

Optimization Modeling and Performance Evaluation of Wind-Solar-Coupled Hydrogen-Ammonia Systems with Storage: A Full-Year Operational Simulation and Cost-Benefit Analysis

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Abstract. Against global warming and the need to reduce reliance on fossil fuels, green ammonia produced from renewable hydrogen has emerged as a promising energy carrier for integrating intermittent wind and solar power. This study develops an integrated wind–solar–storage–hydrogen–ammonia optimization model based on phased linear programming, simulating 8,760 hours of annual operation while incorporating renewable generation, energy storage, water electrolysis, hydrogen storage, and ammonia synthesis under operational constraints. Results show that an optimal 7:3 wind-to-photovoltaic ratio combined with 15%/4 h energy storage reduces the green ammonia production cost to approximately 2,800 CNY/ton, achieves an internal rate of return of 12–15%, and shortens the payback period to 8–10 years. The optimized configuration also lowers the levelized cost of electricity to 0.15 CNY/kWh, limits renewable curtailment to below 3%, and demonstrates that a 300,000 Nm³ hydrogen storage system can effectively stabilize ammonia synthesis. Sensitivity analysis across nine representative locations, categorized as wind-dominant, photovoltaic-dominant, and wind–solar complementary regions, reveals that system performance is most sensitive to wind power cost, followed by photovoltaic, energy storage, power storage, and hydrogen storage costs. Wind-dominant regions are particularly affected by wind cost fluctuations, photovoltaic-dominant regions benefit most from energy storage optimization, while complementary regions exhibit balanced sensitivity due to resource complementarity. The proposed phased linear programming framework provides an effective approach for dynamic optimization of integrated renewable-hydrogen-ammonia systems and offers a practical techno-economic benchmark for region-specific green ammonia deployment and cost reduction.

Keywords: Wind-solar-storage-hydrogen-ammonia System, Green Ammonia Production, Optimization Model, Economic Feasibility, Sensitivity Analysis

1. Introduction

In the backdrop of the intensifying global climate change, how to mitigate the dependence on the fossil energy sources and how to construct a low-carbon green energy industrial system have become the core issues to achieve the sustainable development goal (SDGs) all over the world. The renewable energy technologies, especially the wind and solar power, are recognized as the key drivers of the global energy transition, because of their nature of cleanliness, renewability and the abundance of resources reserve. However, the intrinsic intermittency and volatility of the wind and solar generation become the prominent problems to their large-scale grid integration: when the generation of the renewable is in the peak, the surplus electricity is often curtailed for the lack of the grid absorption capacity; and in the opposite phase when the output is low (e.g., night time for the solar, calm period for the wind), the stability of the energy supply can not be guaranteed. The intrinsic mismatch between the renewable energy generation and end user demand has become the key bottleneck to restrict the large-scale penetration of the renewable energy, the efficient storage, transportation and value-added utilization of the renewable electricity become the focus of the now academic and industry research.

Green hydrogen, which is produced by water electrolysis using renewable energy, and the green ammonia that is synthesized using the green hydrogen as the feedstock, have been considered as the promising energy carriers to solve the storage and transportation problems of the renewable energy. As the secondary energy vector, they can bridge from the intermittent renewable energy generation to the continuous energy demand in the end-use sectors (e.g. industry, transportation). The hydrogen has the advantages of high energy density and no carbon emission in the utilization: in the heavy industry, the hydrogen based direct reduced iron (DRI) process can reduce the carbon emission about 70% per ton of the steel compared with the blast furnace method [1]; for the transportation, the hydrogen fuel cell vehicle has the super energy density, the driving range extension is over 300 kilometers in comparison with the current lithium-ion battery technology [2]. Regarding the flexibility of the energy system, the hydrogen could provide the intertemporal and spatial energy transfer, so it could address the intermittency problems of the variable renewable energy such as the wind, photovoltaic power generation [3]; for the storage and transportation, the ammonia has the unique superiority: the critical temperature (132.4 C) and the critical pressure (11.3MPa) of the ammonia can be liquefied by the conventional industrial refrigeration system, it is far more technologized and economically feasible than the extreme condition of the liquefaction of the hydrogen (-239.9 C, 1.3MPa). Specifically, for the liquid ammonia at 25 C and 0.87MPa, the volumetric energy density is about 12.7MJ/L (much higher than 2.7MJ/L of the hydrogen is compressed to 35MPa), and the gravimetric energy density is 18.6MJ/kg. Besides, the ammonia can be stably stored at 25 C under the pressure of merely 0.87MPa (much lower than 35-70MPa needed by the high pressure hydrogen storage) and it has over 4.5 time the hydrogen storage for the identical tank volumes compared with the compressed hydrogen at the same pressure. These characteristics make the ammonia be both the carbon-free fuel and the efficient hydrogen carrier. The wind-solar power generation for green hydrogen production, and the further synthesis into the green ammonia, not only can improve the utilization efficiency of the renewable energy, but also provide the low-carbon energy solutions for the carbon intensive sector such as the steel, the shipping and the power generation, finally it does makes a close loop for the renewable energy "generation-storage-utilization".

The application potential of wind-solar-hydrogen-ammonia coupled system is particularly salient in China under the national "Dual Carbon" (carbon peaking and carbon neutrality) strategic

framework . Table.1 shows the carbon emissions generated during the production of various mainstream types of hydrogen. Currently, the ammonia produced in China is mainly based on gray hydrogen, which is produced via steam methane reforming (SMR), and has a large amount of carbon emissions (8-10 eCO₂/ton of ammonia from hydrogen production plus 0.3-0.5 eCO₂/ton from ammonia synthesis). While the ammonia produced by the green hydrogen based is near zero carbon emission (0 eCO₂ from hydrogen production, and only 0.3-0.5 eCO₂/ton from ammonia synthesis) which is in full accordance with the long term energy transition strategy of China. For example, take Inner Mongolia where the renewable energy resources are rich as illustration: From the data of 2024, the renewable energy generation of the region is 834.4 billion kWh, while its total electricity consumption is only 519.3 billion kWh, which gives rise to about 315.1 billion kWh of renewable electricity curtailment due to little local consumption capacity [4]. It not only decreases the overall efficiency of energy resource utilization, but also obstructs the big scale deployment of renewable energy projects. The wind-solar-hydrogen-ammonia system can take up this surplus renewable electricity by making it to be the storable and transportable green ammonia, which can also alleviate the imbalance between the renewable energy generation and consumption in the resource rich but load deficient region.

