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Operation Planning of Off-grid Wind Solar Hydrogen Ammonia System Considering Abandonment Rate and Ammonia Load Stability

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Abstract

As an effective way of large-scale consumption of renewable energy for power generation, off grid hydrogen production and ammonia synthesis systems face multiple challenges in terms of stability and economic operation. The key is how to reasonably allocate the number of electrolytic cells and ammonia load to ensure stable operation of the system throughout the year. In response to these technical difficulties, this article constructs an 8760 hours renewable energy electric hydrogen synthesis ammonia production simulation model that comprehensively considers the abandonment rate and load stability. A reasonable operation planning method for the number of electrolytic cell startups and ammonia load has been proposed. On the premise of ensuring compliance with system constraints, the model can dynamically adjust the number of start-up units, optimize ammonia load, and achieve efficient utilization of wind and solar resources. To verify the actual effectiveness of this method, this article selects a specific case study from Da'an District, Jilin Province for analysis. The results indicate that the planning method proposed in this article not only successfully simulated the production process of ammonia through electric hydrogen synthesis based on 8760 hours of off grid renewable energy, but also significantly improved the rationality of the off-grid system.

Keywords: Renewable energy; Off-grid system; Electric hydrogen production; Synthetic ammonia

Introduction

Ammonia is a basic chemical product with wide applications in the industrial field [1]. At present, the synthetic ammonia industry mainly adopts the grey hydrogen synthetic ammonia technology, which not only consumes a large amount of fossil fuels, but also causes significant pressure on the environment with huge carbon emissions. In this context, utilizing renewable energy to produce hydrogen and synthesize ammonia is an important research direction for the green transformation of the synthetic ammonia industry, as its carbon emissions are almost zero and it can promote the effective utilization of renewable energy.

In order to address the above challenges, large-scale renewable energy electrolysis technology for hydrogen production and ammonia production has emerged. This innovative solution not only significantly improves the comprehensive utilization efficiency of renewable energy, but also fundamentally solves the problem of a large amount of carbon emissions in the synthetic ammonia industry [2]. At present, most of the renewable energy electric hydrogen synthesis ammonia systems that have been put into use in China are grid-connected systems. However, with the increasing proportion of renewable energy in the power system, the problem of grid-connected consumption has gradually become prominent, which limits the full utilization of renewable energy power generation. In view of the challenges faced by the grid-connected hydrogen and ammonia synthesis system, the off-grid system, because it does not depend on the external power grid, directly supplies power to the hydrogen and ammonia synthesis devices through the self-built wind and solar power generation facilities, and realizes self-sufficiency from energy production to chemical synthesis. It has become an important research direction for the long-term development of green ammonia transformation [3-4].

However, due to the significant fluctuations and intermittency of wind and solar resources in actual production, the power balance and material balance of off grid wind solar hydrogen synthesis ammonia systems are often difficult to ensure [5]. In terms of power balance, wind and solar power generation is affected by various factors such as weather, season, and geographical location, resulting in significant fluctuations in the power output of the system, making it difficult to match the stable power supply required for the synthesis of ammonia. This mismatch may not only lead to a decrease in production efficiency, but also cause damage to equipment and increase maintenance costs. In terms of material balance, the synthesis of ammonia is a complex chemical reaction process that requires precise raw material ratios and stable reaction conditions. However, due to unstable energy supply, the system may not be able to continuously provide sufficient hydrogen and nitrogen, or may produce excessive hydrogen during certain periods, which not only affects the efficiency of ammonia synthesis, but also may cause resource waste and environmental pollution.

Many scholars have conducted a series of studies on this issue. Reference [6] proposed an intelligent coordinated hydrogen production intelligent algorithm for electrolytic cell distribution and energy storage 24 hours before the day, but did not consider the impact of changes in hydrogen load characteristics on hydrogen production and storage in specific scenarios. References [7-8] established a two-stage 24-hour production simulation model including electrolytic water hydrogen production and hydrogen ammonia synthesis and an eco-nomic analysis model of off-grid electro-hydrogen ammonia system, which verified the feasibility and economy of converting renewable energy into hydrogen energy consumption and hydrogen to ammonia under off-grid conditions. However, 24 hours a day cannot accurately reflect the annual production simulation characteristics. Reference [9] verified that the off-grid wind and solar hydrogen storage system planning method can realize the equipment capacity planning based on 8760 hours of production simulation. Compared with the typical day and typical scene planning method, it can reduce the system cost and achieve lower unit hydrogen production cost. However, this article lacks research on the impact of the number of electrolytic cell startups on system stability. Reference [11] studied the capacity configuration optimization and scheduling analysis of the wind solar synthetic ammonia system, and provided the material balance relationship for hydrogen synthesis of ammonia, but did not consider how to effectively store the synthesized ammonia. Combined with the above researches, this paper mainly studies the following contents:

