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CALCULATION OF INDICATORS AND COST CORRECTION FOR WIND-PV COUPLED GREEN AMMONIA PARKS

DeZhou Jing, Jie Ren*, HaoWen Yang, JiaQi Shi
School of Rail Transportation, Southwest Jiaotong University Hope College, Chengdu 610400, Sichuan, China.
**Corresponding Author: Jie Ren*

Abstract: Against the background of the dual carbon strategy, wind-PV directly connected ammonia parks serve as a vital way to ease renewable energy curtailment and accelerate the low-carbon transformation of chemical industry. Conventional ammonia cost calculation methods only count grid purchase and feed-in revenue while ignoring inherent depreciation costs of wind and PV power, which leads to serious distortion of economic evaluation results. To accurately judge park compliance and real production cost, this paper adopts hour-by-hour power balance analysis to quantify three mandatory green power indicators based on typical daily wind-solar time-series data. This paper redefines the splitting rule of self-consumed wind and PV electricity, and establishes a full-caliber revised ammonia cost model incorporating wind and PV levelized power costs, making up the cost omission defect of traditional accounting frameworks. Numerical results prove that the self-consumption rate and green electricity proportion meet industrial standards, while excess daytime PV output pushes the grid feed-in ratio beyond the limit. Time-series power curves visually verify that the time mismatch between PV generation and ammonia load is the root cause of excessive online power. After correction, the unit ammonia cost rises by 69% compared with traditional calculation, and wind-PV self-consumption cost accounts for over 40% of total operation expenditure. The proposed indicator measurement and cost correction model features clear logic and good adaptability to engineering time-series data, delivering a standardized quantitative paradigm for compliance judgment and economic assessment of similar green ammonia parks.
Keywords: Wind-PV coupling; Direct green power connection; Green ammonia park; Power balance; Ammonia unit cost correction

1 INTRODUCTION

Against the background of China's dual carbon goals, wind-PV direct-coupled green ammonia parks become a core technical path to solve renewable energy curtailment and realize deep decarbonization of chemical industries [1-2]. Such projects are supervised by strict green power assessment standards including self-consumption rate and grid feed-in ratio, while accurate economic evaluation is the premise of project investment decision-making. Timing mismatch between intermittent wind-solar output and stable ammonia production load easily leads to failure of compliance indicators, and unreasonable cost accounting methods will seriously distort the economic evaluation of parks. Therefore, standardized indicator calculation and full-caliber cost correction models are urgently needed to support the operation assessment of green ammonia industrial parks.

Existing research has carried out plenty of work on wind-PV-to-ammonia system modeling and economic analysis. In terms of power balance and indicator evaluation, scholars established hourly energy balance frameworks to quantify new energy consumption capacity, yet most studies adopted simplified power splitting rules without distinguishing wind and PV self-consumed electricity [3-5]. For economic accounting of green ammonia, overseas literatures mainly focus on full life cycle levelized cost of ammonia while ignoring on-site wind and PV generation expenditure [6-7]; domestic studies mostly only count grid purchase and feed-in revenue, failing to incorporate the inherent depreciation cost of renewable power equipment into unit ammonia cost [8-10]. Most current literatures separate compliance indicator calculation and full-cost economic evaluation, lacking a unified quantitative framework that matches actual industrial supervision standards, which restricts the accurate assessment of real park operation status.

To fill the above research gaps, this paper constructs a complete hourly power balance analysis system tailored to direct green power connected ammonia parks. The main marginal contributions are threefold. First, a refined splitting formula for wind and PV self-consumed power is proposed to accurately distinguish the internal consumption of two types of renewable energy under surplus and deficit power conditions. Second, a revised ton ammonia cost model integrating wind and PV levelized power cost is established, which fixes the cost omission defect of traditional accounting methods and quantifies the 69% cost deviation caused by ignoring renewable power expenditure. Third, the internal structural contradiction between wind-solar output timing mismatch and green power compliance indicators is revealed via typical daily simulation curves, providing standardized quantitative calculation tools for subsequent scheduling optimization and policy formulation of similar green ammonia projects.

2 METHODOLOGY

2.1 Model Preparation

This study calculates the operational indicators and grid-connection compliance of the park under typical wind-solar scenarios, which falls into the category of indicator calculation and compliance judgment. The power balance analytical method is adopted for solution. First, the per-unit power data from Appendix 1 and Appendix 2 are multiplied by the installed capacity or peak power of each power source and load to restore the actual power values. Next, based on the dispatching principle of "new energy generation prioritizes internal park loads; power shortages are purchased from the grid, and surplus power is fed to the grid", the purchased and sold power are calculated hour by hour. Then, the 24-hour power values are summed to obtain the daily total electricity statistics. Finally, three green power direct grid-connection indicators and ammonia production cost per ton are calculated to judge compliance.