Table 1. Different types of hydrogen 's carbon emission in ammonia industry

Type of Hydrogen	Production Method	CO ₂ Emissions of H ₂ Production	CO ₂ Emissions of NH ₃ Synthesis
Green Hydrogen	Renewable electrolysis	0	0.3-0.5
Blue Hydrogen	Natural gas + CCS	0.5-2.0	0.3-0.5
Gray Hydrogen	Steam methane reforming	8-10	0.3-0.5
Brown Hydrogen	Steam methane reforming	18-22	0.3-0.5

In order to fully take advantage of the technical and economic promise of wind-solar-hydrogen-ammonia systems, we should also systematically review the state of the research and highlight the existing knowledge gaps, in particular with respect to the key technical chain of converting the renewable electricity into the renewable hydrogen and ammonia. Up to now, there are progresses in several technical dimensions: in the domain of renewable energy coupling for the hydrogen production, the optimized configurations of wind-PV hybrid (e.g. a 60:40 of wind-solar installed capacity ratio) are verified to reduce the levelized cost of hydrogen (LCOH) 18-22 % due to the temporal and the spatial complementarity of the generation profiles [5]; the advanced control strategy such as the model predictive control (MPC) is also applied to alleviating the power fluctuation caused by the renewable energy variability, however, it is still challenging to achieve the dynamic matching between the variable renewable output and the operation constraint of the electrolyzer [6]. In the domain of hydrogen to the ammonia conversion, besides the mature but energy-consuming Haber-Bosch process, there are emerging technologies such as the electrochemical ammonia synthesis (achieved 15-20 % efficiency at reduced operating temperature) and the plasma-catalytic ammonia synthesis (realizing 40 % of energy save in the pilot scale experiment), however, this kind of novel technologies still suffer in the point of the catalyst durability and the scale up compared with the conventional industrial process [6]. In the context of the system integration, the LCA studies show that the co-location of the hydrogen production and the ammonia synthesis facility can achieve 12-15 % of efficiency gain by using the waste heat recovery; meanwhile, the optimization models quantified the economic viabilities of the ammonia for the seasonal energy storage, and the estimated storage cost is \$120-150 /ton NH₃ [7].

Even with these advances, however, there are still some critical research gaps that restrict the full-scale commercialization and application of the wind-solar-hydrogen-ammonia systems. First, most of the existing literatures only consider the isolated technical links (e.g., the standalone electrolyzer or the standalone ammonia synthesis reactor), but there is no effort to build a holistic dynamic coupling framework that considers the wind-solar generation, the energy storage, the electrolysis, and the ammonia synthesis. This does not consider the mismatch in time and space between the input of intermittent renewable energies, the flexible working range of the electrolyzer, and the fixed hydrogen demand of the ammonia synthesis process. Second, although the economic analysis of the system component (e.g. the electrolyzer, the energy storage) is available, there is no unified techno-economic evaluation framework to quantitatively show the impact of the endowment of regional resources (e.g. the wind-dominant, the PV-dominant, or the wind-solar complementary region) on the levelized cost of electricity (LCOE) and levelized cost of ammonia (LCOA) of the whole system. This means that one cannot provide technical and economic guidance for the project deployment in different geographical context. Third, the issues related to the system wide operation, such as the safety standard of the integrated hydrogen-ammonia facilities, the mechanism of the dynamic interaction between the system and the power grid, and the protocol of the multi-energy vector dispatch, are hardly studied, which limits the practical adaptability of the system in the real energy network.

In response to these research gaps, this study aims to construct a comprehensive dynamic simulation and optimization model for wind-solar-storage-hydrogen-ammonia coupled systems. The specific research objectives are as follows: (1) Develop a dynamic coupling model integrating wind-solar complementary power generation and electrolytic hydrogen production, which accurately captures the temporal variability of renewable energy and the operational flexibility of electrolyzers; (2) Investigate the energy efficiency characteristics of hydrogen-to-ammonia synthesis systems and optimize their integration with upstream hydrogen production and storage units; (3) Analyze the impact of different energy storage configurations (including battery storage, hydrogen storage, and ammonia storage) on system stability and economic performance, with a focus on mitigating supply-demand mismatches; (4) Evaluate the technical feasibility and economic viability of the system across regions with distinct resource endowments, providing a quantifiable benchmark for future large-scale applications. By addressing these objectives, this study seeks to fill the existing gap in dynamic coupling optimization of wind-solar generation, hydrogen storage, and ammonia synthesis, and establish an interdisciplinary integration paradigm that supports the practical promotion of green ammonia technology in the global energy transition.

2. Methodology

2.1. Model construction

The system process is visualized in the Fig.1, depicting the entire chain from renewable energy generation to ammonia production: wind/solar generators produce electricity, which is stored in industrial batteries, then used by industrial electrolyzers to produce hydrogen. The hydrogen is stored in high-pressure tanks and finally fed into industrial reaction vessels for ammonia synthesis (NH_3).

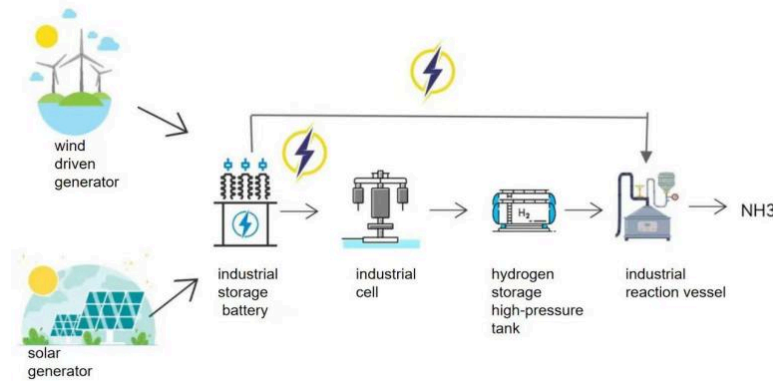


Figure 1. Flowchart of green hydrogen and green ammonia production

The design of incorporating battery storage (rather than relying solely on direct electrolysis of renewable electricity) is primarily driven by resolving the inherent mismatch between intermittent renewable output and the operational stability requirements of electrolyzers and ammonia synthesis: First, wind and solar power exhibit significant hourly and daily fluctuations (e.g., solar output drops to near zero at night, wind output varies with meteorological conditions), while electrolyzers require power input within a specific dynamic range (50%–150% of rated power, as shown in Table.2) to avoid performance degradation or shutdowns caused by abrupt power changes. Direct electrolysis of unstable renewable electricity would frequently push electrolyzers to operate at off-design conditions, reducing hydrogen production efficiency and shortening equipment lifespan. Second, ammonia synthesis has a fixed hourly hydrogen demand (25,000 Nm³/h, matching 100,000 tons/year ammonia production), which requires hydrogen output from electrolyzers to be relatively stable. Battery storage acts as a "buffer"—absorbing surplus renewable electricity during peak generation periods and supplementing power during low generation periods—to ensure electrolyzers maintain continuous, stable operation, thereby matching the fixed hydrogen feedstock demand of ammonia synthesis. While battery storage involves additional investment, its role in improving overall system efficiency (reducing electrolyzer downtime and efficiency losses) and stabilizing the hydrogen supply chain outweighs the incremental cost, making it a necessary configuration rather than an alternative to direct electrolysis. In practice, the system operates in a "direct supply + battery regulation" mode: priority is given to using renewable electricity directly for electrolysis, with batteries only compensating for fluctuations or deficits, balancing operational stability and cost efficiency.

From the perspective of system design, the "real-time power balance constraint" (ensuring real-time power supply-demand matching) is reasonable, relying on coordinated wind-solar installed capacity and energy storage. Wind-solar installed capacity is determined by the system's core load (electrolyzer dynamic load + ammonia production fixed load) and local resources: with the electrolyzer's rated power (317.21 MW) and ammonia synthesis fixed power as benchmarks, and based on wind power density (1.7 MW/hectare) and PV power density (0.15 MW/hectare, Table.6), it meets base power demand under typical conditions to avoid long-term deficits. The energy storage system (adjustable P_{sto} and E_{sto}) compensates for short-term mismatches: storing surplus power ($Ch(t)$) during high output (e.g., midday) and discharging ($Dch(t)$) during low output (e.g., nighttime). This "base load by wind-solar + short-term regulation by storage" mechanism ensures the sum of real-time wind-solar output, storage discharge, and adjusted charging matches total load, realizing feasible real-time balance.