1. Analyze the composition and operation mode of off grid renewable energy hydrogen ammonia synthesis system, and establish comprehensive mathematical models for various equipment including wind power generation, photovoltaic power generation, electrolytic water hydrogen production, synthetic ammonia, hydrogen storage, energy storage, etc.
2. Propose an operation planning method that considers real-time power balance and material balance in production simulation, and adjusts the load of synthetic ammonia in real time to improve the stability of off grid wind solar hydrogen synthesis ammonia system operation.
3. Under the constraints of system operation, combined with the proposed operation planning method, 8760 hours of simulated production operation results were obtained throughout the year.

Materials and Methods

Mathematical model of off grid wind solar hydrogen synthesis ammonia system

Mathematical model of wind power station

The power output expression of the wind power generation system is calculated based on wind speed [12-14] data as follows:

The output power P_{wt} can be calculated by the following formula [15-17]:

$$P_{wt}=\begin{cases}0, v<v_{ci}\\ \dfrac{P_{wt,r}}{v_r^3-v_{ci}^3}v^3-\dfrac{v_{ci}^3}{v_r^3-v_{ci}^3}P_{wt,r}, v_{ci}\le v<v_r\\ P_{wt,r}=\dfrac{1}{2}\rho AC_p v_r^3\eta_1\eta_2, v_r\le v<v_{co}\\ 0, v>v_{co}\end{cases} \tag{1}$$

Among them, v is Regional real-time wind speed; v_{ci} is cut-in wind speed; v_{co} is cut-out wind speed; v_r is rated wind speed; $P_{wt,r}$ is Wind turbine rated power; η_1 and η_2 are mechanical transmission efficiency and power conversion efficiency respectively; ρ A and C_p are air density, wind wheel area and wind energy utilization coefficient respectively.

Mathematical model of photovoltaic power station

The photovoltaic power generation is affected by temperature and solar radiation intensity [18-20], and its output power expression is as follows :

The output power P_{pv} can be calculated by the following formula [21]:

$$P_{\mathrm{pv}}=\begin{cases}\dfrac{P_{sn}I_t^2}{I_{std}R_c}[1-\partial_T(T_C-T_{stc})], 0\le I_t<R_{\mathrm{c}}\\ \dfrac{P_{sn}I_t}{I_{std}}[1-\partial_T(T_C-T_{stc})], R_c\le I_t\end{cases} \tag{2}$$

Among them, P_{sn} is photovoltaic rated output efficiency; T_C is photovoltaic panel cell temperature; R_c is the intensity of the light intensity set by the specific intensity; I_{std} is light intensity per unit area; T_{stc} is battery temperature; It is the actual light intensity at time t.

Mathematical model of electrolytic cell

The alkaline electrolytic cell is the most critical equipment in the hydrogen production system. The alkaline electrolytic cell in operation can be regarded as a nonlinear DC load, and the output voltage model is [22]:

$$\begin{cases}U_{rev}=U_{r0}-K_{rev}(T_{el}-298.15)\\ U_{el}=U_{rev}+\dfrac{r_1+r_2T_{el}}{S_{el}}I_{el}+K_{el}\ln\left(\dfrac{K_{T1}+\dfrac{K_{T2}}{T_{el}}+\dfrac{K_{T3}}{T_{el}^2}}{S_{el}}I_{el}+1\right)\end{cases} \tag{3}$$

Among them, U_{rev} is reversible voltage of electrolytic cell; S_{el} is electrolytic cell electrode surface area; I_{el} is electrolytic cell current; T_{el} is Electrolytic cell working temperature; K_{el} is electrode over-voltage coefficient; K_T is Overvoltage empirical coefficient of electrolytic cell; U_{r0} is reversible voltage at standard condition; K_{rev} is temperature empirical coefficient.

The relationship between single electrolytic cell power and hydrogen production is as follows:

$$P_{el,n} = U_{el} I_{el} \quad (4)$$

$$Q(t) = 0.1977 P_{el,n}(t) + 96.9987 \quad (5)$$

Among them, $P_{el,n}$ is output power of single electrolytic cell; $Q(t)$ is hydrogen production in t period.

Mathematical model of hydrogen ammonia synthesis

In order to maintain a certain ammonia production rate in the ammonia synthesis section, it is necessary to consume a constant amount of hydrogen, which is constrained by thermodynamic balance, catalyst activity, etc. Ammonia production rate should be maintained within a given range, the annual ammonia production rate per hour:

$$\begin{cases} F^{NH_3}(t) = F^{NH_3}(t-1) + r^{NH_3}(t)\Delta t \\ F^{H_2}(t) = F^{NH_3}(t) / C_{h2mA} \end{cases} \quad (6)$$

Among them, F^{NH_3} is Ammonia production per hour; r^{NH_3} is climbing rate of synthetic ammonia production; F^{H_2} is hydrogen production; C_{h2mA} is conversion rate of hydrogen to synthetic ammonia.

