriod = sum(H2OutputFromElectrolyser);
TotalH2DemandOverOptimisationPeriod = sum(H2InputToSOFC);
H2balancecons = TotalH2ProductionOverOptimisationPeriod - TotalH2DemandOverOptimisationPeriod >= 0;
%Capacity constraints
electrolyserconsts = PowerInputToElectrolyser(:) <= CapacityElectrolyser;
SOFCconsts = PowerOutputFromSOFC(:) <= CapacitySOFC;
H2StockLevel = optimexpr(nPeriods,1);

for i = 1:nPeriods
   H2StockLevel(i) = sum(H2OutputFromElectrolyser(1:i)) - sum(H2InputToSOFC(1:i));
end
H2storagecapacitycons1 = H2StockLevel(:) >= CapacityH2StorageValley;
H2storagecapacitycons2 = H2StockLevel(:) <= CapacityH2StoragePeak;
%% The following two constraints are for allowing the computed H2 stock or storage levels to be reported by a decision variable
%% Not essential for the optimisation logic
H2storagecapacitycons3 = H2StockLevel(:) <= H2StorageLevel(:);
H2storagecapacitycons4 = H2StockLevel(:) >= H2StorageLevel(:);

%% Define Objective
CapacityH2Storage = CapacityH2StoragePeak - CapacityH2StorageValley;
TotalCost =AnnualisedCAPEXPV *CapacityPVPower + AnnualisedCAPEXWind *CapacityWindPower + AnnualisedCAPEXH2Storage*CapacityH2Storage...
+ AnnualisedCAPEXEly*CapacityElectrolyser + AnnualisedCAPEXSOFC*CapacitySOFC;

%% Solve the Problem
% Create an optimization problem and include the objective and constraints.
H2SystemOpt = optimproblem('ObjectiveSense','minimize');
H2SystemOpt.Objective = TotalCost;
H2SystemOpt.Constraints.Renewablepowersupplycons = Renewablepowersupplycons;
H2SystemOpt.Constraints.Overallpowerbalancecons = Overallpowerbalancecons;
H2SystemOpt.Constraints.H2balancecons = H2balancecons;
H2SystemOpt.Constraints.electrolyserconsts = electrolyserconsts;
H2SystemOpt.Constraints.SOFCconsts = SOFCconsts;
H2SystemOpt.Constraints.H2storagecapacitycons1 = H2storagecapacitycons1;
H2SystemOpt.Constraints.H2storagecapacitycons2 = H2storagecapacitycons2;
H2SystemOpt.Constraints.H2storagecapacitycons3 = H2storagecapacitycons3;
H2SystemOpt.Constraints.H2storagecapacitycons4 = H2storagecapacitycons4;
```

```matlab
%%
% To save space, suppress iterative display.

options = optimoptions('linprog','Display','iter');
%%
% Solve the problem.

[H2SystemOptsol,fval,exitflag,output] = solve(H2SystemOpt,'options',options);
%% Examine the Solution

total_cost = fval;
CapacityWindPower = H2SystemOptsol.CapacityWindPower;
CapacityPVPower = H2SystemOptsol.CapacityPVPower;
CapacityElectrolyser = H2SystemOptsol.CapacityElectrolyser;
CapacitySOFC = H2SystemOptsol.CapacitySOFC;

CapacityH2StorageValley = H2SystemOptsol.CapacityH2StorageValley;
CapacityH2StoragePeak = H2SystemOptsol.CapacityH2StoragePeak;
capacityH2StorageTank = H2SystemOptsol.CapacityH2StoragePeak - H2SystemOptsol.CapacityH2StorageValley;


% Plot the solution as a function of time.

figure
%bar(H2SystemOptsol.PowerInputToElectrolyser,.5,'g')
ylabel('MW')
title('PowerInputElectrolyser','FontWeight','bold')

figure
%bar(H2SystemOptsol.PowerOutputFromSOFC,.5,'g')
ylabel('MW')
title('PowerOutputFromSOFC','FontWeight','bold')


figure
bar(H2SystemOptsol.H2StorageLevel,.5,'g')
ylabel('T')
title('H2StorageLevel','FontWeight','bold')

figure
bar(H2SystemOptsol.WastedPower,.5,'g')
ylabel('MW')
title('WastedPower','FontWeight','bold')
```