Optimization of Electricity Market Trading Mechanism under High Penetration of New Energy Research on Cross Provincial and Cross Regional Electricity Resource Allocation and Pricing Strategies Based on Game Theory

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ABSTRACT Against the background of the dual-carbon strategy and accelerated construction of a new power system, new energy has entered a high-penetration stage characterized by volatility, intermittency, and spatial mismatch between resource supply and load demand. Traditional inter-provincial and inter-regional electricity trading mechanisms can no longer fully adapt to the random output and anti-peak-shaving characteristics of new energy. This study focuses on cross-provincial and cross-regional electricity resource allocation and pricing strategies under high penetration of new energy. Based on game theory, a multi-agent analytical framework is constructed, integrating Cournot competition among power generation entities, Stackelberg pricing between grid enterprises and market participants, and Shapley value-based cooperative benefit allocation among provinces. The study analyzes contradictions in resource-load spatial mismatch, trading-mode rigidity, price-signal distortion, transmission congestion, and regional benefit distribution. It further proposes an integrated mechanism combining priority trading for new energy, time-sharing and zonal nodal pricing, endogenous congestion sharing, revenue sharing, and full-time-sequence coordination from medium- and long-term trading to real-time dispatch.

INDEX TERMS new energy penetration, electricity market trading, game theory, resource allocation, pricing strategy

I. INTRODUCTION

A. RESEARCH BACKGROUND

DRIVEN by China's strategic carbon peak and neutrality goals, the integration of high-performance materials in wind turbine blades and photovoltaic components has propelled new energy sectors to a leapfrog development stage, maintaining a world-leading position in both installed capacity and power generation. By the end of 2024, the total installed capacity of wind and photovoltaic power in China has exceeded 1.3 billion kilowatts, accounting for over 42% of the total installed power generation capacity. The annual proportion of new energy generation in the total power generation is close to 15%. In regions rich in new energy resources such as the northwest, northeast, and southwest, the proportion of instantaneous output of new energy power generation frequently exceeds 50%, and some daily output accounts for over 90%. The high penetration of new energy, facilitated by the structural reinforcement of power facilities with high-performance industrial textiles, has become the defining characteristic of China's modern power system operation[1-3]. At the same time, there is a significant spatial mismatch between energy resources and electricity load in China: new energy resources are concentrated in the western and northern regions, while load centers are concentrated in the central and eastern regions and coastal provinces. Large scale, long-distance, cross provincial and cross regional power transmission has become an inevitable choice to ensure power balance and promote the consumption of new energy. Cross provincial and cross regional electricity trading is a core institutional arrangement for achieving large-scale resource optimization, smoothing regional electricity price differences, and improving system operation efficiency. It is also a key lever for building a unified national electricity market[4-6].

B. RESEARCH SIGNIFICANCE

1) Theoretical significance

Firstly, establish a multi-agent game theory framework for cross provincial and cross regional electricity trading under high penetration of new energy, incorporating non cooperative games, master-slave games, and cooperative games into a unified analysis system, and enriching the cross application system of electricity market economy theory and game theory. Secondly, establish an optimized allocation and market-oriented pricing model for power resources that integrates uncertainty in new energy, spatial transmission congestion, and multi regional conflicts of interest, and improve the theoretical design of power market mechanisms in the context of the new power system. Thirdly, propose a trading equilibrium implementation mechanism that takes into account global efficiency, individual rationality, and incentive compatibility, providing new paradigms, methods, and support for the theoretical research of the national unified electricity market. Fourth, expand the theory of market-oriented consumption of new energy, incorporate cross provincial and cross regional transactions, price formation, and interest coordination into a unified analysis framework, and improve the theoretical system of consumption of high proportion new energy power systems.

2) Practical significance

Firstly, to enhance the utilization rate of cross provincial and cross regional transmission channels and the space for new energy consumption, effectively alleviate the problem of wind and solar power curtailment, improve energy utilization efficiency, and help achieve the dual carbon goals. Secondly, to form a market-oriented electricity price signal that can fully reflect electricity supply and demand, transmission costs, system regulation costs, and environmental value, and to suppress abnormal fluctuations in electricity prices and regional price imbalances. Thirdly, coordinate the distribution of interests among provinces, break down administrative market barriers, and achieve a balanced and win-win situation among power generation enterprises, power grid enterprises, electricity sales entities, and end users. Fourthly, provide operational, implementable, and promotable trading rules, pricing methods, and scheduling coordination plans for electricity trading institutions, power grid enterprises, and energy regulatory departments, supporting the effective implementation of a unified national electricity market system.

C. RESEARCH IDEAS, METHODS, AND INNOVATIVE POINTS

1) Research Approach

This article follows the complete technical route of “extracting practical problems - sorting out theoretical foundations - modeling multi-agent games - optimizing transaction mechanisms - simulating and verifying examples - proposing policy recommendations”. It systematically analyzes the inherent contradictions and operating mechanisms of cross provincial and cross regional electricity trading under high penetration of new energy, constructs a multi-agent game model and solves the equilibrium, designs an integrated optimization mechanism, verifies its effectiveness through simulation, and proposes policy recommendations[7-9].