Mathematical model of gas storage equipment

In the wind and solar hydrogen production ammonia system, hydrogen and nitrogen are buffered by gas storage tanks. When the power of new energy power generation is large and the capacity of energy storage equipment to absorb new energy power is limited, the operating power of the hydrogen production station is increased, thereby increasing the production load of hydrogen. The excess hydrogen is stored in the gas storage tank for later use. Therefore, the buffering effect of hydrogen storage tank on syngas is mainly considered in the process flow.

$$n_s(t+1) = n_s(t) + \left(Q(t) - \frac{F^{NH3}(t)}{C_{h2ma}} \right), \forall t \in T \quad (7)$$

Among them, n_s is hydrogen storage in gas storage tank; $C_{hs,\max}$ and $C_{hs,\min}$ are upper and lower limits of gas storage tank capacity.

Mathematical model of energy storage device

$$E_{ess}(t) = \begin{cases} E_{ess}(t-1) - \eta_{cha} P_{ess}(t)\Delta t, P_{ess}(t) < 0 \\ E_{ess}(t-1) - \dfrac{P_{ess}(t)\Delta t}{\eta_{dis}}, P_{ess}(t) > 0 \end{cases} \quad (8)$$

Among them, E_{ess} is battery capacity in t period; P_{ess} is charging and discharging power; η_{cha} and η_{dis} are battery charge and discharge efficiency [23].

Operational constraints of off grid wind solar hydrogen synthesis ammonia system

During the operation of the wind-solar hydrogen production ammonia system, the safe and stable operation should be ensured. Therefore, the following constraints are used in the optimization process of the system:

Power balance constraint

The wind solar hydrogen synthesis ammonia system should maintain real-time power balance, and the power balance constraints are as follows:

$$\begin{cases} P_{new}(t)+P_{ess}(t)=P_{loss}(t)+P_{el}(t), \forall t \in T \\ P_{new}(t)=C_w P_{wt,n}(t)+C_s P_{pv,n}(t), \forall t \in T \end{cases} \quad (9)$$

Among them, P_{new} is renewable energy output; P_{loss} is abandoned power; C_w and C_s are installed capacity of wind power and photovoltaic power generation; $P_{wt,n}$ is single wind turbine power; $P_{pv,n}$ is single photovoltaic power generation.

Material balance constraint

The consumption of hydrogen and nitrogen in the process of synthesizing ammonia from hydrogen is scientifically proportional to the production of ammonia and synthetic ammonia (liquid ammonia). The material balance constraints are as follows:

$$\begin{cases} Q(t):F_{N2}(t):F_{gas}^{NH3}(t)=3:1:2 \\ F^{NH3}(t):Q(t)=1:2000 \end{cases} \quad (10)$$

Electrolytic cell operation constraints

The operating power of the alkaline electrolytic cell is guaranteed to be within the operating range, as shown in the following formula:

$$P_{el,\min} \le P_{el,n}(t) \le P_{el,\max} \quad (11)$$

Among them, $P_{el,\max}$ and $P_{el,\min}$ are Upper and lower limits of operating power of electrolytic cell.

Operational constraints of synthetic ammonia equipment

$$\begin{cases} F_{\min}^{NH_3} \le F^{NH_3}(t) \le F_{\max}^{NH_3} \\ r_{\min}^{NH_3} \le r^{NH_3}(t) \le r_{\max}^{NH_3} \end{cases} \quad (12)$$

Among them, $F_{\max}^{NH_3}$ and $F_{\min}^{NH_3}$ are upper and lower limits of synthetic ammonia production; $r_{\max}^{NH_3}$ and $r_{\min}^{NH_3}$ are upper and lower limit of climbing rate of synthetic ammonia production.

Energy storage state constraints

Ensure that the battery energy storage state SOC (the ratio of current battery reserves to rated reserves) is within the allowable capacity range:

$$\begin{cases} SOC(t)-SOC(t-1)=(\frac{\eta_{cha}P_{cha}(t)}{E_{ess}}-\frac{P_{dis}(t)}{E_{ess}\eta_{dis}})\Delta t \\ SOC_{\min} \le SOC(t) \le SOC_{\max} \end{cases} \quad (14)$$

Among them, P_{cha} is charging power; P_{dis} is discharge power; SOC is the proportion of remaining energy storage capacity to its total capacity; $SOC_{\max}$ and $SOC_{\min}$ are Upper and lower limits of the proportion of remaining energy storage capacity to its total capacity.

