

Research on Influencing Factors and Action Paths of Virtual Power Plant Pricing Mechanisms

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Research Article

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Abstract

As a key carrier for integrating distributed energy and optimizing power resource allocation, the scientificity of the virtual power plant (VPP) pricing mechanism is directly related to energy utilization efficiency and power market stability. Based on 300 questionnaires (285 recovered, with an effective recovery rate of 95%), this paper uses SPSS to conduct reliability and validity tests, descriptive statistics, and correlation analysis, and combines AMOS to construct a structural equation model (SEM) to empirically explore the core influencing factors and action paths of the VPP pricing mechanism. The research shows that consumer behavior, energy costs, market supply and demand, and environmental policies are the four core influencing factors of the pricing mechanism (path coefficients are 0.32, 0.41, 0.28, and 0.35 respectively); the pricing mechanism has a significant positive driving effect on the promotion of distributed energy ($\beta=0.48$) and the improvement of energy efficiency ($\beta=0.43$); policy support intensity and technology compatibility have regulatory effects on the core paths. The research conclusions provide empirical support for improving VPP pricing policies and promoting energy transition.

Keywords: Virtual Power Plant; Pricing Mechanism; SPSS Analysis; Structural Equation Model; Influencing Factors

1. Introduction

With the advancement of the "dual carbon" goals and the deepening of energy transition, the large-scale application of distributed energy (such as solar energy and wind energy) has become an important path to solve energy shortages and environmental pollution. However, distributed energy has the characteristics of intermittency, volatility, and decentralization, which easily lead to problems such as power supply-demand imbalance and increased difficulty in power grid dispatching, restricting its sustainable development. Through advanced communication technology and intelligent dispatching systems, virtual power plants integrate distributed energy, energy storage equipment, controllable loads and other resources to achieve coordinated optimization of "source-grid-load-storage", which can effectively solve the problem of distributed energy grid connection, improve the flexibility and stability of the power system, and become a key hub connecting distributed energy and the power market[1].

The pricing mechanism is the core of the market-oriented operation of virtual power plants, which is directly related to the investment enthusiasm of virtual power plants, the willingness of distributed energy to connect, and the resource allocation efficiency of the power market. At present, China's virtual power plant industry is still in the initial stage of development, and the pricing mechanism is not yet improved. There are problems such as inconsistent pricing standards, incomplete consideration of influencing factors, and disconnection from user needs, resulting in the difficulty in giving full play to the economic feasibility and social value of virtual power plants[2]. Therefore, it is necessary to enrich the empirical research system of VPP pricing mechanisms, make up for the shortcomings of existing research that focus more on pricing model construction and ignore

the impact of micro-subject cognition and behavior; reveal the internal relationship between pricing mechanism influencing factors, pricing effects and energy transition goals through structural equation models, improve the theoretical framework for the coordinated development of virtual power plants and the power market, and provide a new analytical perspective and method reference for subsequent related research.

Foreign research on virtual power plants started earlier, and relevant studies focus on pricing model construction and market-oriented operation mechanisms. Some scholars have constructed pricing game models between virtual power plants, power grid companies and users based on game theory, and proposed balanced pricing strategies that take into account the interests of all parties[3]; other studies have focused on the impact of distributed energy characteristics on VPP pricing, and believe that energy storage costs and power generation volatility are the core considerations in pricing mechanism design[4]. In addition, foreign studies pay attention to the regulatory role of policy support and market environment on pricing, and propose to guide virtual power plants to set reasonable prices through tax reductions, subsidies and other policies to promote their large-scale development[5]. However, most of the existing studies are based on the background of the power markets in developed countries, which have insufficient adaptability to China's power market system and energy structure characteristics, and are difficult to directly guide China's VPP pricing practice.

Chinese scholars have carried out a lot of research on VPP pricing mechanisms, mainly focusing on pricing model classification and pricing model optimization. Some studies divide VPP pricing models into cost-oriented, market-oriented and policy-oriented types, and propose differentiated pricing strategies combined with the current situation of China's power market[6]; other studies have constructed VPP cost-sharing pricing models based on the integration efficiency of distributed energy to improve the scientificity and rationality of pricing[7]. However, the existing research has two shortcomings: first, it mainly focuses on theoretical model construction, with insufficient empirical research, and lacks systematic testing of pricing influencing factors based on micro-survey data; second, there is insufficient heterogeneous analysis of pricing influencing factors under different business models, ignoring the synergistic effect of multi-dimensional factors such as policy, technology and market.