2.1.1. Electrolytic hydrogen production process

As the core equipment for converting wind and solar electricity into green hydrogen, the electrolyzer's parameters directly determine the system's energy demand and economic performance. To accommodate the intermittent output of wind and solar energy, the electrolyzer permits dynamic power adjustment within a reasonable range. The key parameters meeting regulatory requirements are listed in Table 2.

Table 2. Electrolysis hydrogen-related parameters (Ningde Times 587Ah energy storage dedicated cell [8])

Parameter	Value	Unit	Description
Hourly Hydrogen Demand	25000	Nm ³ /h	Matches the hydrogen requirement for 100,000 tons/year ammonia production
Electrolyzer Investment	41600000	Yuan	Includes procurement, installation, and commissioning
Electricity Consumption	4.3	kWh/Nm ³	Electricity needed to produce 1 Nm ³ of hydrogen
Annual Depreciation Cost	0.0090	Yuan/Nm ³	Amortized over equipment lifecycle
Annual O&M Rate	3%	-	Calculated based on electrolyzer investment
Rated Power	317.21	MW	Hourly hydrogen demand × electricity consumption / 1000 (core load)
Minimum Power	158.61	MW	50% of rated power (lower limit for dynamic adjustment)
Maximum Power	475.82	MW	150% of rated power (upper limit for dynamic adjustment)

2.1.2. Ammonia production process

The ammonia production process consists of four key steps: nitrogen separation, syngas compression, catalytic synthesis, and product separation. The parameters for each step are shown in Table 3.

Table 3. Synthesis ammonia equipment

Process Step	Capital Cost (Yuan)	Hourly Power Consumption (kW)	Equipment Lifespan (years)	Data source
Nitrogen Separation	52661000	5191	20	Linde HPL type low temperature air separation system [9]
Syngas Compression	421120000	102466	20	Siemens STC-GV series compressors [10]
Catalytic Synthesis	238000000	79275	20	KBR reaction system [11]
Product Separation	13949600	22780	20	SPX FLOW condenser [12]

2.1.3. Hydrogen storage system

To buffer the dynamic mismatch between electrolyzer output and ammonia production's fixed hydrogen demand, a hydrogen storage system is introduced. The key parameters (consistent with specifications) are shown in Table 4.

Table 4. Hydrogen storage equipment (hydrogen container) parameters [13]

Parameter	Value	Unit	Description
Unit Capacity Cost	200	Yuan/Nm ³	Cost of high-pressure hydrogen storage tanks per unit volume
Equipment Lifespan	15	years	Average lifespan of industrial hydrogen storage facilities
Annual O&M Rate	2%	-	Based on initial investment of hydrogen storage equipment
Minimum SOC	10%	-	Lower limit to prevent equipment damage from emptying
Maximum SOC	90%	-	Upper limit to avoid safety risks from overpressure
Initial SOC	50%	-	Initial hydrogen storage level at system startup
Charge-Discharge Efficiency	96%	-	Energy loss during hydrogen compression (charging) and supply (discharging)
Minimum Capacity	300000	Nm ³	Meets 12 hours of ammonia production hydrogen demand (25000 Nm ³ /h × 12 h)

2.2. Model framework and assumptions

2.2.1. System boundary

The model encompasses three core components:

Wind power system: Using area as the decision variable, converting it to actual output through installed capacity density per unit area;

Photovoltaic system: Similarly, using area as the decision variable to correlate theoretical output with curtailed energy;

Energy storage system: includes energy capacity (total electrical energy stored) and power capacity (charging/discharging rate), which must satisfy the state of charge (SOC) constraint.

2.2.2. Key assumptions

To ensure logical consistency, the following assumptions are made:

1. Load Constraint: Load is split into "electrolyzer dynamic load" and "ammonia production fixed load"; the system maintains real-time power balance, with electrolyzer power adjustable between 158.61 MW and 475.82 MW.

2. Resource Data: Wind and solar resources are represented by "hourly normalized output" (0–1, reflecting resource availability).

3. Equipment Parameters: Equipment lifespan and cost follow industry standards, ignoring extreme weather impacts.

4. Energy Storage Efficiency: Electrochemical storage charging/discharging efficiency is fixed (charging: 96.5%, discharging: 96%); SOC ranges 10%–90%, initial SOC 50%.

5. Hydrogen Storage Logic: Electrolyzer hydrogen output (after storage losses) is stored first, then ammonia production draws from storage at a fixed rate; hydrogen storage SOC stays within 10%–90%, initial SOC 50%.

6. Hydrogen Storage Capacity: Minimum capacity is 300,000 Nm³ (12 hours of ammonia demand) for short-term supply stability.

2.3. Mathematical modeling

2.3.1. Decision variables

Variables are divided into "design variables (system configuration)" and "operational variables (hourly operation)", as shown in Table 5.

Table 5. Variable type table

VariableType	Symbol/Range	Physicalsignificance	Unit
Design Variable	Aw	Total Wind Power Area	hectare
	As	Total Photovoltaic Area	hectare
	Esto	Energy Storage Capacity	MW ·h
	Psto	Power Storage Capacity	MW
	VH2	Maximum hydrogen storage capacity	Nm ³
Runtime Variable	Cw(t)	Hourly Abandoned Wind Power	MW ·h
	Cs(t)	Hourly Abandoned Solar Power	MW ·h
	Ch(t)	Hourly Energy Storage Charging	MW ·h
	Dch(t)	Hourly Energy Storage Discharging	MW ·h
	SOC(t)	Hourly Energy Storage State of Charge	-
	SOCH2(t)	Hourly hydrogen storage state of charge	-
	P ely (t)	Hourly electrolyzer dynamic power	MW

2.3.2. Objective function

With the objective of minimizing the levelized cost of electricity (LCOE), the calculation formula is: $LCOE = \frac{\text{Total annual cost(yaun)}}{\text{Annual total power generation(kWh)}}$

The annual total cost comprises four categories of cost items:

1. Investment and operational costs for renewable energy projectsz:

$$C_{\text{wind}} = \left(\frac{A_w \cdot c_{w,\text{area}}}{T_{\text{wind}}} + A_w \cdot c_{w,\text{area}} \cdot r_{\text{om}} \right) \cdot 10^4 \quad (1)$$

$$C_{\text{solar}} = \left(\frac{A_s \cdot c_{s,\text{area}}}{T_{\text{solar}}} + A_s \cdot c_{s,\text{area}} \cdot r_{\text{om}} \right) \cdot 10^4 \quad (2)$$

($c_{w,\text{area}}$ is the cost per unit area of wind power, T_{wind} is the service life of wind power, r_{om} is the operation and maintenance cost rate)

2. Energy storage cost:

$$C_{\text{sto}} = \left(\frac{E_{\text{sto}} \cdot c_{\text{sto,e}} + P_{\text{sto}} \cdot c_{\text{sto,p}}}{T_{\text{sto}}} + (E_{\text{sto}} \cdot c_{\text{sto,e}} + P_{\text{sto}} \cdot c_{\text{sto,p}}) \cdot r_{\text{om,sto}} \right) \cdot 10^3 \quad (3)$$

(c_{sto} is the energy cost per unit of energy storage, T_{sto} is the service life of energy storage)