Abandonment rate constraint

In order to ensure the utilization rate of new energy power generation, the system is not allowed to abandon a large number of wind and light, as shown in the following formula:

$$\frac{\sum_{t=1}^{8760} P_{loss}(t)\Delta t}{\sum_{t=1}^{8760} P_{new}(t)\Delta t} \le \varepsilon \quad (15)$$

Planning method for wind solar hydrogen production operation

The operation planning method in this article first needs to calculate the maximum number of electrolytic cells that can make the system abandonment rate 0. Based on an annual planning cycle of 8760 hours, with wind and solar power generation and initial energy storage capacity as inputs. By coordinating the operation of electrolytic cells and energy storage planning, the energy storage charging and discharging and hydrogen production power are determined based on the new energy generation power and battery capacity status, and then the maximum number of electrolytic cells is calculated when the waste rate of the hydrogen ammonia system is 0.

The maximum number of electrolytic cell when the waste rate in the liquid ammonia system is 0 is calculated as follows:

Firstly, determine whether to carry out energy storage charging and discharging based on the size of wind power generation. If the output of wind and solar power generation is lower than the minimum operating power of the electrolytic cell during period t, and the energy storage discharge still cannot start the electrolytic cell, charge the energy storage equipment to store this part of the wind and solar power output; On the contrary, the energy storage device discharges, and the wind and energy storage supply power to the electrolytic cell. If the output of wind and solar energy in phase T is between the upper and lower limits of the operating power of the electrolytic cell, and the energy storage capacity has not reached the lower limit, the energy storage equipment will discharge, and wind and solar energy as well as energy storage will supply power to the electrolytic cell; On the contrary, wind and solar power output are supplied to the electrolytic cell. If the output of wind and solar energy in phase T is higher than the maximum operating power of the electrolytic cell, the energy storage capacity has not reached the lower limit, the energy storage equipment discharges, and wind and solar energy as well as energy storage supply power to the electrolytic cell; On the contrary, wind and solar power output are supplied to the electrolytic cell. By the above cycle judgment, the maximum number of starts of the electrolytic cell within 8760 hours can be obtained. The specific logic is shown in Figure 1.

The operation planning method for off grid wind solar hydrogen synthesis ammonia system is as follows:

Based on the maximum number of electrolytic cells obtained, n^{max}, with a planning method cycle of 8760 hours per year, the operation is carried out using the number of electrolytic cells, wind and solar power generation, and initial energy storage capacity as inputs. We compared the new energy production and rated power of n electrolytic cells in different periods. Determine the charging and discharging of energy storage based on the capacity status of the battery, calculate the number of electrolytic cells and waste power. Finally, the output system is equipped with corresponding waste rates and hydrogen production rates for different numbers of electrolytic cells.

If the wind and solar power output is less than the minimum operating power of the electrolytic cell during the t period and the energy storage discharge still cannot start the electrolytic cell, the energy storage equipment is charged to store this part of the wind and solar power output; on the contrary, it is judged whether the total power supply power of wind, solar and energy storage exceeds the load. If it exceeds, the energy storage discharge is controlled to make the wind, solar and energy storage power supply just meet the load demand. If it does not exceed, the energy storage discharges as much as possible to supply power to the electrolytic cell.

If the wind and solar power output is between the lower limit of the operating power of the electrolytic cell and the load during the t period, and the energy storage capacity has reached the lower limit, the wind and solar power output is used to supply power to the electrolytic cell; on the contrary, it is judged whether the total power supply power of wind, solar and energy storage exceeds the load. If it exceeds, the energy storage discharge is controlled to make the wind, solar and energy storage power supply just meet the load demand. If it does not exceed, the energy storage discharges as much as possible to supply power to the electrolytic cell.

