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POWER BALANCE MODEL FOR GRID-CONNECTED GREEN POWER-TO-HYDROGEN-TO-AMMONIA PARKS

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Abstract: Against the background of large-scale development of green hydrogen and ammonia industries, green power directly connected parks face prominent challenges in operational compliance and economic performance, due to the inherent conflict between renewable volatility and rigid industrial loads. Existing studies mostly rely on low-temporal-resolution models or focus on single optimization objectives, lacking a systematic framework that uncovers fine-grained power interaction mechanisms and quantifies the coupling of compliance and economy. To address this gap, this paper establishes a refined hourly power balance model that systematically integrates wind-photovoltaic output, conventional load, and rigid loads of electrolyzers and ammonia synthesis units. The core innovation lies in constructing a unified multi-dimensional quantitative framework that simultaneously realizes hourly power matching, green compliance assessment, and ammonia cost accounting, breaking the limitation of isolated single-objective research. Typical day calculation results show that the park's renewable generation reaches 603.45 MWh, exceeding the total electricity consumption of 558.72 MWh. However, significant time mismatch between renewable output and rigid load leads to 172.04 MWh grid purchase and 216.77 MWh surplus feed-in. In terms of compliance, the green power proportion meets standards, while self-consumption rate and feed-in ratio fail policy requirements, with ammonia production cost at 4,287.78 yuan per ton. The findings confirm time mismatch as the core bottleneck. The proposed model provides an effective algorithmic tool and reliable quantitative reference for the operation optimization and policy formulation of grid-connected green power-to-hydrogen-to-ammonia parks.

Keywords: Power balance model; Green power direct connection; Grid-connected operation; Power-to-hydrogen-to-ammonia

1 INTRODUCTION

The global energy transition and industrial deep decarbonization have accelerated the development of green hydrogen and ammonia industries. Green power directly connected parks, as key carriers of renewable energy consumption and low-carbon industrial transformation, have gained widespread attention for their integration of wind-photovoltaic generation, electrolysis, and ammonia synthesis processes [1–3]. These parks aim to achieve large-scale green hydrogen and ammonia production under grid-connected conditions. However, the inherent volatility of renewable output and the rigid nature of electrolyzer and ammonia synthesis loads result in significant temporal mismatches, leading to complex grid interactions, compliance risks, and economic pressures [4–5]. Existing research lacks refined modeling and systematic analysis of such conflicts, limiting operational guidance and policy formulation.

Current studies on green hydrogen-ammonia system optimization focus on macroscopic scheduling, economic assessment, or isolated energy coupling [6–7]. Most adopt daily or weekly time scales, failing to capture hourly temporal mismatch characteristics [8]. Furthermore, few works systematically incorporate green power compliance indicators into power balance analysis, neglecting the coupled impacts of temporal mismatch on compliance and economic performance [9–10]. A unified algorithmic framework integrating fine-grained simulation, compliance evaluation, and cost accounting remains insufficient.

This paper develops a refined hourly power balance model for grid-connected green power-to-hydrogen-to-ammonia parks. The main marginal contributions and innovations are as follows: First, a high-resolution hourly model is constructed to precisely quantify power interactions between volatile renewables and rigid industrial loads, revealing the core temporal mismatch mechanism. Second, green power compliance indicators are innovatively integrated into the power balance framework, enabling joint analysis of operational compliance and economic efficiency. Third, a comprehensive quantitative system is established, covering power matching, compliance judgment, and ammonia cost accounting. The proposed model exhibits strong practicality and scalability, providing reliable technical support and scientific reference for the layout optimization, operation regulation, and policy design of real-world green hydrogen-ammonia projects.

2 METHODOLOGY

2.1 Park Power Load Composition

A typical day is divided into hourly intervals $t=1,\ldots,24$, with a time step of $\Delta t=1\text{h}$. The electrolyzers and ammonia synthesis units operate continuously at full load daily, so the production load is jointly determined by the rated power of alkaline electrolyzers, PEM electrolyzers, and ammonia synthesis units. The conventional park load is determined by the peak power and the normalized hourly load curve. Let the peak conventional load be $P_{\mathrm{load}}^{\max}$, the normalized load at hour t be $\lambda_{L,t}$, and the rated power of alkaline electrolyzers, PEM electrolyzers, and ammonia synthesis units be P_{ALK}, P_{PEM}, and P_{NH3} respectively. Then the total park power load at hour t is:

$$P_{L,t}=P_{\mathrm{load}}^{\max}\lambda_{L,t}+P_{\mathrm{ALK}}+P_{\mathrm{PEM}}+P_{\mathrm{NH3}} \tag{1}$$

Equation (1) superimposes the rigid power demand of continuous production units with the intraday fluctuation of conventional load, forming the load-side constraint for subsequent power balance. As no power loss is considered in this problem, the load-side power can be directly matched with renewable output and grid interaction power.