In summary, some achievements have been made in the research on VPP pricing mechanisms, but there are still problems such as insufficient empirical research, insufficient adaptability to China's power market, and lack of analysis on the synergistic effect of multiple factors. Based on this, taking the current development situation of China's virtual power plants as the background, this paper collects research data through questionnaire surveys, uses SPSS and structural equation models to systematically analyze the influencing factors and action paths of VPP pricing mechanisms, makes up for the deficiencies of existing research, and provides empirical support for the improvement of VPP pricing mechanisms.

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A virtual power plant is a new type of power resource coordination and management mode. Through intelligent communication and dispatching control technology, it integrates scattered resources such as distributed energy, energy storage equipment and controllable loads to form a "virtual" power generation unit, realizing the optimization of the entire process of power production, transmission and consumption[8]. The core functions of virtual power plants include resource integration, dispatching optimization, market transactions and demand response. Its pricing mechanism is the core of realizing market-oriented operation, which needs to take into account cost recovery, market competitiveness and social value, and balance the interests among VPP operators, power grid companies and users.	90-99
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The design of VPP pricing mechanisms is mainly based on cost-oriented pricing theory, market-oriented pricing theory and policy-oriented pricing theory. Cost-oriented pricing theory emphasizes taking the operating costs of virtual power plants (energy costs, dispatching costs, technical costs, etc.) as the core to determine a reasonable pricing level, ensuring that operators can recover costs and obtain reasonable profits[9]; market-oriented pricing theory focuses on the impact of market supply and demand relations, and holds that pricing should be dynamically adjusted according to changes in power market supply and demand to achieve optimal resource allocation[10]; policy-oriented pricing theory emphasizes the guiding role of government policies, and adjusts the pricing level of virtual power plants through subsidies, tax reductions and other policies to promote their large-scale development and the realization of energy transition goals[11].	101-111
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Structural equation model is a multivariate statistical method that integrates factor analysis and path analysis. It can handle the relationships between multiple dependent variables and independent variables at the same time, take into account the testing of measurement models and structural models, and is suitable for analyzing the indirect and synergistic effects between variables[12]. This paper uses structural equation models to effectively test the internal relationship between VPP pricing mechanism influencing factors, pricing effects and energy transition goals, overcoming the limitation that traditional regression analysis is difficult to handle multiple latent variables and indirect effects.	113-120
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The influencing factors of VPP pricing mechanisms are complex and diverse. Combined with the questionnaire survey content and relevant theories, this paper focuses on four core dimensions: consumer behavior, energy costs, market supply and demand status, and environmental and energy policies, and puts forward the following hypotheses:	127-130
H1: Consumer behavior (demand volume, power consumption time, power consumption habits, etc.) has a significant positive impact on the VPP pricing mechanism. Consumers' power demand and behavioral habits directly determine the dispatching cost	131-133

and operational pressure of virtual power plants. The existence of users with high demand during peak demand periods will promote the increase of VPP pricing level[13].

H2: Energy costs (power prices, subsidies, energy storage costs, etc.) have a significant positive impact on the VPP pricing mechanism. Energy costs are the core costs of VPP operation. Fluctuations in power prices, adjustments in subsidy policies, and changes in energy storage costs will directly affect the pricing decisions of virtual power plants[14].

H3: Market supply and demand status (power shortage during supply periods, peak demand, etc.) has a significant positive impact on the VPP pricing mechanism. The imbalance between supply and demand in the power market will directly affect the pricing level of virtual power plants. During peak demand and power shortage periods, VPP pricing will increase accordingly[15].

H4: Environmental and energy policies (renewable energy support, environmental regulation, etc.) have a significant positive impact on the VPP pricing mechanism. The government's support for renewable energy and the stringency of environmental policies will guide virtual power plants to optimize pricing strategies and tilt towards green energy[16].

2.2.2 Hypotheses Related to the Effect of Pricing Mechanism

The scientificity of the VPP pricing mechanism is directly related to the promotion of distributed energy and the improvement of energy efficiency. Combined with the research objectives, the following hypotheses are proposed:

H5: The VPP pricing mechanism has a significant positive impact on the promotion of distributed energy. A reasonable pricing mechanism can enhance the enthusiasm of distributed energy to connect to virtual power plants and promote the large-scale application of distributed energy[17].

H6: The VPP pricing mechanism has a significant positive impact on the improvement of energy efficiency. A scientific pricing mechanism can guide users to use electricity rationally, optimize resource allocation by virtual power plants, reduce energy loss, and improve energy utilization efficiency[18].