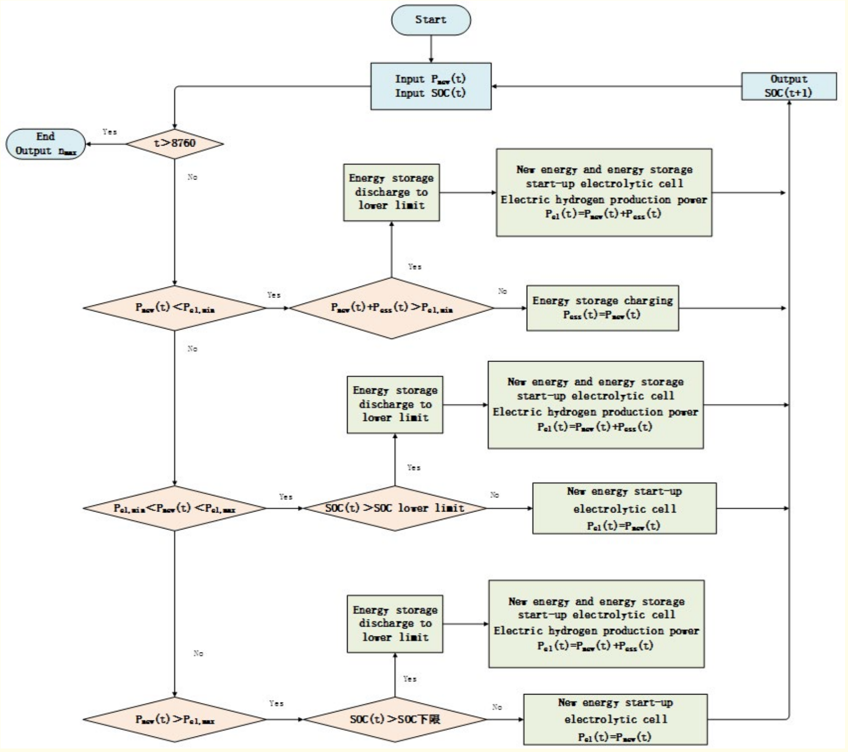

Figure 1: Calculation process for the maximum number of electrolytic cells under a zero abandonment rate.

If the wind-solar output exceeds the load and the energy storage capacity has reached the upper limit during the t period, the wind-solar output will supply power to the electrolytic cell, and the power generation when the wind-solar output exceeds the load will be abandoned. On the contrary, it is judged whether the remaining capacity of the energy storage can charge all the power generated by the wind and solar output exceeding the load. If it can, the energy storage device charges this part of the power. If it cannot, the energy storage will charge the power to the upper limit, and the remaining power will be abandoned. The specific logic is shown in Figure 2.

According to the actual ammonia synthesis process, the ammonia synthesis equipment is allowed to adjust the ammonia load every 24 hours and maintain the load unchanged within 24 hours. The ammonia load planning method for off grid hydrogen synthesis ammonia system is as follows:

Taking the output of new energy and the charging and discharging power of energy storage every 24 hours as inputs, determine the hydrogen supply power within every 24 hours, and sum up the hydrogen supply power. Then calculate the average hydrogen consumption and average ammonia load for each time period as the predicted values for ammonia load regulation. The specific logic is shown in Figure 3.

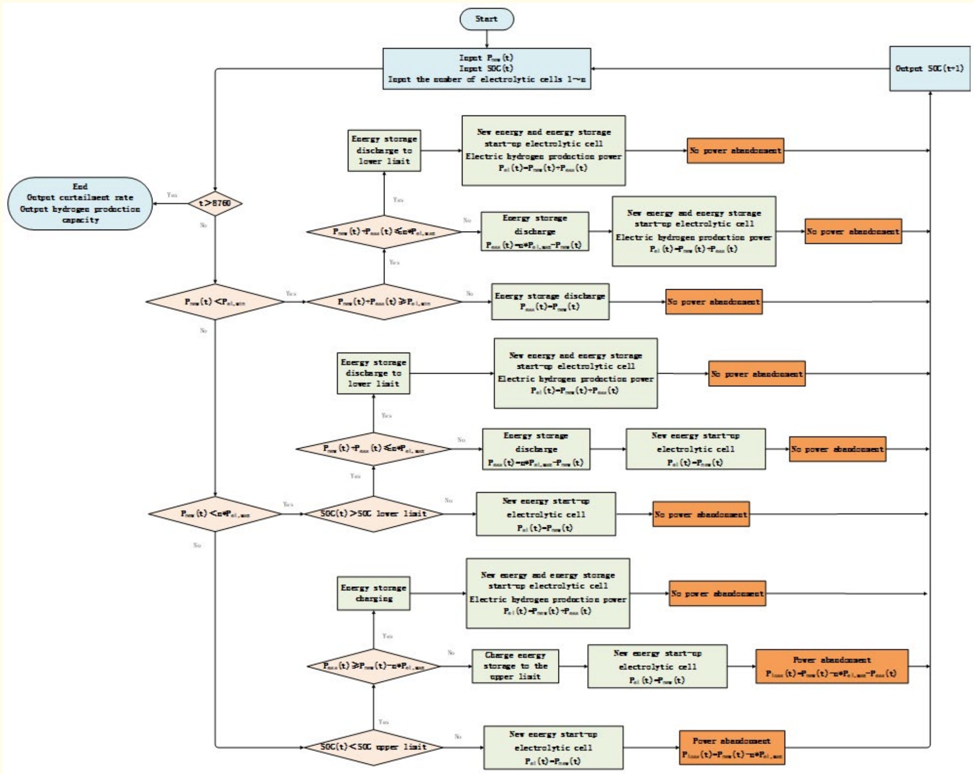

Figure 2: Operation planning method for off grid wind solar hydrogen synthesis ammonia system.