Renewable Output Characterization: Let the installed capacity of wind power and photovoltaic power be $P_{\mathrm{W}}^{\max}$ and $P_{\mathrm{PV}}^{\max}$ respectively, with corresponding typical-day normalized output curves $\lambda_{\mathrm{W},t}$ and $\lambda_{\mathrm{PV},t}$. The output power of wind power, photovoltaic power, and total renewable energy are:

$$P_{W,t}=P_{\mathrm{W}}^{\max}\lambda_{W,t},P_{PV,t}=P_{\mathrm{PV}}^{\max}\lambda_{PV,t} \tag{2}$$

$$P_{R,t}=P_{W,t}+P_{PV,t} \tag{3}$$

Equations (2) and (3) reflect the combined effect of installed capacity and typical-day resource curves on the available power of renewable energy. This part of the output is prioritized to supply the park's electricity demand, with the deficit covered by grid interaction.

2.2 Power Balance and Grid Interaction Judgment

Under grid-connected operation, wind and photovoltaic power are prioritized to meet the park's electricity demand. When the renewable output is lower than the total load, the deficit is supplemented by grid power purchase; when the renewable output is higher than the total load, the surplus power is fed into the grid. Let the grid purchase power be $P_{B,t}$ and the grid feed-in power be $P_{S,t}$. Then the hourly grid interaction relationship is:

$$P_{B,t}=max\{0,P_{L,t}-P_{R,t}\},P_{S,t}=max\{0,P_{R,t}-P_{L,t}\} \tag{4}$$

Equation (4) uses the power difference as the judgment basis to separate the power deficit and surplus states in the same period. This relationship ensures the hourly supply-demand balance, and the daily grid purchase and feed-in electricity can be directly accumulated from the hourly power.

Daily-Scale Electricity Statistics: By integrating the hourly power, the park's typical-day total electricity consumption, renewable generation, grid purchase, and grid feed-in electricity can be obtained. Let the daily wind generation be E_{W}, daily photovoltaic generation be E_{PV}, total daily renewable generation be E_{R}, total daily park electricity consumption be E_{L}, and daily grid purchase and feed-in electricity be E_{B} and E_{S} respectively. Then:

$$E_W=\sum_{t=1}^{24}P_{W,t}\Delta t,E_{PV}=\sum_{t=1}^{24}P_{PV,t}\Delta t \tag{5}$$

$$E_R=\sum_{t=1}^{24}P_{R,t}\Delta t,E_L=\sum_{t=1}^{24}P_{L,t}\Delta t \tag{6}$$

$$E_B=\sum_{t=1}^{24}P_{B,t}\Delta t,E_S=\sum_{t=1}^{24}P_{S,t}\Delta t \tag{7}$$

The above electricity statistics are the basis for green power direct connection indicators and cost accounting. Due to the time mismatch between renewable output and load, even with high daily renewable generation, large grid purchase and feed-in electricity may occur simultaneously.

2.3 Green Power Direct Connection Indicator Judgment

Based on the given indicators for green power direct connection projects, three indicators are constructed: the proportion of on-site self-consumed renewable electricity to total available generation, the green power proportion in total electricity consumption, and the proportion of renewable feed-in electricity. Let these three indicators be η_1,η_2, and η_3 respectively:

$$\eta_1=\frac{E_L-E_S-E_B}{E_R}\times 100\% \tag{8}$$

$$\eta_2=\frac{E_L-E_B}{E_L}\times 100\% \tag{9}$$

$$\eta_3=\frac{E_S}{E_R}\times 100\% \tag{10}$$

The compliance of green power direct connection is determined by the threshold constraints:

$$\eta_1>60\%,\eta_2>30\%,\eta_3<20\% \tag{11}$$

Equations (8) to (11) convert daily operation results into policy indicator constraints. Among them, η_1 and η_3 directly reflect the distribution of renewable generation between local consumption and external transmission, while η_2 reflects the proportion of total park electricity consumption covered by local renewable energy.