For the conventional loads with a peak power of 6 MW, the actual load power at hour t is $P_t^L = p_t^L \times 6\text{MW}$, where p_t^L is the per-unit load value. For wind power and photovoltaic power with installed capacities of 40 MW and 64 MW respectively, the actual output is $P_t^W = p_t^W \times 40\text{MW}$ and $P_t^S = p_t^S \times 64\text{MW}$. It provides time-of-use electricity prices for peak, flat and valley periods: the peak period is 10:00–15:00 and 18:00–21:00 with a price of 0.8024 CNY/kWh; the flat period covers 07:00–10:00, 15:00–18:00 and 21:00–23:00 at 0.6074 CNY/kWh; the valley period is 23:00 to 07:00 the next day at 0.3424 CNY/kWh. The on-grid electricity price for surplus power adopts the unified benchmark price of 0.3779 CNY/kWh for wind and photovoltaic power specified.

2.2 Model Preparation

In this model, the electrolyzer and ammonia synthesis unit operate at full load for 24 consecutive hours. The total rated power of the electrolyzers is $P^E = 10 + 10 = 20\text{MW}$ (alkaline + PEM), and the rated power of the ammonia synthesis unit is $P^A = 0.75\text{MW}$. The total park power demand is $P_t^{demand} = P_t^L + P^E + P^A$, and the total new energy generation power is $P_t^{gen} = P_t^W + P_t^S$.

Hourly power balance follows the judgment rules below:

If $P_t^{gen} \geq P_t^{demand}$, the park generates excess power to be fed into the grid: $P_t^{sell} = P_t^{gen} - P_t^{demand}$, $P_t^{buy} = 0$;

If $P_t^{gen} < P_t^{demand}$, power deficit is purchased from the grid: $P_t^{buy} = P_t^{demand} - P_t^{gen}$, $P_t^{sell} = 0$.

Daily total electricity is obtained by summing hourly power values:

Total electricity consumption: $E^{use} = \sum_{t=0}^{23} P_t^{demand}$; Total new energy generation: $E^{gen} = \sum_{t=0}^{23} P_t^{gen}$; Total grid-purchased electricity: $E^{buy} = \sum_{t=0}^{23} P_t^{buy}$; Total on-grid surplus electricity: $E^{sell} = \sum_{t=0}^{23} P_t^{sell}$.

The three green power direct grid-connection indicators are defined as:

$$R_1 = \frac{E^{use} - E^{buy}}{E^{gen}} \times 100 \tag{1}$$

$$R_2 = \frac{E^{gen} - E^{sell}}{E^{use}} \times 100 \tag{2}$$

$$R_3 = \frac{E^{sell}}{E^{gen}} \times 100 \tag{3}$$

Note: The competition problem defines R_1 as $(E^{use} - E^{buy} - E^{sell})/E^{gen}$. Substituting the power balance equation $E^{gen} + E^{buy} = E^{use} + E^{sell}$, this expression can be simplified to $(E^{gen} - 2E^{sell})/E^{gen} = 1 - 2R_3$, which means R_1 and R_3 form an algebraic equivalence relation—they will either both meet or both fail compliance standards simultaneously. This contradicts the original design intention of three mutually independent indicators, and this formula imposes stricter constraints where R_1 can only exceed 60% if R_3 stays below 20%. Based on the physical definition of R_1—the proportion of self-consumed new energy generation to total generated power—this paper adopts $(E^{use} - E^{buy})/E^{gen}$ (equivalent to $(E^{gen} - E^{sell})/E^{gen}$) for R_1 calculation. This definition aligns with industrial standards and ensures the three indicators form an independent constraint system.