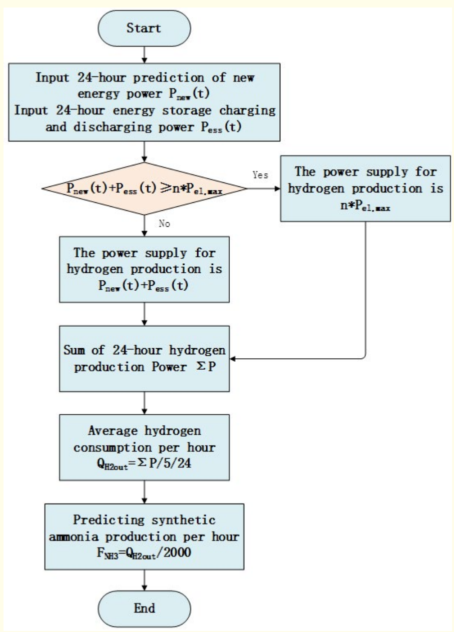

Figure 3: Planning method for synthetic ammonia load.

Results and Discussion

Input parameter settings

This section takes the Da ‘an area of Baicheng City, Jilin Province as an example. Based on the historical wind speed and light data of the area, the power generation of wind and solar energy is calculated. Considering the local wind resources and investment costs, the total scale of wind turbines is 70 MW, and the total scale of solar cell arrays is 70 MW, as an example of planning and operation.

According to the system’s operational constraints, set the following operational parameters:

Parameter name	*Electrolytic cell*
Power Adjustment Range	[20%, 100%]
Electric-to-hydrogen ratio (kWh/Nm^3)	5.0
Climbing ability	100%/h
Unit cost (Yuan/Nm^3)	3000

Table 1: Electrolytic cell parameter data.

1. Gas storage tank parameter setting: For a single gas storage tank, the lower limit of gas storage capacity is set to 4000Nm ^{3} to ensure sufficient hydrogen storage capacity; The upper limit of gas storage capacity is set at 30000 Nm ^{3} to prevent safety hazards caused by excessive gas.
2. Parameter setting of energy storage device: The SOC of the energy storage battery is limited between 0.15 and 0.85, and the charging and discharging efficiency is set to 92% to ensure the safe operation of the battery. The specific parameters are shown in Table 2.

Parameter name	*Energy storage devices*
SOC Range	[15%, 85%]
Charge and Discharge Efficiency Initial SOC	92% 0.5
Maximum energy storage capacity	80
Unit cost (Yuan/Nm^3)	1500

Table 2: Energy storage devices parameter data.

3. Hydrogen ammonia synthesis unit: 1 ton of ammonia can be produced for every 2000 Nm^3 of hydrogen gas.
4. Power curtailment rate requirement: In order to improve energy utilization efficiency, the system’s power abandonment rate is required to be less than 5%, in order to maximize the consumption of wind and solar energy resources and reduce the waste of wind and solar energy.

In addition, other economic data are shown in Table 3.

Parameter name	*Unit costs*
Wind power (Yuan/kW)	4500
Solar power (Yuan/kW) Gas storage tanks(Yuan/ Nm^3)	4000 250
Ammonia(Yuan/Nm^3)	4000

Table 3: Other economic data.

Result analysis

The wind and solar power generation data in Da'an area calculated based on wind speed, lighting and other data are shown in Figure 4.

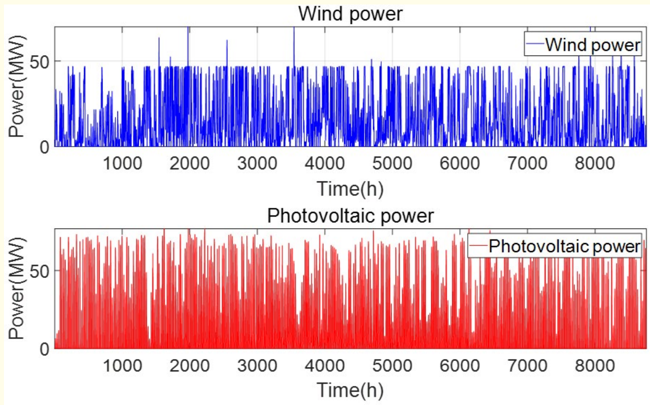

Figure 4: Data on wind and solar power generation in Da'an region.

Based on the above example data, Figure 5 shows the number of electrolytic cell startups calculated by the algorithm for finding the maximum number of electrolytic cells. During the 8760 hours planning period throughout the year, the maximum number of electrolytic cells that can be started is 25.