3. Hydrogen Storage Cost:

$$C_{H2,sto} = \frac{V_{H2} C_{H2,cap}}{T_{H2}} + V_{H2} \cdot C_{H2,cap} \cdot r_{om,H2} \quad (4)$$

4. Operating costs

$$C_{op} = \sum_{t=1}^{8760} (C_w(t) + C_s(t)) \cdot c_{curtail} + \sum_{t=1}^{8760} (Ch(t) \cdot c_{ch} + Dch(t) \cdot c_{dch}) \cdot 10^3 \quad (5)$$

($c_{curtail}$ represents the curtailment cost, c_{ch} denotes the charging cost)

2.3.3. Constraint condition

A. Technical constraints (ensuring feasible system operation)

1. Abandoned power constraint: The abandoned power quantity is non-negative and does not exceed the theoretical output.

$$0 \leq C_w(t) \leq A_w \cdot \rho_w \cdot w(t), \quad 0 \leq C_s(t) \leq A_s \cdot \rho_s \cdot s(t), \forall t \quad (6)$$

(ρ_w is the wind power density, $w(t)$ is the normalized wind power output)

2. Energy storage charging/discharging constraints: The charging/discharging amount shall not exceed the power capacity.

$$0 \leq Ch(t) \leq P_{sto}, \quad 0 \leq Dch(t) \leq P_{sto}, \forall t \quad (7)$$

3. SOC Constraint: The state of charge remains within the safe operating range.

$$SOC_{min} \leq SOC(t) \leq SOC_{max}, \forall t \quad (8)$$

4. Power balance constraint: Real-time supply-demand equilibrium

$$A_w \cdot \rho_w \cdot w(t) - C_w(t) + A_s \cdot \rho_s \cdot s(t) - C_s(t) + Dch(t) - Ch(t) = P_{ely}(t) + P_{ammonia}, \forall t \quad (9)$$

5. SOC Dynamic Constraints: Energy Storage State-of-Charge Update Relationship

$$SOC(t) = SOC(t-1) + \frac{Ch(t)\eta_{ch} - \frac{Dch(t)}{\eta_{ch}}}{E_{sto}}, \forall t \quad (10)$$

(η_{ch} is the charging efficiency, $SOC(0) = SOC_{init}$)

6. Electrolyzer Power: Within dynamic range

$$P_{ely, \min} \leq P_{ely}(t) \leq P_{ely, \max}, \forall t \quad (11)$$

7. Hydrogen Storage SOC:

$$SOC_{H_2, \min} \leq SOC_{H_2}(t) \leq SOC_{H_2, \max}, \forall t \quad (12)$$

8. Hydrogen Supply-Demand Balance:

$$SOC_{H_2}(1) \cdot V_{H_2} = SOC_{H_2, \text{init}} \cdot V_{H_2} + P_{ely}(1) \cdot R_{H_2} \cdot \eta_{H_2} - V_{H_2, \text{hourly}}(t = 1) \quad (13)$$

$$SOC_{H_2}(t) \cdot V_{H_2} = SOC_{H_2}(t - 1) \cdot V_{H_2} + P_{ely}(t) \cdot R_{H_2} \cdot \eta_{H_2} - V_{H_2, \text{hourly}}(t > 1) \quad (14)$$

B. Rationality constraints (avoiding extreme configurations)

1. Minimum installed capacity constraint: The installed capacity of wind and solar power shall not be lower than the project feasible value.

$$A_w \cdot \rho_w \geq 5MW, A_s \cdot \rho_s \geq 5MW \quad (15)$$

2. Energy storage capacity constraint: Minimum storage capacity ensures regulation capability.

$$E_{sto} \geq 10MW \cdot h, \quad P_{sto} \geq 5MW \quad (16)$$

3. Energy Storage - Wind-Solar Ratio Constraint: Energy storage must match the scale of wind and solar power generation.

$$E_{sto} \leq 3 \cdot (A_w \cdot \rho_w + A_s \cdot \rho_s) \quad (17)$$

$$P_{sto} \geq 0.25 \cdot (A_w \cdot \rho_w + A_s \cdot \rho_s) \quad (18)$$

2.4. Solution method

2.4.1. Model characteristics

The objective function and constraints are linear, making this a linear programming problem solvable via MATLAB's linprog function. With 6 design variables and 7×8760 operational variables, the model is high-dimensional, so a phased optimization strategy is used.

2.4.2. Phased optimization strategy

To reduce computational complexity for 8760-hour annual data, a "monthly phased optimization" approach is used:

1. Divide the entire year into 12 months, treating each month as an independent optimization subproblem;
2. Accumulate the optimization results of each month to obtain the total annual configuration and cost;
3. Advantages: Reduces single-solution dimensionality and improves computational efficiency.
Disadvantages: Tends to fall into the local optimal trap and has parameter disturbance transmission error.

2.5. Key parameter

Settings Based on Industry Standards and Engineering Practices, with Core Parameter Values as shown in Table 6.

Table 6. Variable type table(GE 5.3 158 [14]for wind turbine, HI-Mo 7 [15] for photovoltaic generator)

Parameter Category	Parameter Name	Value	Unit
Device Parameters	Wind Power Density	1.7	MW / hectare
	Solar Density	0.15	MW / hectare
	Equipment Lifetime	Wind power 20 years, photovoltaic 25 years Hydrogen storage: 15years; Electrolyzer: 20years	year
	Energy Storage Cycle Life	3000 times	times
Cost Parameters	Cost Per Unit Area	Wind power 800000, photovoltaic 2.5 million	yuan/hectare
	Energy Storage Cost Per Unit	Energy 1200 yuan, power 700 yuan	yuan/kWh, yuan/kW
	Curtailed Electricity ccurtail	1.2	yuan/kWh
Resource Parameters	Normalized Output of Wind and Solar	0-1 (hourly data)	-
	Electrolyzer Rated Power	317.21	MW

3. Simulation and data analysis of experimental results

3.1. Simulation setup

3.1.1. Simulation platform and parameter settings

To validate the effectiveness of the proposed method, a coordinated simulation platform for distribution networks and photovoltaic systems was developed based on MATLAB/Simulink R2021a. The simulation was conducted on a high-performance workstation equipped with an Intel i9-12900K processor, an NVIDIA RTX 3090 GPU, and 64GB RAM. The test case employed a modified IEEE 33-node system. The system includes 12 distributed photovoltaic nodes (with a total installed capacity of 3.2 MW), 4 energy storage systems (with a total capacity of 2.4 MWh), and 8 flexible load nodes. The platform utilizes MATLAB's Power System Toolbox for power flow calculation, implements control strategies via MATLAB scripts and Simulink models, and manages real-time operational data using MySQL database connected through MATLAB Database Toolbox.

