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The mechanism and impact of negative electricity price formation in the electricity spot market under the background of "double carbon"

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Abstract: In recent years, with the continuous promotion of power market reform, negative electricity price has gradually become a term of concern. Under the background of "new electricity reform", it is necessary to study the formation mechanism of negative electricity price in the electricity spot market, which is of great significance to the stable development of the electricity market. In addition, in the context of new energy development and "double carbon", it is very important to study the impacts of negative electricity price on new energy power generation for the renewable energy industry and governmental departments to take policy and technical measures to cope with negative parity and ensure the healthy development of renewable energy. Therefore, this paper selects negative electricity price as the research object, establishes Granger causality model to explore the impact of fluctuation of new energy output on the formation of negative tariff in the spot market, establishes a system dynamics model to study and analyze the radiation impact of negative electricity price on new energy power generation as well as carbon emissions, draws conclusions and puts forward suggestions to provide references for the subsequent research on more negative electricity price.

1. Introduction

1.1 Problem background

In recent years, with the rapid development of clean energy market and the promotion of power market reform, negative electricity price has gradually emerged in many parts of the world and become a word that has attracted much attention. April 29 - May 3, 2023, the electricity load in Shandong Province decreased, and the demand for new energy increased in daytime. Serious oversupply led to a total of 46 negative electricity prices in real-time electricity spot transactions, refreshing the record of negative electricity price in the domestic power spot market, indicating that negative electricity price has a strong development trend.

Negative electricity prices are price signals on the wholesale electricity market. With the development of technology, new energy power generation is gradually become more and more mature, and its proportion is gradually increasing in the operation process of power spot market. However, the new energy power generation is unstable, which will bring about large fluctuations in the market electricity price. When the electricity spot market is in a state of oversupply, that is, the new energy generation exceeds the demand for electricity load, the power generation enterprises will lower their quotation to attract more users to buy their electricity. But if the offer to zero is not enough, then the offer can only be further reduced, so that the offer falls below zero, which appears a negative electricity price.

In the context of the "double carbon" goal, in order to achieve the long-term goal of China's carbon emissions, while establishing a clean, low-carbon, safe and efficient modern energy system, promoting the construction of the power market mechanism has become a necessary step. We should improve the trading mechanism of the power spot market in which new energy participates, and build a decision support method for the trading of the power spot market with a high proportion of new energy penetration, so as to realize the effective allocation of resources, promote the consumption of new energy, reduce the economic losses caused by the phenomenon of wind and light abandonment, so as to maximize the economic significance of negative electricity prices.

1.2 Literature review

1.2.1 Domestic research status

At present, there are few researches on the formation mechanism and influence of negative electricity price in spot market of power, mainly focusing on the analysis of negative electricity price spot market, energy storage and market regulation. Zhang Ye [1] suggested that negative tariffs are not necessarily a bad thing; they allow for a wider range of tariff fluctuations, which creates some incentives for both the generation side and the demand side. On the generation side, power sources with high prices will be uncompetitive, which helps to correct blind power investments. Zhao Ziyuan [2] explained the relationship between energy output and negative tariffs, indicating that when the grid has no more adjustable capacity and new energy power cannot be consumed, negative prices will occur, which is a reflection of the role of the spot market. Peng Qiang [3] mentioned in the article that the relationship between negative tariffs and new energy is echoing each other, and the emergence of negative tariff mechanism is precisely to consume new energy.

1.2.2 Foreign research status

Many foreign scholars have also carried out some research on negative electricity price. Nicolosi M. [4] analyzed the phenomenon of negative electricity prices in Germany and believed that the mechanism of negative electricity prices increased the overall social welfare. When the supply in the power market exceeds the demand, the introduction of the negative electricity price mechanism can slow down the situation that the power generation enterprises blindly chase economic interests and generate electricity without limit, avoid power waste, and alleviate the phenomenon of waste of new energy such as wind curtailment. Keles D, Genoese M, Mst D, et al [5] introduced the reasons for the occurrence of negative electricity price, and believed that the economic rationality of negative electricity price was that the generator start-up and shutdown cost was greater than the loss of accepting negative electricity price.