Ammonia Production Cost Accounting: The typical-day total cost consists of wind power generation cost, photovoltaic power generation cost, grid purchase cost, surplus power feed-in revenue, and operation and maintenance (O&M) cost of electrolyzers and ammonia synthesis units. Let the unit generation cost of wind and photovoltaic power be c_W and c_{PV} respectively, the hourly grid purchase price be $c_{B,t}$, the grid feed-in price be c_S, and the unit O&M cost of the three production units be μ_{ALK}, μ_{PEM}, and μ_{NH3} respectively. The typical-day net cost is:

$$C_{\text{day}}=c_W E_W+c_{PV}E_{PV}+\sum_{t=1}^{24} c_{B,t}P_{B,t}\Delta t-c_S E_S+C_{\text{om}} \tag{12}$$

where the O&M cost of production units is calculated based on the full-load continuous operation power consumption:

$$C_{\text{om}}=1000\Delta t\sum_{t=1}^{24}\left(\mu_{\text{ALK}}P_{\text{ALK}}+\mu_{\text{PEM}}P_{\text{PEM}}+\mu_{\text{NH3}}P_{\text{NH3}}\right) \tag{13}$$

Let the typical-day ammonia production be M_{NH3}, then the ammonia production cost per ton is:

$$C_{\text{ton}}=\frac{C_{\text{day}}}{M_{\text{NH3}}} \tag{14}$$

Equations (12) to (14) link the power supply-demand status with economic results. The grid purchase cost reflects the external grid dependence when renewable generation is insufficient, the feed-in revenue reflects the external transmission offset when renewable generation is surplus, and the O&M cost reflects the continuous operation cost of full-load production units.

3 RESULTS

3.1 Solution for Model

1. Construct hourly load and renewable output, based on the given rated power, installed capacity, and typical-day normalized curves, $P_{L,t}$ is obtained from Equation (1), and $P_{W,t}$, $P_{PV,t}$, and $P_{R,t}$ are obtained from Equations (2) and (3). This step converts the attached curves into hourly power sequences, forming a unified input for the load side and power source side.

2. Determine grid interaction status based on power difference, Compare $P_{R,t}$ and $P_{L,t}$ for each time period, and determine the grid purchase power and feed-in power from Equation (4). The core judgment basis of this step is the hourly power difference:

$$\Delta P_t=P_{R,t}-P_{L,t} \tag{15}$$

When ΔP_t is positive, surplus power is fed into the grid; when ΔP_t is negative, grid power purchase occurs. This judgment ensures priority local consumption of renewable energy, and converts intraday time mismatch into accumulable grid purchase and feed-in power sequences.

3. Accumulate daily electricity and calculate green indicators, Use Equations (5) to (7) to accumulate the hourly power daily, obtaining E_W, E_{PV}, E_R, E_L, E_B, and E_S. Then calculate the three green power direct connection indicators from Equations (8) to (10), and complete the compliance judgment according to Equation (11).

4. Account for typical-day cost and ammonia production cost, Based on the known grid purchase/feed-in power and renewable generation, calculate the typical-day net cost from Equation (12), and obtain the ammonia production cost per ton from Equation (14). This step unifies the operation power, electricity interaction, and economic parameters into the same cost framework, enabling operation indicator analysis to simultaneously address economic issues.

3.2 Result Analysis

The typical-day calculation results provide power curves, electricity summary, green indicators, and cost indicators simultaneously. This paper analyzes the core questions: whether renewable output and load are matched, whether indicators meet standards, and what the cost is supported by the electricity structure.Typical-Day Operation Characteristic Curves of Green Power Direct Connection Park are as shown in Figure 1.The key indicators are shown in Table 1.