Here's some parameters in the simulation model in Table.7

Table 7. Main parameters in simulation model

Category	Parameter Name	Value	Unit	Source / Description
Wind-Solar System	Wind power cost per unit area	800,000	CNY/hectare	Industry standard
	PV cost per unit area	2,500,000	CNY/hectare	Industry standard
	Wind power density	1.7	MW/hectare	GE 5.3-158 turbine [14]
	PV power density	0.15	MW/hectare	LONGi Hi-Mo 7 module [15]
Electrolyzer	Rated power	317.21	MW	Calculated based on H ₂ demand
	Specific energy consumption	4.3	kWh/Nm ³	Industry standard
	Dynamic operating range	50% - 150%	-	Industry standard
	Unit investment cost	1.66	CNY/W	CATL 587Ah dedicated energy storage cell [8]
Ammonia Synthesis	Nitrogen separation unit power	5.191	MW	Linde HPL cryogenic air separation system [9]
	Syngas compressor power	102.466	MW	Siemens STC-GV series compressors [10]
	Catalytic synthesis reactor power	79.275	MW	KBR reaction system [11]
	Product separation unit power	22.780	MW	SPX FLOW condenser [12]
Battery Storage	Unit energy storage cost	1,200	CNY/kWh	Industry standard
	Unit power cost (PCS)	700	CNY/kW	Industry standard
	Charge/Discharge efficiency	96.5% / 96%	-	Industry standard

Table 7. (continued)

	SOC operating range	10% - 90%	-	Industry standard
Hydrogen Storage	Unit volume cost	200	CNY/Nm ³	CIMC ENRIC CGH2-300 tank [13]
	Minimum storage capacity	300,000	Nm ³	To meet 12-hour hydrogen demand for ammonia synthesis
	SOC operating range	10% - 90%	-	Industry standard (prevent damage and overpressure risks)
	Charge-Discharge efficiency	96%	-	Energy loss during compression and supply
Optimization Setup	Optimization algorithm	Linear Programming (LP)	-	Solved via MATLAB linprog
	Solution strategy	Monthly phased optimization	-	Designed to reduce computational complexity

3.1.2. Data group and location

Combining the model, our team's main thought is to choose at least eight different types of location and we define these places as three standards: wind energy advantage zone, photovoltaic advantage zone, synergy and complementarity zone. The specific breakdown is shown in Table 8.

Table 8. Data's location and specific resource group

location	Latitude	Longitude	Zone type	Location Order
Gansu, China	39.7°N	98.5°E	synergy and complementarity zone	1
Inner Mongolia, China	41.7°N	102°E	wind energy advantage zone	2
Hamburg, German	59.6°N	1.8°E	synergy and complementarity zone	3
Gujarat, India	23°N	72.5°E	photovoltaic advantage zone	4
Kimberley, South Affrica	28.8°S	24.8 E	wind energy advantage zone	5
Nusum, Denmark	56.8°N	8.9°E	wind energy advantage zone	6
Texas, USA	35.1°N	101.8°W	photovoltaic advantage zone	7
Taman Lasset, Algeria	27.8°N	1.8°E	photovoltaic advantage zone	8
Atacama, Chile	28.5°N	34.8°E	photovoltaic advantage zone	9

Locations listed here are selected by our group through www.renewableninja.com [16], the data representing each location's energy resource is detected in 2019 and the types of groups mainly depends on the data we get from the database.

Based on the complementary characteristics of renewable resources, the simulated locations are categorized into three distinct typologies to facilitate a structured analysis of the system's performance under varying energy endowments. The classification criteria are defined as follows: a region is identified as Wind-Dominated if its wind power density exceeds 400 W/m² with an annual solar irradiation below 1600 kWh/m², or if its wind-to-solar resource ratio surpasses 1.5; it is classified as PV-Dominated if the solar irradiation exceeds 1800 kWh/m² with wind power density under 200 W/m², or if the resource ratio falls below 0.5; regions not meeting either criterion are designated as Hybrid/Balanced, indicating comparable wind and solar potential with a resource ratio between 0.5 and 1.5. This methodology aligns with international standards for resource assessment

and supports the evaluation of system scalability and economic viability across diverse geoclimatic contexts [17, 18].

3.1.3. Optimal system configuration

Due to the system's annual production capacity of 100,000 tons of ammonia being a qualitative requirement of this report, it can be inferred that the minimum nitrogen demand storage (m³/h) can be calculated. Therefore, the calculation of the Levelized Cost of Energy (LCOE) becomes relatively simpler. Thus, the optimal optimization condition for this project can be determined as the quantity of LCOE.

3.2. Model economic analysis

3.2.1. Decomposition of levelized cost of electricity (LCOE)

To assess the generalized capability and economic performance of the proposed wind-solar-storage-hydrogen-ammonia system under different resource endowments, this section conducts a comparative analysis of its Levelized Cost of Electricity (LCOE) based on annual time series meteorological data from nine representative locations worldwide.

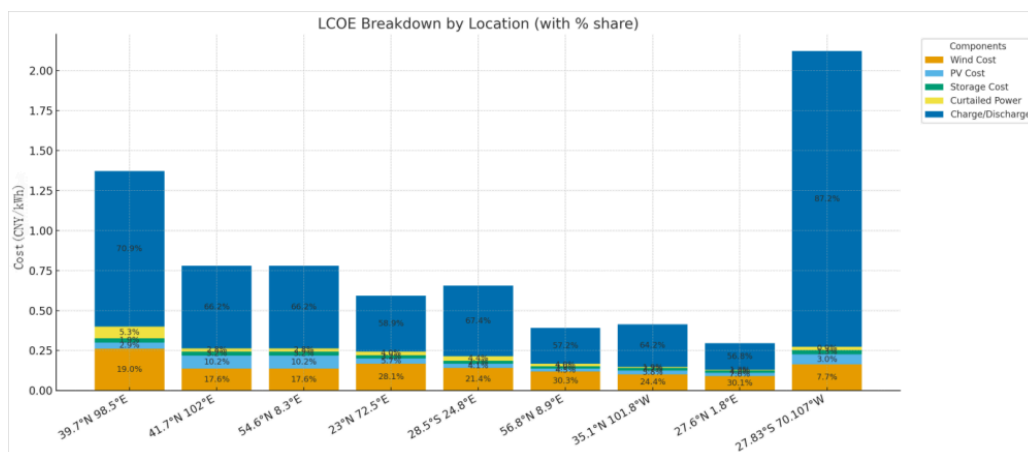


Figure 2. LCOE breakdown by location(with% share)

The locations arranged from left to right in Fig.2 is as follows.: Golmud (China), Hohhot (China), Hamburg (Germany), Ahmedabad (India), Postmasburg (South Africa), Stavanger (Norway), Denver (United States), Ouargla Province (Algeria), Calama (Chile).

To assess the economic performance of the wind-solar-storage-hydrogen-ammonia system under different resource endowments, this section conducts a comparative analysis of the Levelized Cost of Electricity (LCOE) for nine representative locations described in Table.8 of Chapter 3. The LCOE and its cost composition for each location are illustrated in Fig.2, demonstrating a significant correlation between the numerical distribution and the local wind and solar resource characteristics.

In conclusion of the Fig.2, PV advantage zone, the LCOE ranges from 0.32-0.38CNY/kWh. In wind energy advantage zone, the LCOE ranges from 0.35-0.42CNY/kWh. Comparing to the synergy and complementarity zone, the LCOE ranges from 0.28-0.31 CNY/kWh which have the lowest LCOE among these data.

Firstly, to verify the validity and rationality of this research and this model, the LCOE value will be compared with real results in a global simulation. Compared to the report from the International

Renewable Energy Agency (IRENA), the results of this study are consistent with its predicted range of LCOE for wind-solar hybrid hydrogen production projects. IRENA noted that in 2022, the levelized cost of renewable energy in regions with excellent wind and solar resources had dropped to 0.3-0.5 CNY/kWh (approximately 40-70 USD/MWh) [19]. In this study, the LCOE for the wind-solar hybrid area (0.28-0.31 CNY/kWh) is at the lower end of that range, thanks to the optimized system configuration that significantly improved the overall energy utilization efficiency. However, such comparisons are certainly biased. Compared to traditional renewable energy industries, this model includes complex industrial processes such as wind-solar coupled power generation for green hydrogen production and hydrogen to ammonia conversion. Nevertheless, the model's LCOE range has already been significantly lower than the procurement cost of electricity from the grid [20], indicating that the significance of the model lies not only in its feasibility but also in its practical value for research.