1.3 Significance of the research

Due to the instability of new energy power generation, it is difficult to respond to the needs of the grid or users in real time, and its competitiveness in the power spot market is weak. With the gradual popularization of renewable energy and the development of the power market, negative electricity prices will become more and more common, which will lead to changes in the valuation model of new energy assets, also means that the underlying logic of new energy development will change. In addition, it can also lead to unstable supply on the power side, posing a huge challenge to the safe and stable operation of the power system.

Since the current domestic research on the spot market for electricity mainly focuses on the design of market trading mechanism and market regulatory mechanism, the research on the negative tariff mechanism in the spot market for electricity is relatively less, in the context of "double carbon" and "new electricity reform", it is very necessary to study and analyze the negative tariff mechanism in China, which can support the safe and stable operation of the power system. Under the background of "double carbon" and "new electricity reform", it is very necessary to study and analyze the mechanism of negative electricity price, which can provide support for the safe and stable operation of the power system. This paper will objectively analyze the formation mechanism and impact of negative tariffs, broaden the research field of negative tariffs in the electricity spot market, provide reference for the improvement of the spot market mechanism, and provide new ideas for the reform of the electricity system tariff mechanism.

1.4 Research approach

On the basis of literature research, this paper selects negative electricity price as the research object, establishes Granger Causality Analysis model to explore the influence of new energy output fluctuations on the formation of negative electricity price in the power spot market, establishes system dynamics model to study and analyze the influence of negative electricity price on new energy generation and carbon emission radiation, and draws conclusions and puts forward suggestions. The research idea of this paper is as follows (Figure 1).

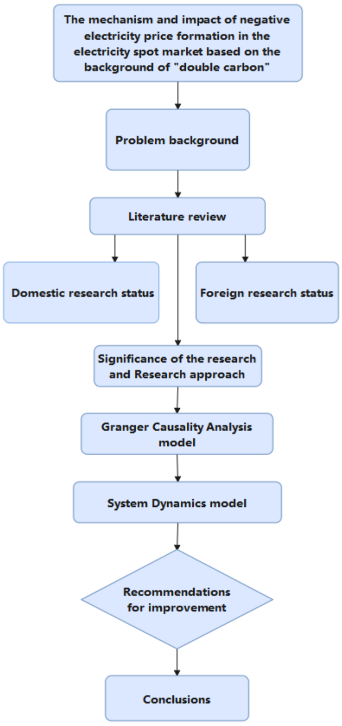


Figure 1: Idea design flowchart

2. Granger Causality Analysis model

2.1 Theoretical part

Granger Causality Analysis is mainly used to determine whether changes in one time series can be used to predict changes in another time series. The core idea of Granger Causality Analysis is based on causality in time series data. By comparing the prediction models of two time series, it uses the autoregressive distributed lag model of two variables displayed by two equations to test causality, and judges whether the change of one time series can be explained by the past value of the other time series. Suppose there are two variables X and Y, if X is helpful in the prediction of Y, or if the correlation coefficient between X's lag term and Y is statistically significant, then "X is the Granger cause of Y" can be considered. The formula used in the Granger causality test process is as follows:

$$Y_t = \beta_0 + \sum_{i=1}^{p} \beta_i Y_{t-1} + \sum_{i=1}^{p} \alpha_i X_{t-i} + \mu_t \tag{1}$$

$$X_t = \delta_0 + \sum_{i=1}^{p} \delta_i X_{t-i} + \sum_{i=1}^{p} \gamma_i Y_{t-1} + v_t \tag{2}$$

If αi≠0, γi=0, it means that X has a unidirectional effect on Y.
If αi=0 and γi≠0, it means Y has a unidirectional effect on X.
If αi≠0, γi≠0, it indicates that there is a bidirectional effect between X and Y.
If αi=0 and γi=0, Y and X are independent.
The constrained F-test formula is:

$$F= \frac{(RSS_R - RSS_u)/p}{RSS_u/(n-k)} \tag{3}$$

Where RSSR is the sum of squares of residuals for regression without the lag term of another variable, RSSU is the sum of squares of residuals for regression with the lag term of another variable, p is the number of lag terms of X or Y, n is the sample size, k is the number of parameters to be estimated for unconstrained regression with constant term and other variables.