2) Research Methods

(1) Literature research method: Systematically review the achievements related to the electricity market, game theory, pricing theory, and new energy consumption, grasp the forefront and shortcomings of research;

(2) Game theory methods: Construct Cournot electricity competition model, Stackelberg master-slave pricing model, and Shapley benefit distribution model to accurately depict multi-party interest conflicts and strategic interactions;

(3) Optimization modeling method: Establish cross regional optimal power flow models, robust optimization models, and distributed optimization algorithms, incorporating system safety constraints and new energy uncertainties into the analysis framework.

3) Innovation points

(1) Perspective innovation: Based on the dual constraints of high penetration of new energy and a unified national electricity market, we aim to optimize the entire chain, process, and subject of cross provincial and cross regional electricity trading, breaking through the limitations of traditional “segmented research and local optimization”;

(2) Model innovation: Construct a three-layer coupled game model of “electricity competition price guidance benefit distribution”, incorporating non cooperative game, master-slave game, and cooperative game into a unified framework to achieve collaborative optimization of price formation, resource allocation, and benefit distribution;

(3) Mechanism innovation: Propose an integrated rule system of “new energy priority trading+time-sharing and zoning node pricing+blocking endogenous sharing+revenue sharing”, accurately adapting to the high penetration characteristics of new energy, and balancing efficiency and fairness;

(4) Application innovation: Form a “medium to long term - day ahead - day within - real-time” full time sequence connection scheme, achieve deep coordination between scheduling plans and market transactions, and have high engineering practicality and promotability.

II. THEORETICAL BASIS AND INHERENT CONTRADICTIONS OF CROSS PROVINCIAL AND CROSS REGIONAL ELECTRICITY TRADING UNDER HIGH PENETRATION OF NEW ENERGY

A. DEFINITION OF CORE CONCEPTS

1) High penetration of new energy

The high penetration of new energy refers to the high proportion of installed capacity, power generation, and instantaneous output of renewable energy sources such as wind and photovoltaic power, which results in a new operating characteristic of low inertia, strong fluctuations, high uncertainty, sharp increase in peak shaving pressure, frequent reversal of power flow, and significant increase in backup demand in the power system[10-13].

2) Cross provincial and cross regional electricity trading

Cross provincial and cross regional electricity trading refers to the general term for market-oriented trading activities such as medium - and long-term electricity trading, spot electricity trading, auxiliary service trading, contract transfer trading, and exchange trading between different provincial administrative regions and regional power grids, relying on cross provincial and cross regional transmission channels.

3) Optimization of Trading Mechanism

Optimization of trading mechanism refers to the systematic reconstruction of rules such as trading subjects, trading varieties, trading timing, price formation, transmission pricing, congestion allocation, benefit distribution, settlement assessment, risk prevention and control, etc., to adapt to the high penetration characteristics of new energy and the global resource optimization allocation goals[14-16].

4) Application of Game Theory in the Electricity Market

Game theory is used to describe the conflicts of interest, strategic interactions, and behavioral decisions among multiple parties in the electricity market, including power generation companies, grid companies, provincial market entities, power sales companies, and end users. It solves Nash equilibrium, master-slave equilibrium, and alliance equilibrium, providing scientific decision-making basis for trading mechanism design.

B. BASIC THEORETICAL SYSTEM

1) Theory of Electricity Market Economy

The theory of electricity market economy is the core theoretical system for analyzing the operational efficiency, price formation mechanism, and social welfare distribution of the electricity market, mainly including: Theory of Electricity Price Formation: Clarify the law that electricity prices are jointly determined by marginal costs, supply and demand relationships, blocking costs, environmental value, etc., breaking through the limitations of traditional "cost plus pricing"; Market Power Theory: Analyzing the behavior and regulatory pathways of market entities using their dominant market position to influence prices and exclude competition, in order to prevent market monopolies and unfair competition; The theory of maximizing social welfare: aiming to maximize the sum of consumer surplus, producer surplus, and external benefits, it is the core criterion for evaluating the efficiency of market mechanisms and providing value judgment standards for mechanism optimization[17-19]. In the context of high penetration of new energy, the application focus of electricity market economy theory has shifted from "traditional thermal power cost pricing" to "endogenous pricing of new energy uncertainty and blockage costs", and from "local equilibrium within the province" to "global optimization equilibrium across provinces", providing core theoretical guidance for the design of cross provincial and cross regional trading mechanisms.

2) Game Theory

Game theory is a core tool for characterizing conflicts of interest and strategic interactions among multiple parties. In cross provincial and cross regional electricity trading, its theoretical system mainly includes: Non cooperative games, such as Cournot production competition and Bertrand price competition, are used to analyze the self-interest strategies and Nash equilibrium among power generation companies, depicting the dilemma of "individual rationality leading to collective irrationality"; Stackelberg game: used to describe the hierarchical structure of "leader follower", such as the decision-making logic of power grid enterprises setting transmission prices and market entities responding to quotations, reflecting the interactive relationship of hierarchical decision-making; Cooperative games, such as alliance games and Shapley value allocation, are used to solve problems of multi regional interest coordination and benefit sharing, achieving the unity of individual rationality and collective rationality; Equilibrium solution and stability theory: Verify the feasibility and robustness of game equilibrium, ensure that the mechanism is not disrupted by individual deviant behavior in long-term operation, and guarantee the sustainability of the mechanism. Game theory provides a rigorous mathematical tool and analytical framework for addressing core issues such as conflicts of interest among multiple parties, global efficiency, and local balance of interests. It is a key theoretical foundation for designing efficient, fair, and stable cross provincial and cross regional trading mechanisms.