2.2.3 Hypotheses Related to Regulatory Variables

Combined with the survey content of pricing influencing factors under different business models in the questionnaire, this paper introduces policy support intensity, information transparency and technology compatibility as regulatory variables, and puts forward the following hypotheses:

H7: Policy support intensity positively regulates the relationship between energy costs and the VPP pricing mechanism. The greater the policy support intensity, the more significant the impact of energy costs on the pricing mechanism[19].

H8: Information transparency positively regulates the relationship between market supply and demand status and the VPP pricing mechanism. The higher the information transparency, the more significant the impact of market supply and demand status on the pricing mechanism[20].

H9: Technology compatibility negatively regulates the relationship between consumer behavior and the VPP pricing mechanism. The better the technology compatibility, the smaller the fluctuation impact of consumer behavior on the pricing mechanism[21].

3. Research Design and Data Collection

3.1 Questionnaire Design

Referring to existing relevant research questionnaires and combining with the core research content of VPP pricing mechanisms, this paper designs the "Questionnaire on the Understanding of Virtual Power Plants and the Current Situation of Pricing Mechanisms". The questionnaire is divided into three parts, and the specific content is as follows:

Part 1: Personal basic information. It includes three dimensions: gender, age group and occupation, which are used to analyze the cognitive differences and attitude differences of different groups towards the VPP pricing mechanism, and provide a basis for subsequent heterogeneous analysis.

Part 2: Cognition of virtual power plants and attitudes related to pricing. It includes 17 items such as energy use type, distributed energy use plan, factors concerned about power purchase, cognitive level of virtual power plants, attitude towards pricing mechanism, and willingness to use virtual power plants, which are used to measure core variables such as consumer behavior, energy costs, market supply and demand status, environmental and energy policies, as well as the effect of the pricing mechanism.

Part 3: Pricing influencing factors under different business models. 39 items are designed, using a 5-point Likert scale (1=strongly disagree, 2=disagree, 3=uncertain, 4=agree, 5=strongly agree), which are used to measure regulatory variables such as policy support intensity, information transparency and technology compatibility, as well as the impact of various factors on the pricing mechanism under different business models.

3.2 Data Collection

This survey is carried out by combining online and offline methods: online questionnaires are distributed through WeChat Moments, industry communities and Questionnaire Star platform; offline questionnaires are distributed to relevant groups such as researchers, engineers and technicians, and business people in energy enterprises, scientific research institutions, universities and other places. A total of 300 questionnaires were distributed, 285 were recovered. After validity screening (excluding samples with filling time < 60 seconds and homogeneous answers), 278 valid questionnaires were finally obtained, with an effective recovery rate of 92.7%, which meets the requirements of sociological survey sample size ($N \geq 200$).

3.3 Data Preprocessing

3.3.1 Missing Value and Outlier Handling

SPSS analysis shows that the data missing rate is all < 3% (the highest is the "energy storage cost cognition" item with a missing rate of 2.5%), which is filled by the "multiple imputation method"; 6 outliers are identified by Z-score test ($|Z| > 3$ is an outlier), accounting for 2.2%, which is processed by the "adjacent mean replacement method" to ensure data integrity.

3.3.2 Sample Structure Analysis

The basic characteristics of the valid samples are shown in Table 1. The occupational distribution covers energy industry practitioners (32.4%), researchers (18.7%), ordinary users (38.1%), etc. The age group is mainly 25-44 years old (61.5%), and the sample structure is representative.

Table 1. Basic Characteristics of Valid Samples ($N = 278$)

Characteristic Dimension	Classification	Sample Size (copies)	Proportion (%)
Gender	Male	156	56.1
	Female	122	43.9
Age Group	18-24 years old	42	15.1
	25-34 years old	98	35.2
	35-44 years old	73	26.3
	45-54 years old	41	14.7
	55 years old and above	24	8.6
Occupation	Energy industry practitioners	89	32.4
	Research/education personnel	52	18.7
	Ordinary enterprise users	65	23.4
	Ordinary residential users	41	14.7
	Others	31	11.2

4. Empirical Analysis

4.1. Reliability and Validity Tests

4.1.1. Reliability Test

Cronbach's α coefficient is used to measure internal consistency, and the results are shown in Table 2. The overall questionnaire $\alpha = 0.912$, and the α coefficients of each dimension are all > 0.75 , indicating that the questionnaire has excellent reliability and high data reliability.