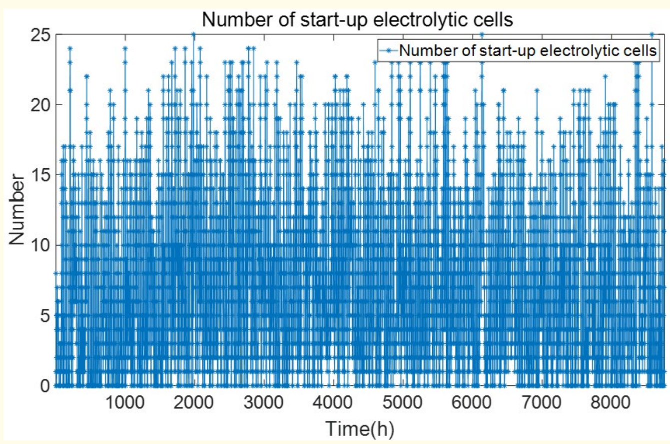

Figure 5: 8760 hours of electrolytic cell start-up quantity situation.

The abandonment rate and hydrogen production corresponding to the number of different electrolytic cells are shown in Figure.6 and 7. As the number of electrolytic cells increases, the abandonment rate of the system gradually decreases and the hydrogen production gradually increases.

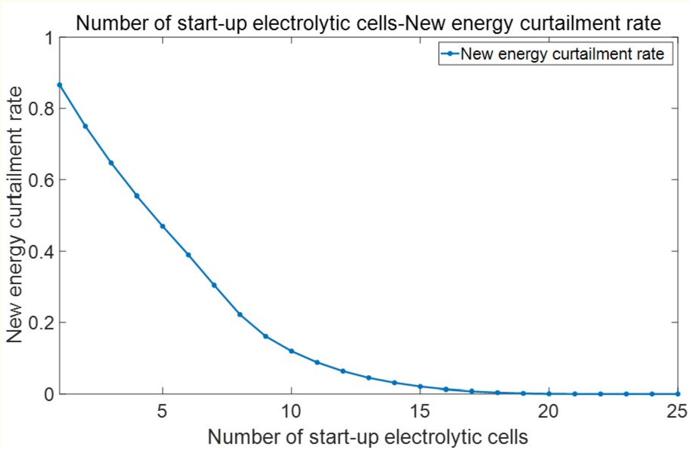

Figure 6: Power Abandonment Rate Corresponding to Different Numbers of Electrolytic Cells.

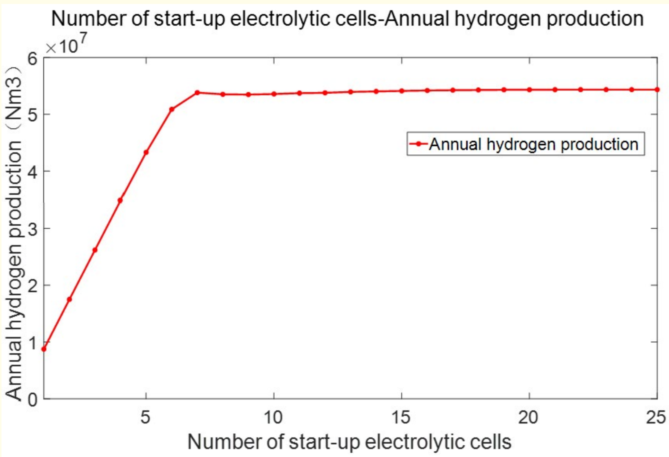

Figure 7: Different numbers of electrolytic cells correspond to hydrogen production.

In order to ensure the utilization efficiency of wind and solar resources, the next operation plan selects the number of electrolytic cells to be 25.

According to the actual ammonia synthesis process, the ammonia load of the ammonia plant is allowed to be adjusted every 24 h, and the load remains unchanged within 24 h. The daily ammonia load curve calculated by the ammonia load planning method is shown in Figure 8. The synthetic ammonia load is basically stable at 1.5 ~ 4.5 tons / hour. It can be seen that the synthetic ammonia load forecasting proposed in this paper can better adjust the load according to the change of daily energy output, so that the synthetic ammonia system can operate more stably.