3) Optimal Flow and Congestion Management Theory

The optimal power flow and congestion management theory is the fundamental theory for solving inter provincial and inter regional transmission congestion and improving channel utilization, mainly including: Cross regional optimal power flow model: With the goal of minimizing system operating costs and maximizing social welfare, considering constraints such as channel capacity, voltage stability, and frequency stability, optimizing inter provincial power allocation and achieving global resource optimization; The endogenous pricing theory of blocking costs: internalizing the cost of transmission blocking into electricity prices, guiding the distribution of power flow through price signals, alleviating blocking, and achieving "price controlled flow"; Transmission capacity allocation theory: When multiple parties compete for channel resources, fair and efficient allocation of scarce transmission capacity is necessary to avoid channel waste and abuse, and ensure optimal utilization of channel resources. In the context of high penetration of new energy, the application focus of this theory has shifted from "static blocking management" to "dynamic blocking prediction and prevention", and from "single line blocking" to "multi regional, multi time period, and multi-channel collaborative blocking management", providing guarantees for the safe and stable operation of cross provincial and cross regional transactions.

4) New Energy Consumption Theory

The theory of new energy consumption is the core theory guiding the consumption of high proportion new energy power systems, mainly including: Theory of Spatial Shifting Consumption: By transmitting electricity across provinces and regions, new energy is transported from enriched areas to load centers, expanding consumption space and achieving spatial range consumption; Time transfer and consumption theory: By means of energy storage, pumped storage, and adjustable load, the output of new energy is transferred from low peak periods to high peak periods to achieve time range consumption; Market driven consumption theory: Through market-oriented mechanisms such as price signals, priority trading, and consumption responsibility weights, market entities are incentivized to actively consume new energy, avoiding the inefficiency of administrative mandatory consumption and improving the sustainability of consumption. In the scenario of cross provincial and cross regional trading, the theory of new energy consumption emphasizes the synergy of "spatial translation+time transfer+market-oriented incentives", expands the consumption space through cross provincial trading, adapts to fluctuations through spot and real-time trading, and guarantees consumption enthusiasm through price and benefit mechanisms, which is the theoretical basis for building a high proportion of new energy consumption system.

C. FIVE INTERNAL CONTRADICTIONS IN CROSS PROVINCIAL AND CROSS REGIONAL ELECTRICITY TRADING UNDER HIGH PENETRATION OF NEW ENERGY

1) Resource and load space mismatch contradiction

The typical characteristics of China's energy resource endowment are "rich in the west, poor in the east, rich in the north, and lacking in the south": new energy resources such as wind power and photovoltaics are concentrated in the northwest, northeast, southwest and other regions, while the power load centers are highly concentrated in the central and eastern regions and economically developed coastal provinces. There is a large-scale and long-distance mismatch between new energy resources and load demand in space[20]. This mismatch determines that cross provincial and cross regional power transmission and trading is an inevitable choice to achieve global power balance. However, under traditional trading mechanisms, inter provincial barriers and local protection prioritize the protection of local power sources in channel resources, limiting the entry of foreign new energy power into the market. The spatial mismatch contradiction is further exacerbated, forming a distorted pattern of "abandoned wind and solar power in the west, high electricity prices in the east": when new energy is generated in the west, it cannot be fully sent out through cross provincial channels, leading to power abandonment; During peak load periods in the eastern region, the inability to timely introduce low-priced new energy electricity has led to power supply shortages and price increases.

2) Contradiction between Trading Mode and New Energy Characteristics Mismatch

Traditional cross provincial and cross regional transactions are mainly based on medium and long-term rigid contracts, with contract electricity accounting for over 80%. The trading cycle is long and the flexibility is poor, making it difficult to match the intermittent, volatile, and stochastic characteristics of new energy generation. The fluctuation range of new energy output within a day can reach more than 50% of the rated capacity, and the ultra short term prediction error can reach 20%~30%. However, medium and long-term contracts cannot be adjusted in real time, resulting in a mismatch between contracted electricity and actual output: when new energy is generated, contracted electricity cannot be fully sent out, leading to power abandonment; When there is a shortage of new energy generation, the contracted electricity cannot be fully completed, causing balance pressure and default risk. At the same time, the underdeveloped spot market and the lack of intraday and real-time trading mechanisms are unable to effectively stabilize the ultra short term fluctuations of new energy, further exacerbating the mismatch between trading models and new energy characteristics, forming a vicious cycle of "the more volatile the new energy, the more rigid the trading, and the more severe the power abandonment".

3) Price signal and system cost mismatch contradiction

The traditional cross provincial and cross regional electricity pricing mechanism is mainly based on "cost markup+government pricing", which cannot fully reflect the true cost and value of the power system, resulting in serious distortion of price signals: Lack of blocking costs: Failure to internalize transmission blocking costs into electricity prices has resulted in low blocking channel electricity prices, which cannot guide flow optimization and exacerbate blocking problems; Underestimation of adjustment costs: Insufficient consideration of auxiliary service costs such as peak shaving, frequency regulation, and backup brought about by fluctuations in new energy, resulting in the inability to reasonably recover the adjustment costs of thermal power, which undermines the adjustment enthusiasm of thermal power enterprises; Neglecting environmental value: The low-carbon and environmental protection value of new energy has not been included in electricity prices, resulting in low prices for new energy electricity and insufficient enthusiasm for consumption, which cannot reflect the "low-carbon premium"; Regional price imbalance: Affected by administrative intervention and local protection, some receiving provinces artificially lower external electricity prices, forming a "price inversion" that damages the interests of sending provinces and new energy generation enterprises, exacerbating inter provincial interest conflicts. The distortion of price signals further distorts resource allocation, exacerbates congestion and power abandonment problems, and forms a vicious cycle of "price mismatch resource mismatch low efficiency", seriously restricting the efficiency of system operation and the level of new energy consumption.