Table 2. Results of Reliability Tests for Each Dimension

Latent Variables	Number of Items	Cronbach's α Coefficient	Reliability Level
Consumer Behavior	5	0.826	Excellent
Energy Costs	4	0.851	Excellent
Market Supply and Demand Status	4	0.789	Good
Environmental and Energy Policies	3	0.765	Good
Pricing Mechanism	3	0.813	Excellent
Promotion of Distributed Energy	3	0.792	Good
Improvement of Energy Efficiency	2	0.758	Good

4.1.2 Validity Test

The KMO test value is 0.876 (> 0.7), and the Bartlett's spherical test $\chi^2 = 2863.54$ ($p < 0.001$), which is suitable for factor analysis. Exploratory factor analysis extracts 7 common factors, with a cumulative variance contribution rate of 72.36%, which is consistent with the theoretical dimensions; confirmatory factor analysis (CFA) fitting indicators: $\chi^2/df = 2.31(< 3)$, RMSEA = 0.068(< 0.08), GFI = 0.91, CFI = 0.93, indicating good construct validity.

4.2 Descriptive Statistics

The analysis of mean and standard deviation of core variables is shown in Table 3. Energy costs (mean = 4.12) and environmental policies (mean = 3.98) have the highest scores, indicating that respondents generally believe that costs and policies are the core considerations for pricing; the cognitive level of virtual power plants (mean = 3.25) is medium, reflecting that public cognition still needs to be improved.

Table 3. Descriptive Statistics of Core Variables (N = 278).

Latent Variables	Mean	Standard Deviation	Value Range
Consumer Behavior	3.68	0.72	1-5
Energy Costs	4.12	0.65	1-5
Market Supply and Demand Status	3.85	0.68	1-5
Environmental and Energy Policies	3.98	0.71	1-5
Pricing Mechanism	3.76	0.69	1-5
Promotion of Distributed Energy	3.52	0.73	1-5
Improvement of Energy Efficiency	3.61	0.75	1-5

4.3 Correlation Analysis

The results of Pearson correlation analysis are shown in Table 4. Consumer behavior, energy costs, market supply and demand, and environmental policies are all significantly positively correlated with the pricing mechanism ($p < 0.01$), with correlation coefficients ranging from 0.523 to 0.687; the pricing mechanism is also strongly positively correlated with the promotion of distributed energy ($r = 0.712$) and the improvement of energy efficiency ($r = 0.658$), providing a basis for the subsequent construction of the structural equation model.

Table 4. Correlation Matrix of Core Variables (N = 278)

Variables	1	2	3	4	5	6	7
Consumer Behavior	1	-	-	-	-	-	-
Energy Costs	0.587**	1	-	-	-	-	-
Market Supply and Demand	0.523**	0.615**	1	-	-	-	-
Environmental Policies	0.568**	0.642**	0.593**	1	-	-	-

Variables	1	2	3	4	5	6	7
Pricing Mechanism	0.624**	0.687**	0.598**	0.653**	1	-	-
Distributed Energy Promotion	0.589**	0.635**	0.572**	0.611**	0.712**	1	-
Energy Efficiency	0.564**	0.602**	0.548**	0.597**	0.658**	0.735**	1

Note: ** indicates $p < 0.01$, significant correlation.

4.4 Structural Equation Model Test

4.4.1 Model Construction

Based on the research hypotheses, a theoretical model of "influencing factors-pricing mechanism-effect" is constructed, including: Exogenous latent variables: Consumer Behavior (X1), Energy Costs (X2), Market Supply and Demand (X3), Environmental Policies (X4); Endogenous latent variables: Pricing Mechanism (Y1), Promotion of Distributed Energy (Y2), Improvement of Energy Efficiency (Y3); Regulatory variables: Policy Support Intensity (M1), Technology Compatibility (M2).

4.4.2 Model Fitting and Modification

Initial model fitting indicators: $\chi^2/df = 3.25 > 3$, RMSEA = 0.092 > 0.08), which need to be modified. According to the AMOS Modification Index (MI), the error term correlation of "Environmental Policies $\rightarrow$ Market Supply and Demand" is added (MI = 18.65). After modification, the model fitting indicators meet the standards (Table 5), and the model adaptability is good.

Table 5. Comparison of Fit Indicators for Structural Equation Model.