Ammonia production cost per ton consists of four components: grid purchase cost, wind-photovoltaic self-consumption cost, on-grid power revenue, and equipment operation & maintenance (O&M) cost. Per Appendix 5, the levelized cost of wind power $c^W = 0.15$ CNY/kWh and photovoltaic power $c^S = 0.12$ CNY/kWh, which represent the actual generation costs of on-site wind and photovoltaic facilities. Therefore, the ammonia cost per ton model incorporates wind-solar self-consumption expenses:

$$C^{NH_3} = \frac{C^{buy} + C^{W_s elf} + C^{S_s elf} + C^{om} - R^{sell}}{Q} \tag{4}$$

Where grid purchase cost is weighted by time-of-use electricity prices: $C^{buy} = \sum_t P_t^{buy} \times 1000 \times p_t^{grid} \times 1\text{h}$; On-grid revenue: $R^{sell} = \sum_t P_t^{sell} \times 1000 \times 0.3779 \times 1\text{h}$. Wind and photovoltaic self-consumption costs require splitting self-consumed generation hourly: When $P_t^{gen} \geq P_t^{demand}$, the park's internal load fully consumes P_t^{demand}, split by generation proportion: $P_t^{W_s elf} = P_t^{demand} \times \frac{P_t^W}{P_t^{gen}}$, $P_t^{S_s elf} = P_t^{demand} \times \frac{P_t^S}{P_t^{gen}}$; When $P_t^{gen} < P_t^{demand}$, all wind and photovoltaic generation is self-consumed: $P_t^{W_s elf} = P_t^W$, $P_t^{S_s elf} = P_t^S$. Cumulative daily self-consumed wind power $E^{W_s elf} = \sum_t P_t^{W_s elf}$ (MWh), cumulative self-consumed photovoltaic power $E^{S_s elf} = \sum_t P_t^{S_s elf}$ (MWh). Wind self-consumption cost: $C^{W_s elf} = E^{W_s elf} \times 1000 \times 0.15$ CNY. Photovoltaic self-consumption cost: $C^{S_s elf}=E^{S_s elf}\times1000\times0.12$ CNY; O&M cost: $C^{om}=24\times(P^E\times1000\times\overline{\omega}^E+P^A\times1000\times\omega^A)$. Where $\overline{\omega}^E=0.125$ CNY/kWh is the average O&M coefficient for the two electrolyzer types, and $\omega^A=0.002$ CNY/kWh is the O&M coefficient for the ammonia synthesis unit. Daily ammonia output Q=1.5×24=36 tons.

3 RESULTS

Calculations are carried out for the typical daily wind-solar output profile based on the above model, and the results are presented below Table 1.

Table 1 Typical Daily Operational Indicator Results

Indicator	Value	Standard	Compliance
Total electricity consumption (MWh)	558.72	—	—
Total new energy generation (MWh)	603.45	—	—
Grid-purchased electricity (MWh)	172.04	—	—
On-grid surplus electricity (MWh)	216.77	—	—
Self-consumed wind power (MWh)	191.77	—	—
Self-consumed photovoltaic power (MWh)	194.90	—	—
Self-consumption rate R_1 (%)	64.08	>60%	Compliant
Green power proportion R_2 (%)	69.21	>30%	Compliant
On-grid power ratio R_3 (%)	35.92	<20%	Non-compliant
Total grid purchase cost (CNY)	97721.03	—	—
Total on-grid revenue (CNY)	81918.06	—	—
Wind self-consumption cost (CNY)	28765.84	—	—
PV self-consumption cost (CNY)	23388.47	—	—
Total O&M cost (CNY)	60036.00	—	—
Ammonia cost per ton (CNY/ton)	3555.37	—	—

As shown in Table 1, among the three green power direct grid-connection indicators, $R_1=64.08$ and $R_2=69.21$ satisfy the thresholds of above 60% and 30% respectively, while the on-grid power ratio $R_3=35.92$ far exceeds the 20% upper limit and fails compliance inspection.

As illustrated in Figure 1, the park power balance exhibits obvious diurnal disparity. During daytime hours (08:00–17:00), photovoltaic output concentrates, and total new energy generation far surpasses total load demand, generating massive surplus power fed to the grid. At night, photovoltaic output drops to zero, and partial power deficits must be covered by grid purchases when wind generation cannot meet full demand. The primary cause of excessive on-grid power ratio lies in the relatively large photovoltaic installed capacity (64 MW). The full-load power demand of electrolyzers and ammonia synthesis equipment (20.75 MW) plus conventional peak loads (6 MW) cannot fully absorb the midday photovoltaic generation peak. The power gap between the photovoltaic generation peak (approx. 46 MW around noon) and the combined conventional + ammonia production load (23–25 MW) exceeds 20 MW; this excess electricity is inevitably exported to the grid, pushing R_3 above the 20% limit.