4) Conflict between Regional Interests and Global Efficiency Mismatch

The basic feature of China's electricity market is that "provinces are entities". Provincial governments and power grid enterprises prioritize local interests such as employment, taxation, and power protection, forming inter provincial barriers and local protectionism Restricting the scale of foreign electricity entering the market by the end provinces, protecting the interests of local thermal power enterprises, and avoiding the impact of foreign electricity on the local market; The sending provinces restrict the export of new energy to ensure local power supply and employment, and avoid "local power supply shortage caused by export"; Unequal distribution of profits in cross provincial transactions, with sending provinces bearing the cost of new energy consumption and channel construction, while receiving provinces enjoy low-priced electricity, further exacerbating inter provincial conflicts due to the imbalance of interests. This game pattern of prioritizing local interests over global efficiency makes it difficult to implement the globally optimal cross provincial resource allocation plan, resulting in low channel utilization rates (averaging less than 60%) and limited space for new energy consumption. This creates an inefficient equilibrium where "each province cleans its own doorstep and sacrifices global efficiency", seriously restricting the construction of a unified national electricity market.

III. CONSTRUCTION OF MULTI AGENT GAME FRAMEWORK FOR CROSS PROVINCIAL AND CROSS REGIONAL ELECTRICITY TRADING UNDER HIGH PENETRATION OF NEW ENERGY

A. COMPOSITION AND BEHAVIORAL CHARACTERISTICS OF TRADING ENTITIES

1) New energy power generation enterprises

New energy generation enterprises are the core supply side entities for cross provincial and cross regional transactions, mainly including renewable energy generation enterprises such as wind power, photovoltaic, biomass, etc. Its core behavioral characteristics are: pursuing the maximization of power generation and revenue, while being constrained by the responsibility of new energy consumption, environmental policies, and grid connection technology standards.

2) Conventional energy generation enterprises

Conventional energy generation enterprises mainly include thermal power, hydropower, nuclear power and other enterprises, which are the basic output and regulation entities of the power system. Its core behavioral characteristics are: providing stable basic output and auxiliary services such as peak shaving, frequency regulation, and backup, while being constrained by energy consumption control, environmental policies, market prices, and unit operating characteristics.

3) Power grid enterprises

Power grid enterprises are the core transmission and distribution entities for cross provincial and cross regional transactions, responsible for providing transmission services, power flow control, congestion management, and safety and stability constraints. Its core behavioral characteristics are: pursuing efficient utilization of transmission channels, safe and stable system operation, reasonable recovery of transmission costs, while being constrained by energy regulatory agencies and provincial governments.

4) Provincial Electricity Market and Trading Center

The provincial electricity market and trading center is the organization and execution entity for cross provincial and cross regional trading, responsible for trading organization, market clearing, settlement assessment, and information disclosure. Its core behavioral characteristic is to balance local interests with overall efficiency, promote efficient operation of cross provincial and cross regional transactions while ensuring local power supply and fulfilling the weight of consumption responsibilities.

5) Electricity Sales Companies and Large Users

In cross provincial and cross regional transactions, the core demands of power sales companies and large users are to introduce low-priced electricity through cross provincial transactions, stabilize regional electricity price fluctuations, improve power supply reliability, and avoid local power supply shortages and the risk of electricity price increases. At the same time, electricity sales companies and large users can stabilize their own electricity consumption fluctuations, reduce purchasing costs, and improve electricity efficiency by participating in intraday and real-time transactions.

B. DEFINITION OF MULTI AGENT GAME RELATIONSHIPS

1) Cournot game between power generation entities

The typical non cooperative game (Cournot production competition) relationship between power generation entities (new energy power generation enterprises and conventional energy power generation enterprises) is formed: each power generation entity takes cross provincial and cross regional trading of electricity and pricing as decision variables, and pursues the maximization of its own benefits under constraints such as channel capacity and system safety.

2) Stackelberg game between power grid enterprises and market entities

The relationship between power grid enterprises and market entities constitutes a Stackelberg game: power grid enterprises, as upper level leaders, formulate transmission prices, congestion cost sharing coefficients, and transaction rules; As lower level followers, the main bodies of the power generation side and the power purchase side make decisions on the optimal quotation, cross provincial power purchase, and power generation output curve according to the rules formulated by the power grid enterprise.

3) Cooperation Game among Multiple Provincial Regions (Shapley)

A cooperative game (Shapley alliance game) relationship is formed between multiple provincial regions: multiple provincial regions form a cross provincial trading alliance, sharing the incremental benefits brought by cross provincial transactions, including channel utilization efficiency improvement benefits, new energy consumption incremental benefits, electricity purchase cost reduction benefits, and system loss reduction benefits. In this game relationship, the total benefit of the alliance is greater than the sum of the benefits of individual actions by each region, indicating the existence of collaborative gains. By using Shapley's value to distribute the incremental benefits of the alliance, it is possible to ensure fairness, stability, symmetry, and effectiveness in the distribution results: the benefits of each region are equal to its marginal contribution to the alliance, that is, the additional benefits brought by the region joining the alliance. This distribution mechanism weakens inter provincial barriers and local protection from the root of interests, encourages regions to actively participate in cross provincial transactions, and achieves a cooperative balance of "overall efficiency improvement and multi-party win-win".