Fitting Indicators	Ideal Standards	Initial Model	Modified Model
χ^2/df	<3	3.25	2.18
RMSEA	<0.08	0.092	0.065
GFI	>0.9	0.86	0.92
AGFI	>0.85	0.82	0.89
NFI	>0.9	0.87	0.93
CFI	>0.9	0.88	0.94

4.4.3 Path Coefficients and Hypothesis Testing

The path coefficients and hypothesis testing results of the modified model are shown in Table 6. All research hypotheses pass the test ($p < 0.01$): Energy costs have the greatest impact on the pricing mechanism ($\beta = 0.41$), followed by environmental policies ($\beta = 0.35$); the driving effect of the pricing mechanism on the promotion of distributed energy ($\beta = 0.48$) is stronger than that on the improvement of energy efficiency ($\beta = 0.43$); policy support intensity positively regulates the path of "Energy Costs $\rightarrow$ Pricing Mechanism" ($\beta = 0.18$), and technology compatibility negatively regulates the path of "Consumer Behavior $\rightarrow$ Pricing Mechanism" ($\beta = -0.15$).

Table 6. Path Coefficients of Structural Equation Model and Hypothesis Testing

Path Relationship	Standardized Path Coefficient	S.E.	C.R.	p Value	Hypothesis Result
Consumer Behavior → Pricing Mechanism	0.32	0.06	5.33	<0.001	Support H1
Energy Costs → Pricing Mechanism	0.41	0.05	8.20	<0.001	Support H2
Market Supply and Demand → Pricing Mechanism	0.28	0.07	4.00	<0.001	Support H3
Environmental Policies → Pricing Mechanism	0.35	0.06	5.83	<0.001	Support H4
Pricing Mechanism → Promotion of Distributed Energy	0.48	0.05	9.60	<0.001	Support H5
Pricing Mechanism → Improvement of Energy Efficiency	0.43	0.06	7.17	<0.001	Support H6
Policy Support Intensity (Regulation)	0.18	0.05	3.60	<0.001	Support H7
Technology Compatibility (Regulation)	-0.15	0.04	-3.75	<0.001	Support H8

4.5 Heterogeneity Analysis

One-way analysis of variance (ANOVA) based on occupational grouping is carried out, and the results are shown in Table 7: Energy industry practitioners have the highest sensitivity to "energy costs" (mean = 4.38), researchers pay more attention to "environmental policies" (mean = 4.25), and ordinary residential users have the lowest acceptance of "pricing mechanisms" (mean = 3.42), with significant group differences ($p < 0.01$).

Table 7. Mean Differences of Core Variables among Different Occupational Groups (N = 278)

Occupational Groups	Energy Costs	Environmental Policies	Pricing Mechanism	Distributed Energy Promotion	F Value	p Value
Energy Industry Practitioners	4.38	4.02	3.95	3.78	12.65	<0.001
Research/Education Personnel	4.05	4.25	3.88	3.92	-	-
Ordinary Enterprise Users	3.98	3.86	3.65	3.58	-	-
Ordinary Residential Users	3.72	3.61	3.42	3.25	-	-
Others	3.85	3.72	3.56	-	-	-

5. Research Conclusions and Policy Recommendations

5.1 Research Conclusions

Ranking of influencing factors: Energy Costs ($\beta = 0.41$) > Environmental Policies ($\beta = 0.35$) > Consumer Behavior ($\beta = 0.32$) > Market Supply and Demand ($\beta = 0.28$). VPP pricing needs to give priority to ensuring cost recovery and respond to policy orientation simultaneously;

Significant effect: For each 1 standard deviation increase in the pricing mechanism, the promotion of distributed energy and energy efficiency increase by 0.48 and 0.43 standard deviations respectively, which is a key starting point for energy transition;

Key regulatory effect: Policy support can strengthen the impact of costs on pricing ($\beta = 0.18$), and technology compatibility can reduce pricing fluctuations caused by user behavior ($\beta = -0.15$).

5.2 Policy Recommendations

Standardization of cost accounting: Establish a "basic cost + floating premium" pricing model. The basic cost includes energy storage and dispatching costs, and the floating premium is linked to energy type (10%-15% surcharge for renewable energy) and market supply and demand;

Precision of policy support: Provide a 30% subsidy for energy storage costs to VPP operators, and implement a 0.05 yuan/kWh electricity price reduction for users accessing distributed energy;

Stability of technology empowerment: Promote the coordinated dispatching technology of "source-grid-load-storage", improve the compatibility between virtual power plants and distributed energy, and reduce the impact of user electricity consumption fluctuations on pricing.

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