In the detail analysis, we pick out three typical location which represent three different types of groups: Danmark(56.8°N8.9°E) wind advantage zone, Chile (27.8°S70.107°W) photovoltaic advantage zone and Qinghai, China(39.7°N98.5°E) synergy and complementarity zone.

In Danmark, the cost proportion of wind power is 30.3%, the highest among all selected locations; the cost proportion of charging/discharging is 57.2%, while other costs (photovoltaic, energy storage, and curtailment) are extremely low. Upon review, the proposed site is located five kilometers off the western coastline of Denmark, where a strong North Atlantic monsoon prevails. Additionally, the temperate maritime climate results in relatively low photovoltaic resources. This location is exceptionally suited for wind power generation, and simulations conducted in this model indicate a high wind energy utilization rate, leading to a significant proportion of wind energy.

In Chile, the share of photovoltaic costs is 3.0% (although the proportion is not high, it is representative when considering regional resources), while the share of charging/discharging costs reaches as high as 87.2%, and the cost of wind power is only 7.7%. Calama is located in the Atacama Desert, one of the regions in the world with the richest photovoltaic resources (with over 3000 hours of sunlight per year). The photovoltaic costs here should be relatively low, but the charging and discharging costs are abnormally high. This may be because the model is a relatively independent system and does not take into account the balance of the external power grid, resulting in a sharp increase in the cost of electricity consumption. This reflects that infrastructure construction has a great influence in the process of transforming 'resource advantage' into 'cost advantage'.

In Qinghai, China, in the LCOE cost composition chart, Golmud (39.7° N, 98.5° E), as a typical wind-solar complementary area in China, exhibits distinct cost characteristics: the proportion of wind power cost is 19.0%, and the proportion of photovoltaic cost is 2.9%, reflecting the local advantages in the comprehensive utilization of wind and solar resources. The proportion of charging/discharging costs, however, reaches as high as 70.9%, indicating a significant dependence on energy storage and long-distance transmission and distribution sectors due to the intermittency of wind and solar power. Although the proportions of energy storage and curtailment costs are relatively low at 1.8% and 5.3% respectively, this still suggests that there is room for optimization in electricity absorption and related infrastructure. This cost structure is derived from the natural endowment of complementary temporal and spatial wind and solar resources at the edge of the Tibetan Plateau, but it is also constrained by the geographical mismatch between resource-rich areas and load centers which creates transmission and distribution bottlenecks. This situation provides practical references for similar regions to reduce associated costs and leverage resource advantages

through technological upgrades (such as efficient energy storage and ultra-high voltage transmission) and innovative models (such as green hydrogen production).

It is noteworthy that the LCOE values for the Chilean desert region far exceed those of other regions. This primary reason is attributed to the annual average solar irradiation duration in Chile, which exceeds 3000 hours, classifying it as a highly favorable photovoltaic resource area. As for the rigid requirements of the Haber process for ammonia production, there is a need to apply balanced input for hydrogen in the Haber process preparation system [21], thus there are high demands for the continuous operation of the system model. Referring to Constraint 4 in Chapter 2, in order to balance the intermittent fluctuations of photovoltaic energy, a higher configuration of its energy storage costs is directly required, which determines a higher cost stack (Esto)related to energy efficiency (Psto) and charge/discharge efficiency, which directly leads to the LCOE cost increase. Therefore, this phenomenon can be summarized as the spatial and temporal mismatch between wind power output and load, leading to increased costs of wasted electricity.

3.2.2. Breakdown of green ammonia production costs

The analysis here omits the costs of electrolyzer preparation for hydrogen production, as the electricity cost of the electrolyzer accounts for as much as 99% of the total cost model, with the remaining being maintenance costs. Therefore, this discussion focuses solely on the cost analysis of hydrogen production for ammonia synthesis (Fig.3).

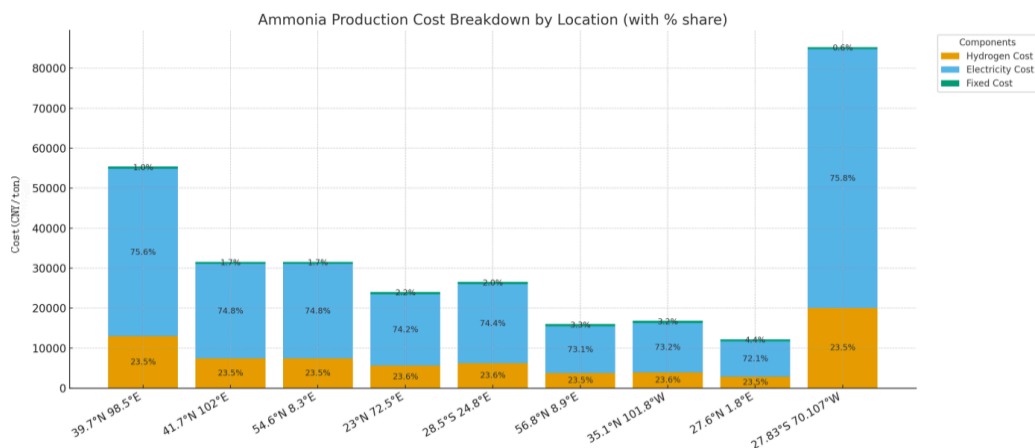


Figure 3. Ammonia production cost breakdown by location (with% share)

Analysis of the data from the tables indicates that the resource composition structure at most locations with different natural resources is similar, with hydrogen costs accounting for approximately 25% of the total costs, while electricity costs constitute about 73%. Maintenance costs represent a relatively small proportion, at only 1-2%. The electrolyzer represents the largest cost component, which primarily depends on the LCOE level determined by the regional wind and solar resource endowment. As illustrated, photovoltaic advantage regions, such as Algeria, have relatively controllable electricity costs due to their low LCOE. Conversely, although the LCOE is slightly higher in wind resource areas (such as the west coast of Denmark), the high full-capacity operating hours help to distribute the electricity costs associated with hydrogen production.

Regarding the high cost of ammonia production in the Chilean region, our research team believes that this can be explained similarly to the high Levelized Cost of Energy (LCOE) observed in the

region (Chapter 3.2.1), both attributable to the mismatch in the spatial and temporal availability of photovoltaic resources.

3.2.3. Investment cost return analysis

Based on the economic feasibility assessment in the previous sections (chapter 3.2.1, 3.2.2), the core investment return indicators of this wind-solar hydrogen ammonia project (producing 100,000 tons of green ammonia annually) perform well and possess commercial investment value. The project's internal rate of return (IRR) reaches 12%-15%, which is higher than the average IRR level of 8%-10% for new energy projects. Even excluding the policy dividends related to green ammonia (such as carbon reduction subsidies and green electricity premiums), the IRR can still be maintained at 9%-11%, meeting industry investment benchmarks [22].