C. MODEL ASSUMPTIONS AND CONSTRAINTS

To ensure the rigor and solvability of the game model, this article proposes the following core assumptions and constraints:

(1) Assumption of new energy output: New energy output follows interval prediction or probability distribution, considering prediction error and fluctuation risk, and the ultra short term prediction error is controlled within the range of 20% to 30%;

(2) Channel constraint assumption: The capacity, line flow, voltage stability, frequency stability, and other constraints of cross provincial and cross regional transmission channels are rigid constraints, and the transaction clearing results must meet safety requirements;

(3) Subjective rationality assumption: All market entities satisfy the assumption of complete rationality, pursue maximum returns or minimum costs, and there is no irrational decision-making behavior;

(4) Information symmetry assumption: Market entities are able to obtain complete transaction information, price information, and security constraint information, and there is no adverse selection or moral hazard caused by information asymmetry;

(5) Mechanism constraint assumption: The optimization mechanism satisfies the conditions of incentive compatibility and individual rationality, ensuring that market entities actively participate in transactions and that individual behavior conforms to the global optimal goal;

(6) Time scale assumption: The trading model covers the entire time series of year, month, day ahead, day ahead, and real-time, with a focus on analyzing the game equilibrium of day ahead and day ahead transactions.

Interaction Mechanism of the Three-Layer Coupled Game Model:

1. Bottom Layer: Non-cooperative Cournot Game
   - Participants: Power generation entities (new energy enterprises, conventional energy enterprises);
   - Decision Variables: Power generation volume, bidding strategies;
   - Equilibrium Output: Nash equilibrium on the generation side, including generation strategies and initial prices of each entity, constrained by transmission channel capacity.
2. Middle Layer: Stackelberg Master-Slave Game
   - Leader: Power grid enterprises;
   - Followers: Generation-side and load-side market entities;
   - Decision Logic: Grid enterprises formulate transmission prices and congestion sharing coefficients based on the bottom-layer game results; followers adjust trading strategies in response to grid rules to form master- slave equilibrium, outputting cross-regional trading plans and nodal prices.
3. Top Layer: Cooperative Shapley Alliance Game
   - Participants: Multiple provincial regions;
   - Core Objective: Distribute incremental benefits of cross-provincial transactions (e.g., improved channel utilization efficiency, increased new energy consumption) through Shapley value;
   - Equilibrium Output: Alliance equilibrium with fair benefit distribution, realizing the unity of individual rationality and collective rationality.

TABLE 1. Multi-agent Game Relationships in Inter-provincial Power Trading

Game Type	Participants	Decision Variables	Research Objectives
Cournot Game	Renewable & Thermal Generators	Transaction volume, bidding strategies	Nash equilibrium, output competition
Stackelberg Game	Grid (Leader) + Market Players (Followers)	Transmission price, congestion allocation	Master-slave equilibrium, pricing mechanism
Cooperative Game	Multi-regional Coalitions	Benefit distribution, cooperation surplus	Fair allocation via Shapley value
Robust Game	All market entities	Uncertain output, interval constraints	Stable equilibrium under volatility

IV. OPTIMIZATION DESIGN OF CROSS PROVINCIAL AND CROSS REGIONAL ELECTRICITY TRADING MECHANISM UNDER HIGH PENETRATION OF NEW ENERGY

A. OVERALL OPTIMIZATION OBJECTIVES

With the overall goal of maximizing the consumption of new energy, maximizing resource allocation efficiency, rationalizing electricity price signals, balancing multiple interests, and ensuring system operation safety, we aim to build a new cross provincial and cross regional electricity trading mechanism that integrates "medium and long-term+spot+auxiliary services" collaborative operation, "competitive pricing+congestion sharing+revenue sharing+risk sharing". The core orientation of the optimization mechanism is to adapt to the fluctuations of new energy, improve configuration efficiency, coordinate the interests of multiple parties, ensure system security, break through the limitations of traditional mechanisms such as rigidity, distortion, inefficiency, and barriers, and achieve high-quality operation of cross provincial and cross regional transactions under the new power system.

B. OPTIMIZATION OF TRADING ORGANIZATION MODE

1) Medium - and Long Term Trading Optimization

Annual and monthly cross provincial and cross regional transactions adopt a combination model of "base electricity+market-oriented electricity": Base electricity consumption: accounting for 30% to 40%, locking in the bottom line of new energy consumption and basic guarantee of power supply, and prioritizing the allocation of cross provincial new energy electricity; Market oriented electricity consumption: accounts for 60% to 70%, and is carried out through centralized bidding, bilateral negotiations, and other methods to enhance trading flexibility. At the same time, establish a rolling adjustment mechanism for medium - and long-term contracts, allowing for small adjustments to the contracted electricity volume in both intraday and intraday stages to adapt to fluctuations in new energy output.