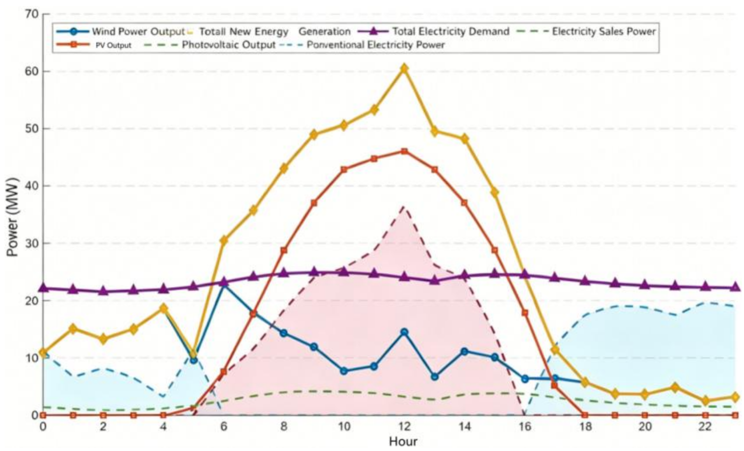

Figure 1 Typical Daily Park Power Balance Curve

As displayed in Figure 2, grid purchase activities mainly occur overnight and early morning (00:00–07:00 and 20:00–23:00), which correspond to valley and flat electricity price periods with zero PV output and insufficient wind generation to cover total demand. Power export concentrates in the daytime PV peak window (09:00–16:00), overlapping peak and flat price windows. The temporal distribution of power purchase and export aligns with time-of-use price signals, proving economically rational park operation, yet exposing structural temporal mismatch between photovoltaic generation and ammonia production power demand.

Figure 2 Typical Hourly Grid Purchase/Export Distribution and Time-of-use Prices

The ammonia production cost per ton reaches 3555.37 CNY/ton, including grid purchase cost of 97721.03 CNY, on-grid revenue of 81918.06 CNY, wind self-consumption cost of 28765.84 CNY, photovoltaic self-consumption cost of 23388.47 CNY, and O&M cost of 60036.00 CNY. Combined wind and photovoltaic self-consumption expenses total 52154.31 CNY, accounting for approximately 41% of comprehensive costs as an indispensable major expenditure item. If wind-solar self-consumption costs are omitted (only grid purchase, on-grid revenue and O&M are counted), the ammonia cost per ton falls to 2106.64 CNY/ton. After integrating wind and photovoltaic generation costs, the unit ammonia cost rises to 3555.37 CNY/ton, representing a 69% cost increase. This verifies that wind and photovoltaic generation costs occupy a critical share in comprehensive economic accounting. Although on-grid revenue partially offsets grid purchase expenses, ignoring wind-solar generation costs severely underestimates overall power-related comprehensive costs compared with calculations that only include grid transaction and O&M expenses.

4 CONCLUSIONS

This paper constructs a full-hour power balance calculation framework tailored to wind-PV direct-coupled green ammonia parks, and proposes a corrected full-caliber unit ammonia cost model that incorporates wind and photovoltaic self-generation expenses. Based on typical daily wind-solar time-series data, the study quantitatively calculates three core green power compliance indicators by distinguishing wind and PV internal consumption under power surplus and deficit scenarios. Simulation results reveal that the park's self-consumption rate and green electricity ratio meet regulatory thresholds, yet the severe temporal mismatch between midday photovoltaic peak output and stable ammonia loads leads to an excessive grid feed-in ratio. Numerical comparison demonstrates that traditional cost calculation methods ignoring renewable generation costs underestimate unit ammonia cost by 69%, with wind-PV self-consumption expenditures accounting for over 40% of total operating expenses. The proposed indicator splitting rule and cost correction formula feature clear physical logic and full compatibility with engineering time-series data, which can be directly adopted for compliance inspection and economic benefit evaluation of newly built or operational green ammonia industrial parks with similar power supply structures.

Despite the standardized quantitative tool provided in this work, the current model only adopts fixed full-load ammonia production settings without considering adjustable power operation modes. Follow-up research can introduce variable ammonia load constraints to establish a multi-output comparative analysis system, and further combine scheduling optimization algorithms to balance green power compliance and production economy. Besides, the model uses fixed wind and PV levelized costs; subsequent studies can integrate multi-scene resource fluctuation and equipment depreciation curves to build a dynamic cost prediction model. Off-grid energy storage matching schemes can also be embedded into the framework to expand its applicability to independent wind-PV green ammonia microgrids, forming a more complete analysis tool covering grid-connected and off-grid operation modes.

COMPETING INTERESTS

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

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