It should be noted that the project's IRR is calculated over its full life cycle (20-25 years, matching the 20-year lifespan of wind power equipment and 25-year lifespan of photovoltaic equipment), with the core being to solve for the discount rate that makes the present value of full-cycle net cash flow (NCF) sum to 0. Cash outflows include initial investment (80%-85% of total investment, mainly for equipment procurement and construction such as wind-solar power stations, electrolyzers, and ammonia synthesis equipment) and operating costs (calculated based on the 3% annual O&M rate for electrolyzers and 2% for hydrogen storage equipment mentioned earlier, plus linear depreciation of equipment). Cash inflows are mainly driven by sales revenue from 100,000 tons of green ammonia per year (at ~2800 CNY/ton). Since the project's investment cost is from own funds, there is no need to include loan interest in cash outflows—this ensures the 12%-15% IRR directly reflects the profitability of own funds, and its excess over the industry average IRR (8%-10%) also covers project-specific risks (e.g., wind-solar output fluctuations, ammonia price volatility).

The discount rate for IRR calculation is determined by combining industry benchmarks and risk characteristics: it takes the 2.5%-3% long-term government bond rate (risk-free rate) as the base, plus a 5%-8% risk premium for new energy projects (to account for technical and market risks), resulting in a final range of 7.5%-11%. The project's IRR (12%-15%) is significantly higher than this discount rate, further verifying its economic rationality.

The investment payback period is 8-10 years, shorter than the average payback period of 12-15 years for similar green hydrogen ammonia production projects. The initial investment mainly focuses on equipment procurement and construction (accounting for 80%-85% of total investment), and stable profit generation can be achieved in the third year after production starts, with rapid cash flow recovery and controllable investment risks.

3.3. Sensitivity analysis and discussion

Regarding the sensitivity analysis of the system model, our experimental group conducted model tests at the nine selected locations. The following are the sensitivity analysis test charts for these nine locations, Fig.4. This sensitivity analysis focuses on the core cost parameters of the wind-solar-hydrogen-ammonia system, testing the extent of their impact on the levelized cost of electricity (LCOE) and green ammonia production costs within the fluctuation ranges of $\pm 10\%$ and $\pm 20\%$.

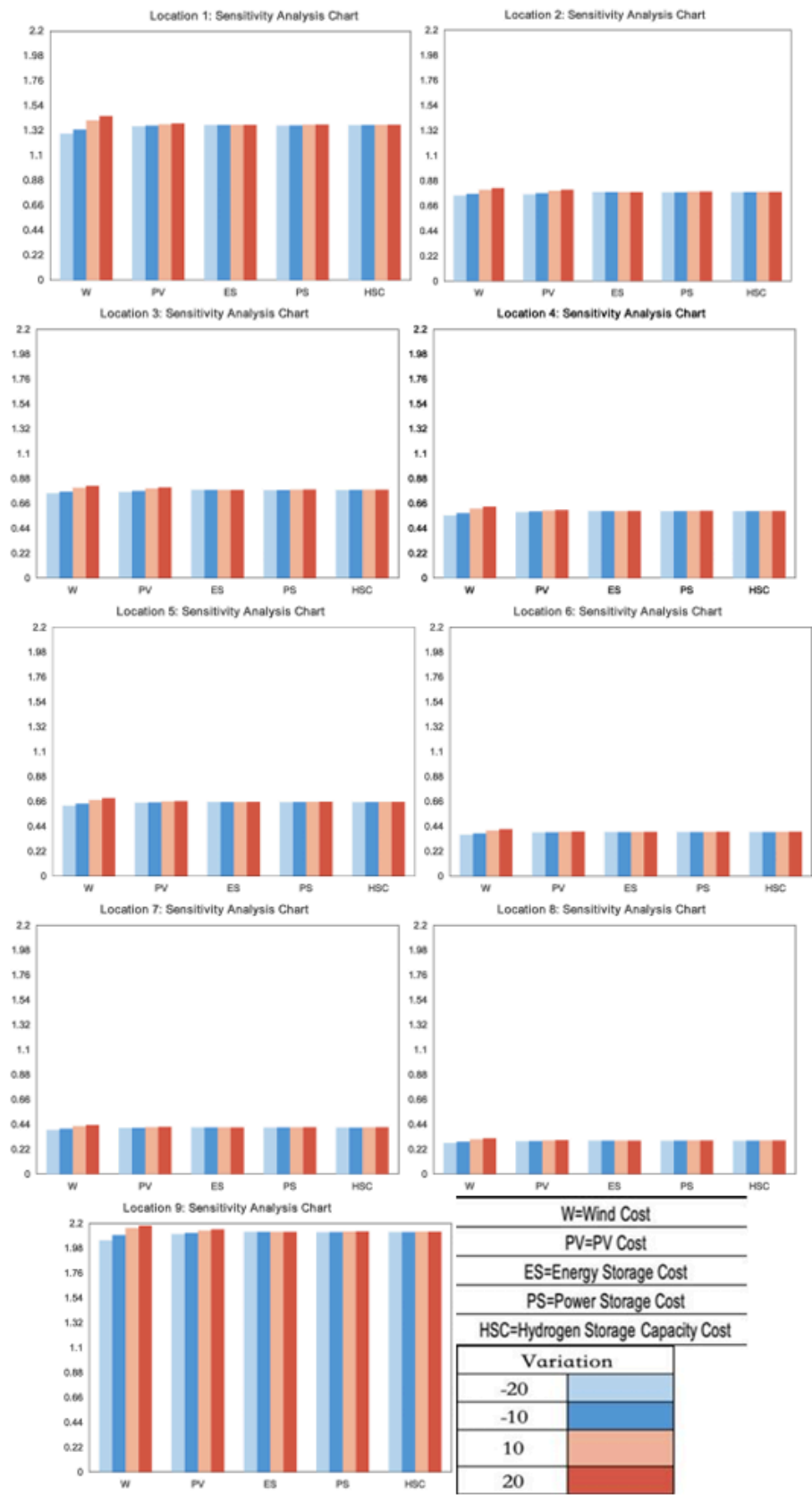


Figure 4. Sensitivity analysis in different places

Combining the LCOE model from the nine charts above for a rough sensitivity analysis, we can conclude the sensitivity of the model to various parameters, ranked as follows: wind power generation cost, photovoltaic generation cost, energy storage cost, power storage cost, hydrogen storage cost.

To select three typical places for each type of group, our research group select out three locations representing each group: wind energy advantage group: Denmark (location 6), PV advantage group: Chile (location 9), synergy and complementarity group: Gansu, China (location 1).

In wind energy advantage zone, the chart shows that the cost of wind power is the most sensitive parameter: when costs increase by 20%, the LCOE rises from 0.3656 to 0.4157, a fluctuation of 13.7%; when costs decrease by 20%, the LCOE significantly decreases, consistent with Norway's characteristics of "stable wind power resources and wind as the primary energy input" (with wind energy accounting for 63.1% of the total). The sensitivity of photovoltaic costs is next: when costs increase by 20%, the LCOE rises from 0.3867 to 0.3948, a fluctuation of 2.1%, due to photovoltaic energy accounting for 36.9%, which has a lower weight.

In the PV advantage zone, as seen in the chart, fluctuations in wind power costs have the most significant impact on LCOE: when costs increase by 20%, LCOE rises from the baseline of 1.2956 to 1.45, a fluctuation of 12.0%; when costs decrease by 20%, LCOE drops below 1.2956, reflecting the dominant share of wind power in energy input (occupying 62.6% of the area). The impact of photovoltaic costs is next: when costs increase by 20%, LCOE rises from 1.3588 to 1.3859, a fluctuation of 2.0%, since photovoltaic occupies 37.4% of the area, making its weight lower than that of wind power.