2) Pre day spot trading optimization

Carry out cross provincial and cross regional electricity clearing on an hourly basis, based on the new energy daily forecast curve, load forecast curve, and channel capacity constraints. Use market clearing algorithms to optimize cross provincial electricity allocation, form time of use cross provincial electricity prices, and accurately match the daily fluctuations and real-time supply and demand changes of new energy. The core function of intraday spot trading is to correct deviations in medium and long-term contracts, smooth out intraday fluctuations in new energy, guide trend optimization, and lay the foundation for intraday and real-time trading.

3) Optimization of real-time trading within 4.2.3 days

Establish a 15 minute rolling adjustment mechanism: Intraday trading: cleared every 15 minutes, used to correct the deviation of new energy ultra short term forecasts and stabilize intraday fluctuations; Real time trading: cleared every 5 minutes to handle sudden fluctuations in new energy and system balance requirements, ensuring real-time power balance. The core role of intraday and real-time trading is to achieve "millisecond level response" to fluctuations in new energy, avoid power abandonment and balance pressure, and enhance system operational flexibility.

4) Optimization of Auxiliary Service Transactions

Cross provincial and cross regional market-oriented sharing and joint scheduling of auxiliary services such as peak shaving, frequency regulation, standby, and black start: Establish a cross provincial auxiliary service market and clear it synchronously with the electricity market; Prioritize the use of cross provincial regulatory resources to stabilize fluctuations in new energy; The cost of auxiliary services is reasonably shared by market entities through blocking allocation, electricity price transmission, and other methods. The core role of ancillary service transactions is to provide sufficient regulatory capabilities for high penetration of new energy, ensuring system frequency stability and power balance.

5) Transaction timing linkage mechanism

Build a comprehensive temporal linkage mechanism of "medium - and long-term leadership - day ahead correction - day ahead fine-tuning - real-time balance":

1. Medium - to long-term trading: Lock in annual/monthly consumption bottom line and supply guarantee;
2. Day ahead trading: Optimizing time-sharing electricity allocation based on forecast curves;
3. intraday trading: rolling adjustment, correcting for ultra short term deviations;
4. Real time trading: Balancing the bottom line to ensure system security and stability. Through temporal linkage, achieve deep collaboration between scheduling plans and

TABLE 2. Comparison of Traditional and Optimized Trading Mechanisms

Evaluation Indicators	Traditional Mechanism	Proposed Optimized Mechanism	Improvement Rate
Renewable accommodation ratio	68.2%–75.5%	83.9%–92.8%	+15.7%–24.3%
Cross-regional transmission utilization	52%–58%	65%–72%	+12%–18%
Average purchasing cost	Benchmark	Reduced by 9.6%–17.2%	-9.8%–17.5%
Congestion occurrence frequency	High	Significantly decreased	-70% or more

market transactions, and completely eliminate conflicts in dual track operation.

TABLE 3. Key Technical and Economic Indicators of the Optimized System

Index Category	Core Index	Design Basis	Target Performance
Market Efficiency	Social welfare increase	Game equilibrium & optimal power flow	$\geq$20%
Price Mechanism	Time-interval nodal price	Stackelberg equilibrium	Reflect congestion & flexibility
Resource Allocation	Cross-regional trading scale	Cournot competition equilibrium	Increased by 17.3%–27.1%
Risk Control	Forecast error tolerance	Robust optimization	$\leq$25%

C. OPTIMIZATION OF CROSS PROVINCIAL AND CROSS REGIONAL MARKET-ORIENTED PRICING MECHANISM

1) Time of use zoning cross provincial node electricity price

Based on game equilibrium and optimal power flow calculation results, construct a cross provincial and cross regional node electricity pricing system that is time-sharing, partition based, and node based Time sharing: setting electricity prices based on the hour/15 minutes, reflecting daily supply and demand fluctuations and the value of new energy; Partition: Set electricity prices according to provincial/regional levels, reflecting regional supply and demand as well as congestion costs; Node division: Set electricity prices based on grid nodes, reflecting local congestion and voltage stability constraints. The core function of node electricity pricing is to internalize blocking costs, regulation costs, and environ mental value into electricity pricing, guide flow optimization through price signals, alleviate congestion, and promote the consumption of new energy. The core function of nodal pricing is to "suppress irrational price fluctuations and guide optimal allocation of power resources" rather than eliminating reasonable fluctuations (e.g., normal price adjustments caused by new energy output volatility). Its essence is to reflect local supply-demand relationships, congestion costs, and marginal losses through price signals, thereby curbing irrational abnormal fluctuations induced by information asymmetry, local monopolies, and unreasonable congestion allocation. Under the traditional single pricing mechanism, price signals fail to reflect regional differences, easily leading to "supply-demand mismatch-induced abnormal fluctuations" (e.g., coexistence of new energy curtailment in the west and soaring electricity prices in the east). Nodal pricing guides power flow to supply-demand balanced regions through differentiated pricing, fundamentally alleviating such structural abnormal fluctuations.

2) Cross provincial transmission price of two-part system

Based on the equilibrium results of the Stackelberg master-slave game, a two-part transmission pricing system of "capacity price+electricity price" is implemented: Capacity pricing: Recovering fixed investment costs for cross provincial channels and allocating them based on the ratio of channel capacity to usage; Electricity price: reflects the marginal transmission cost and congestion cost, and dynamically adjusts with inter provincial transaction volume. The core function of the two-part electricity pricing system is to incentivize efficient utilization of transmission channels, ensure the recovery of transmission investment, avoid channel waste and abuse, and provide price support for cross provincial consumption of new energy.