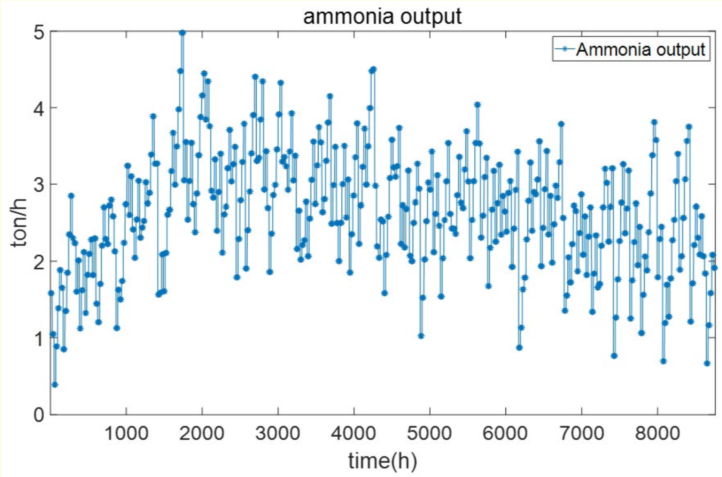

Figure 8: Daily adjustment of synthetic ammonia load.

The curve of hydrogen storage in gas storage tanks throughout the year is shown in Figure 9. The maximum hydrogen storage is about 126,000 cubic meters, and the minimum hydrogen storage is about 8,900 cubic meters.

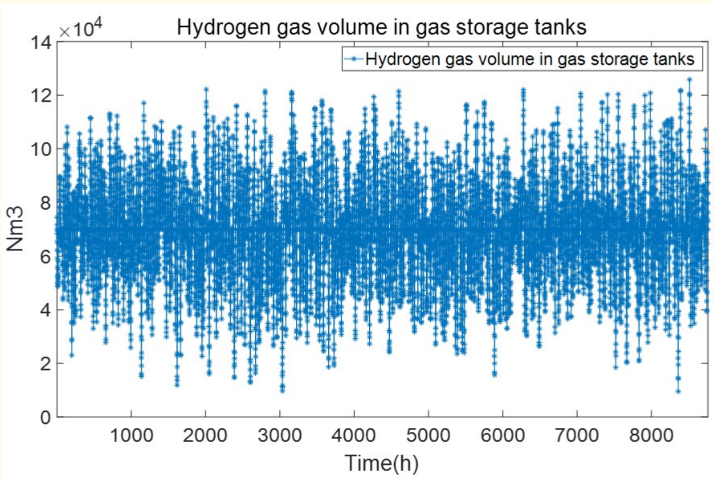

Figure 9: Hydrogen storage capacity of 8760 hours gas storage tank.

The change of energy storage SOC is shown in Figure 10. Energy storage is at the lower limit of SOC in most of the time. When there is less wind-solar power generation or too much wind-solar power generation, energy storage will store electric energy, which is consistent with the operation planning method.

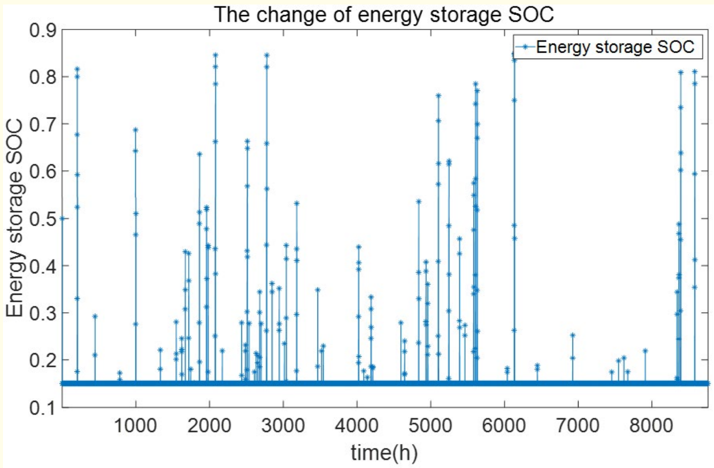

Figure 10: The change of energy storage SOC.

Conclusion

Off grid wind solar hydrogen ammonia system is an important way to achieve effective utilization of wind solar energy resources and alleviate the impact of wind solar power generation on the power grid, which is conducive to the efficient preparation of large-scale green hydrogen and green ammonia. This article comprehensively considers the power abandonment rate and ammonia load stability of the electric hydrogen ammonia system, and develops an off grid wind solar hydrogen synthesis ammonia system operation planning method, which is studied with a case study. The main research conclusions are as follows:

1. Through the collaborative operation method of electrolytic cell energy storage planning, the annual operation of the system with different numbers of electrolytic cells can be calculated, including the number of electrolytic cells started at various time periods throughout the year, the load of synthetic ammonia, the hydrogen storage capacity of the gas storage tank, and the change in energy storage SOC.
2. The use of synthetic ammonia load planning method can effectively maintain the stability of synthetic ammonia load, reduce the impact of load changes and fluctuations on the wind solar hydrogen production synthetic ammonia system, and enhance the dynamic operating characteristics of the system.

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