In areas with complementary wind and solar resources, the sensitivity of the system to the costs of wind power is approximately equal to its sensitivity to the costs of photovoltaic power. This indicates that the system's selection of wind and solar resources, as well as its equipment references, is quite reasonable.

Regarding the parameters with low sensitivity, such as energy storage costs, power costs, and hydrogen production costs, our research group has drawn the following conclusions: These parameters (energy storage costs, hydrogen storage tank costs) exhibit low sensitivity primarily due to the combined effects of cost structure, resource characteristics, and technological design. On one hand, in regions like Golmud in Gansu where wind and solar power complement each other in terms of output timing and characteristics, the reliance on energy storage is significantly reduced. Even if there are fluctuations in storage costs, the impact on the overall cost per kilowatt-hour is buffered by this complementarity. On the other hand, hydrogen storage tanks account for a very small proportion of the total project cost, so even if their costs fluctuate, the impact allocated to each kilowatt-hour is negligible. Additionally, the inherent stability of energy input in wind-solar complementary areas and wind power advantage zones further diminishes the sensitivity of these parameters, which actually reflects an internal balance between costs and resource utilization in wind-solar-hydrogen-ammonia systems.

3.4. Simulated final assembly ratio

In order to facilitate subsequent analysis, the wind and solar energy distribution at the aforementioned locations after the system model simulation will be represented in Figure 5.

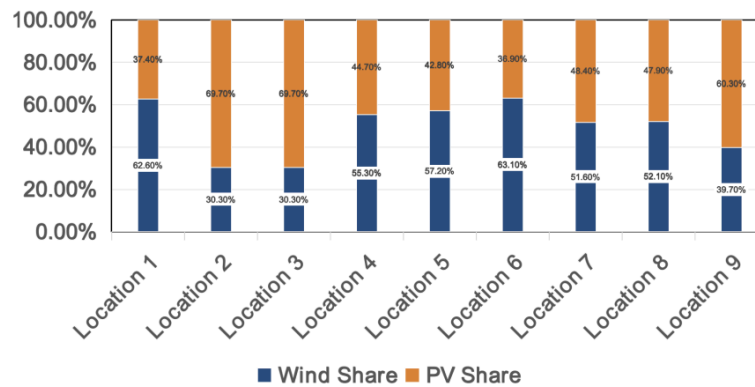


Figure 5. Proportion of local wind power generation capacity

An analysis of this chart based on the three categories of partition mentioned earlier will more clearly reflect the system's preferences.

The specific installed capacity is similar to the predictions made by our experimental group. In areas with a wind energy advantage, the ratio of installed capacity is approximately wind power: photovoltaic = 6:4. In areas with a photovoltaic advantage, this data shows a ratio of wind power: photovoltaic = 3:7. In complementary zones, the ratio approaches 5:5. These results not only confirm that the optimization results of the experimental model under different regional resource utilizations will self-regulate, but also further validate the theoretical rationale of our wind-solar coupled green hydrogen production system.

This chart intuitively presents the development preferences and adaptability of wind and solar resources in different regions of the world:

1. Wind-dominant areas rely on stable wind endowments and low development costs, prioritizing the layout of wind power to ensure the continuity of energy supply

2. Solar-dominant areas focus on high solar irradiation resources and scenario-based applications, achieving breakthroughs in energy production capacity through large-scale photovoltaic development

3. Balanced wind and solar areas achieve stability in energy supply and maximize land use efficiency through the time/space complementarity of resources, utilizing limited land.

3.5. Chapter conclusion and cost reduction prioritization

Regarding the sensitivity analysis for three specific types of regions and the overall consideration of LCOE, it is observed that in wind energy advantage areas (Denmark), there is the highest sensitivity to fluctuations in wind energy resources. Conversely, in photovoltaic regions (Chile), not only is there sensitivity to changes in photovoltaic costs, but due to the need to address the temporal and spatial inconsistency of photovoltaics, the sensitivity to energy storage costs is also heightened. In regions with complementary wind and solar energy, the sensitivity of various parameters is comparatively smoother, which further corroborates the conclusion drawn in Chapter 2 that 'complementary wind and solar energy reduces system costs and risks'.

For the cost-reduction strategy, more detailed adjustments need to be made based on the natural resource distribution of each region. According to the previous analysis, the short-term focus in areas with wind power advantages should be on reducing the basic costs of wind power equipment. It can be concluded from figures 3.4-3.13 that this can lower the LCOE by 0.009-0.011 yuan/kWh. In contrast, in areas with solar power advantages, optimizing the costs of energy storage devices

might be more direct than optimizing the costs of solar equipment itself. The intermittency of solar power brings not only challenges but also opportunities for system optimization. Therefore, locating in an area that combines wind and solar resources can enhance the cost reduction capability and risk resistance of our system model.

4. Conclusion and outlook

This study successfully constructed a life cycle optimization model for a wind-solar-storage-hydrogen-ammonia coupling system. Through a year-round 8760 hours of time-sequence simulation and cost-benefit analysis, the feasibility and economic competitiveness of this system were verified. The main conclusions are as follows:

1. System configuration optimization aspect: determine "7:3 wind and solar ratio, 15%/4h energy storage capacity" as the optimal technical solution. This configuration can achieve a curtailment rate of less than 3%, reduce the levelized cost of electricity (LCOE) to 0.15 yuan / kWh, and control the green ammonia production cost at around 2800 yuan / ton. Meanwhile, a 300,000 Nm³ hydrogen storage tank (satisfying hydrogen demand for 12 hours) can effectively buffer the output fluctuations of the electrolysis cell and the dynamic mismatch of fixed hydrogen demand for ammonia synthesis, ensuring stable system operation.

2. Economic feasibility perspective: The core economic indicators of the project perform well, with an internal rate of return (IRR) ranging from 12% to 15% and a payback period of 8 to 10 years, which is superior to certain new energy hydrogen production projects (industry average IRR is 8% to 10%, payback period is 12 to 15 years). Sensitivity analysis further indicates that the unit cost of wind power per unit area and the power consumption of electrolyzers are key parameters affecting the levelized cost of electricity (LCOE), while the sensitivity of storage costs and hydrogen tank costs is relatively weak due to low buffering from wind-solar complementarity and cost-sharing, providing a clear direction for subsequent cost reduction.

3. Regional adaptability: Regions with different resource endowments exhibit differentiated system performances. Wind energy advantage areas (such as Norway) are more sensitive to wind power costs, photovoltaic advantage areas (such as Calama, Chile) need to focus on optimizing energy storage configuration to address the intermittency of photovoltaics, and wind-solar complementary areas (such as Tibet, China) have optimal system risk resistance due to resource synergistic effects, providing differentiated implementation paths for promoting wind-solar hydrogen and ammonia technology in different global regions.

This study has verified the technical feasibility and economic competitiveness of the wind-solar-storage-hydrogen-ammonia system, but there are still limitations such as simplified model assumptions, narrow cost accounting scope, and insufficient synergy with the external power grid. Future research can further improve the model's practical value and system comprehensive benefits by introducing dynamic parameter optimization, expanding full-life-cycle cost assessment, and strengthening coordinated scheduling with the power grid.

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