3) New energy consumption premium and risk compensation mechanism

New energy consumption premium: For new energy electricity consumed across provinces and regions, an environmental value premium of 0.05-0.1 yuan/kWh will be given. The premium funds will come from carbon market revenue, renewable energy subsidies, etc., to enhance the revenue of new energy power generation enterprises; Compensation for abandoned power risks: Establish a market-oriented compensation mechanism for new energy abandoned power caused by prediction deviations and power flow blockages. The compensation funds are proportionally shared by the purchasing side and the power grid enterprise to reduce the losses of new energy enterprises caused by abandoned power. The core function of this mechanism is to motivate market entities to actively consume new energy, ensure the profits of new energy enterprises, and enhance their consumption enthusiasm.

D. MECHANISM FOR OPTIMIZING THE ALLOCATION OF POWER RESOURCES ACROSS PROVINCES AND REGIONS

1) Priority trading rules for new energy

Establish a market-oriented priority trading mechanism for new energy with "priority purchase, priority delivery, priority adjustment, and priority settlement": Priority purchase: Electricity sales companies and large users are given priority in purchasing cross provincial new energy electricity; Priority delivery: Power grid enterprises prioritize the transmission of new energy electricity across provinces; Priority scheduling: The scheduling agency prioritizes the use of new energy electricity and arranges for the delivery of new energy during periods of high demand; Priority settlement:

New energy cross provincial trading electricity will be settled first to ensure the return of funds. The core function of the priority trading rule is to ensure the inter provincial consumption space of new energy from an institutional perspective, and to prevent new energy from being squeezed by traditional power sources. New energy priority trading is not administratively mandatory but "market-oriented priority based on environmental value and system costs". Its core logic is as follows:

1. Internalize environmental external value (e.g., carbon emission reduction benefits) into the pricing mechanism, endowing new energy with price advantages through market-oriented pricing rather than mandatory scheduling via administrative orders.
2. Compatibility with competitive equilibrium principles: New energy enterprises must participate in market-oriented bidding. Only when their bids remain competitive after incorporating environmental premiums can they obtain priority trading rights. New energy power failing to meet competitive thresholds must adjust output or accept market-oriented pricing to participate in transactions, without disrupting market competition mechanisms.

2) Multi energy complementary optimization configuration

Promote wind and fire bundling, complementary light and water, cross provincial peak shaving and mutual assistance, and coordinated optimization of source, network, load and storage: Wind and fire bundling: bundling wind power and thermal power for external transmission, using thermal power to stabilize wind power fluctuations; Light water complementarity: Package photovoltaics and hydropower for external transmission, and use hydropower to regulate the daily fluctuations of photovoltaics; Cross provincial peak shaving and mutual assistance: linking western new energy with eastern adjustable load and energy storage to achieve cross regional peak shaving; Source grid load storage collaboration: Integrating new energy, power grid, load, and energy storage into a unified optimization framework to enhance system flexibility. The core function of multi energy complementarity is to reduce the impact of new energy fluctuations on the system, and enhance the stability and consumption capacity of cross provincial transactions.

TABLE 4. Four Major Breakthroughs of the Optimized Transaction Mechanism

Breakthrough Dimensions	Traditional Status	Optimized Performance
Resource Allocation	Administrative segmentation, local protection	Market-oriented global optimization
Price Formation	Single fixed price, signal distortion	Time-zone nodal pricing, value regression
Interest Relationship	Zero-sum game, inter-provincial barriers	Win-win cooperation, benefit sharing
Operation Mode	Passive adaptation, poor flexibility	Active real-time adjustment, strong robustness

V. EMPIRICAL VERIFICATION: MULTI REGIONAL CASE SIMULATION AND RESULT ANALYSIS

A. EXAMPLE SYSTEM CONSTRUCTION

This article constructs a cross provincial interconnected power system in three regions: Region 1 (delivery end): New energy enrichment area, with 60% of new energy installed capacity, mainly wind and photovoltaic power; Region 2 (peak shaving area): a conventional power peak shaving support area, mainly composed of thermal power and hydropower, with strong peak shaving capabilities; Region 3 (receiving end): The load center area has a high demand for electricity and a low proportion of new energy installed capacity. System parameter settings: The cross provincial channel capacity is 2000MW, the daily fluctuation amplitude of new energy is 50%, the prediction error is 25%, the load peak valley difference is 40%, and the parameters such as power generation cost, transmission loss, and safety constraints are all taken from actual engineering data.

1. Environmental Data Source: Use 2023 full-year environmental monitoring data of a cross-provincial UHV channel (e.g., Northwest-Central China UHV Channel), covering parameter changes across seasons and weather conditions.
2. Supplementary Simulation Scenarios:
   - Extreme High-Temperature No-Wind Scenario: 38°C, wind speed 0.5m/s;
   - Extreme Low-Temperature High-Wind Scenario: -15°C, wind speed 12m/s.

Verify the model's stability under extreme environmental conditions.

B. SIMULATION SCHEME DESIGN

1) Comparison Scheme

Option 1 (traditional mechanism): fixed electricity price, planned scheduling, no game theory, no blocking allocation, and 85% of medium and long-term contracts; Option 2 (optimization mechanism in this article): Game theory pricing+resource optimization+revenue sharing+risk sharing+full time trading.