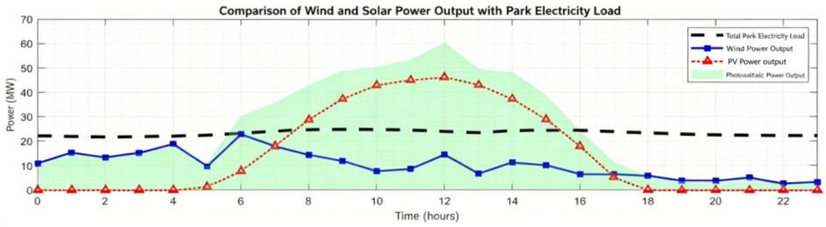

Figure 1 Typical-Day Operation Characteristic Curves of Green Power Direct Connection Park

Table 1 Key Typical-Day Electricity, Green Indicators, and Cost Results

Indicator Category	Indicator Name	Calculation Result	Judgment
Average Power	Park Typical-Day Total Load Power	23.28 MW	—
Average Power	Park Typical-Day Wind Generation Power	25.14 MW	—
Average Power	Park Typical-Day Grid Purchase Power	7.17 MW	—
Average Power	Park Typical-Day Grid Feed-in Power	9.03 MW	—
Daily Electricity	Park Typical-Day Total Electricity Consumption	558.72 MWh	—
Daily Electricity	Park Typical-Day Total Renewable Generation	603.45 MWh	—
Daily Electricity	Park Typical-Day Grid Purchase Electricity	172.04 MWh	—
Daily Electricity	Park Typical-Day Grid Feed-in Electricity	216.77 MWh	—
Green Indicator	Proportion of On-Site Self-Consumed Renewable Electricity	28.16%	Not Compliant
Green Indicator	Green Power Proportion in Total Electricity Consumption	69.21%	Compliant
Green Indicator	Proportion of Renewable Feed-In Electricity	35.92%	Not Compliant
Economic Indicator	Park Typical-Day Ammonia Production Cost	4287.78 RMB/ton	—

Combining Figure 1 and Table 1, the typical-day renewable generation of 603.45 MWh is higher than the park's electricity consumption of 558.72 MWh, indicating sufficient total energy supply. However, the park still purchases 172.04 MWh from the grid and feeds 216.77 MWh into the grid. The core contradiction is the time mismatch between renewable output and rigid load, with alternating surplus and deficit within the day.The typical periodic power balance results are shown in Table 2.

Table 2 Typical Period Power Balance Results

Time	Wind Output (MW)	Photovoltaic Output (MW)	Total Load (MW)	Grid Purchase Power (MW)	Grid Feed-In Power (MW)
0:00	10.90	0.00	22.12	11.22	0.00
5:00	9.63	1.28	22.38	11.47	0.00
12:00	14.52	46.08	24.01	0.00	36.59
16:00	6.38	17.92	24.50	0.20	0.00
22:00	2.50	0.00	22.31	19.81	0.00
23:00	3.19	0.00	22.23	19.04	0.00

From the typical period power balance: at night and evening, photovoltaic output is low, and wind power cannot meet full-load production, requiring grid purchase at 0:00, 5:00, 22:00, and 23:00; at noon, both wind and photovoltaic output are high, with a grid feed-in power of 36.59 MW at 12:00. The alternating periodical surplus and deficit directly increase grid feed-in electricity and reduce the self-consumption rate.

In terms of compliance, the green power proportion in total electricity consumption is 69.21% (meeting the ≥30% requirement), but the self-consumption rate is only 28.16% (<60%) and the feed-in rate is 35.92% (>20%), both failing the standards. The root cause is the time mismatch between renewable output and load, and the inflexible full-load rigid production, forming an operation state of "high abandonment and feed-in at peak, high grid purchase at valley".The typical daily cost composition results are shown in Table 3.

Table 3 Typical-Day Cost Composition Results

Cost Item	Value
Wind Power Generation Cost	36757.20 RMB
Photovoltaic Power Generation Cost	43008.00 RMB
Grid Purchase Cost	96476.89 RMB
Grid Feed-In Revenue	81918.06 RMB
Daily O&M Cost of Electrolyzers and Ammonia Synthesis	60036.00 RMB
Park Typical-Day Total Cost	154360.02 RMB
Ammonia Production Cost per Ton	4287.78 RMB/ton

In terms of economy, the typical-day total park cost is 154360.02 yuan, with an ammonia production cost of 4287.78 yuan per ton. Both the grid purchase cost of 96476.89 yuan and the grid feed-in revenue of 81918.06 yuan are high, consistent with the time mismatch and the operation characteristic of "high feed-in at peak, high grid purchase at valley".

Wind and photovoltaic generation costs and O&M costs form the basic production expenses, while grid interaction significantly affects the overall economy.