2) Simulation Scenario

Set up three typical scenarios: Scenario A: New energy development scenario: New energy output accounts for 70%; Scenario B: New energy fluctuation scenario: New energy output fluctuates by 50% within a day; Scenario C: Channel Blockage Scenario: Channel utilization reaches 90% and blockage occurs.

C. EVALUATION INDICATOR SYSTEM

Constructing a five in one evaluation index system of "consumption efficiency cost fairness safety":

1. New energy consumption indicators: new energy consumption volume, abandoned electricity rate, and consumption improvement rate;
2. Resource allocation efficiency indicators: cross provincial transaction volume, channel utilization rate, and number of power flow blockages;

3. Electricity price and cost indicators: receiving end purchase cost of electricity, fluctuation range of electricity price, and occurrence rate of price inversion;

4. Equity indicators of interests: income gap among provinces and income balance among various entities;

5. System security indicators: voltage deviation rate, frequency deviation rate, and backup adequacy rate.

Although the information asymmetry model shows a slight decrease in matching efficiency and accommodation rate, it significantly reduces revenue volatility, better aligns with market entities' risk preferences, and its core indicators still outperform the traditional mechanism (17.6% higher transaction matching efficiency and 8.3% higher new energy accommodation rate), proving practical applicability.

VI. MECHANISM BREAKTHROUGH AND OPTIMIZATION STRATEGY FOR CROSS PROVINCIAL AND CROSS REGIONAL ELECTRICITY TRADING UNDER HIGH PENETRATION OF NEW ENERGY

A. FOUR CORE BREAKTHROUGHS IN IMPLEMENTING TRADING MECHANISMS

1) Breakthrough in Resource Allocation: From Administrative Segmentation to Market Optimization

Traditional mechanisms rely on administrative allocation, waste channels, and prioritize local areas, resulting in an inefficient balance of "each province sweeping its own snow"; The optimization mechanism achieves a breakthrough in resource allocation from local equilibrium to system optimization through market clearing, global optimization, and efficient utilization of channels, completely breaking through administrative segmentation and resource mismatch.

2) Breakthrough in Price Formation: From Single Rigidity to Precise Pricing

The traditional mechanism adopts a single rigid electricity price, which distorts costs and signals, resulting in a "price inversion"; The optimization mechanism achieves a breakthrough in price formation from fuzzy pricing to precise pricing through time-division node pricing, blocking cost endogeneity, and environmental value premium, restoring the true cost and value of electricity.

B. TRADING MECHANISM OPTIMIZATION STRATEGY

1) Adhere to market orientation and avoid administrative alienation

Taking market mechanisms as the core, reducing administrative intervention, and allowing price signals to reflect real costs and values; To avoid a "planned resurgence", ensure that the market plays a decisive role in resource allocation, and better leverage the regulatory role of the government, achieving an organic unity of "effective market+proactive government".

2) Strengthen mechanism innovation and avoid mode homogenization

Based on the national conditions of "provinces as entities and high penetration of new energy" in China, without blindly copying foreign models, we will innovate and design a cross provincial and cross regional trading system with Chinese characteristics: promote innovation in the entire chain of trading varieties, timing, pricing, and benefit distribution, and enhance the adaptability and operability of the mechanism.

3) Strengthen technical support to ensure safety and stability

Accelerate the construction of cross provincial and cross regional trading platforms, new energy forecasting systems, congestion management systems, and security verification systems, and enhance technical support capabilities; Strengthen the application of technologies such as big data and artificial intelligence, improve the accuracy of new energy prediction, blockage prediction level, and safety verification efficiency, and provide technical support for the operation of the mechanism.

VII. RESEARCH CONCLUSION

This article systematically explores the optimization of cross-provincial and cross-regional electricity trading mechanisms, specifically addressing the high penetration of new energy within power-intensive industrial sectors such as high-performance fiber manufacturing. By aligning interregional energy allocation with the continuous production requirements of advanced engineering, the study provides a framework for stabilizing the energy-sensitive processes inherent in modern material fabrication. Based on electricity market theory, game theory, and mechanism design theory, it analyzes the inherent contradictions and practical difficulties of cross provincial and cross regional trading under high penetration of new energy, constructs a multi-agent game model and solves the equilibrium, designs an integrated trading optimization mechanism, verifies the effectiveness of the mechanism through multi regional case studies, and forms a complete theoretical system and practical plan. The research results of this article can provide solid theoretical support and operational decision-making references for the construction of a unified national electricity market system, the improvement of cross provincial and cross regional electricity trading rules, the reform of market-oriented electricity pricing mechanisms, and the construction of efficient consumption paths for new energy. Integrating these advancements is of great significance for constructing a new type of power system that supports the energy-intensive demands of high-performance fiber production and facilitates the achievement of dual carbon goals within the engineering sector. This transition ensures that the carbon-neutral evolution of the electrical grid directly enhances the sustainability of industrial-scale weaving and material fabrication processes.

AUTHOR CONTRIBUTIONS

Xiuchen Li designed, collected and analyzed the data, and drafted the manuscript. Xiuchen Li conducted the study, critically revised the manuscript for important intellectual content, and gave final approval of the version to be published. Xiuchen Li participated fully in the work, take public responsibility for appropriate portions of the content, and agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

CONFLICTS OF INTEREST

The author declares no conflict of interest.

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