The comprehensive results show that the green power proportion in the park's total electricity consumption meets the requirements, but the on-site self-consumption proportion of renewable energy and the proportion of renewable feed-in electricity do not meet the green power direct connection project indicators. The reason is that the full-load continuous operation of electrolyzers and ammonia synthesis units forms a rigid load, while renewable output has significant intraday fluctuations, leading to the coexistence of renewable surplus and deficit periods. The established model, with hourly power balance as the core, unifies the expression of operation process, indicator constraints, and cost accounting, and can directly support the compliance judgment and cause analysis of typical-day operation.

4 CONCLUSIONS

This paper systematically investigates the grid-connected operation characteristics of green power-to-hydrogen-to-ammonia parks by constructing a refined hourly power balance model. The model comprehensively integrates wind-photovoltaic generation, conventional electricity demand, and rigid industrial loads of electrolyzers and ammonia synthesis units, and establishes a unified analytical framework that couples power flow analysis, green compliance assessment, and ammonia production cost accounting. The research clarifies the intrinsic relationship between renewable volatility, rigid load characteristics, and grid interaction behavior, and quantitatively identifies temporal mismatch as the core bottleneck that simultaneously undermines operational compliance and economic efficiency. The proposed modeling method provides a clear mechanism explanation and reliable quantitative basis for understanding the operational logic of green hydrogen-ammonia parks, offering scientific support for their planning, operation, and policy formulation.

Nevertheless, this study has several limitations. The current model adopts deterministic parameters and typical-day data, without fully considering long-term weather fluctuations, equipment degradation, and real-time price volatility, which may affect the generalization of results. Additionally, the model does not involve flexible resource scheduling such as energy storage and demand response, and the optimization of operational strategies is not explored. Future research will incorporate multi-year stochastic scenarios and dynamic parameter adjustments to enhance model robustness. Meanwhile, energy storage configuration and flexible load regulation will be integrated into the framework to mitigate temporal mismatch. Furthermore, multi-objective optimization considering carbon constraints and market mechanisms will be developed to promote the sustainable development of green hydrogen-ammonia industries.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

REFERENCES

[1] Yang Chao, Li Dong, Wang Yang, et al. Optimal Power Purchase Model and Pricing Mechanism of Green Power Parks Considering Power Quality Responsibility Sharing. Energies, 2025, 18(22): 6065.

[2] Xiang Yu, Kang Zhe, Ma Yang, et al. Optimal Carbon Emission Reduction Cooperation Models for Electricity Supply Chain of Existing Communities. Emerging Markets Finance and Trade, 2025, 61(12): 3895-3912.

[3] Sun Xu, Ding Yu, Bao Ming, et al. Strategic bidding model for multi-energy industrial parks considering spatio-temporal carbon emission factors in carbon and electricity markets. Renewable and Sustainable Energy Reviews, 2025, 219: 115764.

[4] Chatterjee S, Roy J, Mukherjee A, et al. Power sector transition plan of a coal-rich region in India with high-resolution spatio-temporal data based model. Energy for Sustainable Development, 2024, 83: 101560.

[5] Kandpal B, Backe S, Granado D C P. Power purchase agreements for plus energy neighbourhoods: Financial risk mitigation through predictive modelling and bargaining theory. Applied Energy, 2024, 358:122589.

[6] Felix B, Philipp H, S. R S, et al. Increasing electrical reserve provision in districts by exploiting energy flexibility of buildings with robust model predictive control. Advances in Applied Energy, 2023, 10.

[7] Nikolas S, Jassem K, Boris H. Model-based techno-economic evaluation of power-to-hydrogen-to-power for the electrification of isolated African off-grid communities. Energy for Sustainable Development, 2022, 70: 592-608.

[8] Erkki M, Eija P, Juha H. Forest owners' interest in participation and their compensation claims in voluntary landscape value trading: The case of wind power parks in Finland. Forest Policy and Economics, 2021, 124.

[9] Adam D, Richard I, Mengran Yang, et al. Validating grid-forming capabilities of hybrid power park technologies in future OFTO networks. IET Renewable Power Generation, 2020, 14(19): 3927-3935.

[10] Yáñez-Campos C S, Cerda-Villafaña G, Lozano-Garcia M J. Two-Feeder Dynamic Voltage Restorer for Application in Custom Power Parks. Energies, 2019, 12(17).