If F>Fα (p,n-k), then the null hypothesis is rejected. Y is the Granger cause of X, or X is the Granger cause of Y.

2.2 Model construction and data explanation

According to the Peng Q [6], it is known that the volatility of new energy output makes a great contribution in the formation of negative tariffs. New energy sources such as wind and solar have volatility, and it may be difficult to predict and control their output at the time of generation.. Therefore, this paper explores the causal relationship between negative electricity price and new energy output by establishing Granger Causality model. When considering the output of new energy, Referring to the study by ZHAO Zhifang [7], because wind power and photovoltaic power generation have become an important part of the world's countries to promote the energy transition and achieve the goal of clean energy, and also has an important impact on the formation of negative electricity prices, this paper selects wind power and photovoltaic power generation as a representative of new energy generation.

The idea of model construction in this paper is as follows: First, the sum of negative electricity prices in a typical day with negative electricity prices in one day is selected as the X variable, and the sum of wind power and photovoltaic output, that is, new energy output, is selected as the Y variable. Next, we collect the historical time series data of the two variables and test their stationarity to establish an autoregressive distributed lag model for the two variables. Finally, the fitting effect of the two models is compared by statistical test to determine whether there is a causal relationship.

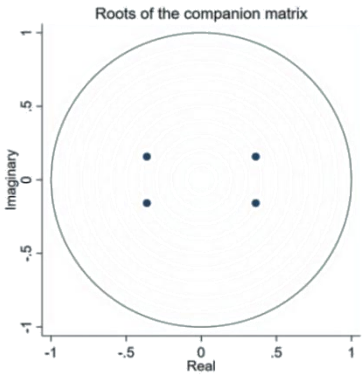
Considering that Shandong Province is a representative province with frequent negative electricity prices, this paper selects the corresponding data of the sum of new energy output and negative electricity prices in 80 typical days from May to December 2023 in Shandong Province as the research sample. The data comes from the information disclosure of Shandong Electric Power Trading Center. After processing these data, the statistical description results of the plotted model variables are shown below (Table 1).

Table 1: Statistical description of variables

variable	unit	maximum value	minimum value	mean value	Standard deviation
X	rmb/mwh	-34	-950.73	-303.0568	219.5662
Y	10,000 kwh	1392.9	19.3	655.2023	383.712

2.3 Model results and analysis

The searched data is imported into stata, the second-order distributed lag model of X and Y is established, and the unit circle graph of the eigenroot adjoint matrix of the corresponding time series data was drawn for stationarity test. The unit circle plot shows the position of the eigenroots (otherwise known as eigenvalues) on the complex plane, and if all the eigenroots fall within the unit circle (i.e., the absolute value is less than 1), it indicates that the time series is stationary. The test results are shown below (Figure 2). The analysis of Figure 2 shows that the model has passed the stationarity test and can be analyzed and judged in the next step. Then, statistical variables are constructed for Granger Causality analysis (Figure 3). The analysis of Figure 3 shows that Y can be considered as the Granger cause of X in 95% of cases, that is, Y information has certain predictive ability to predict the future change of X at past time points, and the change of X is one of the reasons for the change of Y, but it does not mean that X is the direct cause of the change of Y. There's just a statistical correlation.



Granger causality Wald tests

Equation	Excluded	chi2	df	Prob > chi2
X	Y	4.4238	1	0.035
X	ALL	4.4238	1	0.035
Y	X	.45592	1	0.500
Y	ALL	.45592	1	0.500

Figure 2: Smoothness test unit circle plot   Figure 3: Plot of results of Granger analysis

According to the above, X is the sum of the negative electricity price of a typical day, and Y is the power generation of new energy. Combined with the operation results, it can be concluded that the change of new energy output is a Granger cause for the change of negative electricity price. Therefore, this paper proves statistically that an important reason for the formation of negative electricity price is: the fluctuation of new energy output.

3. System Dynamics model

3.1 Theoretical part

System dynamics model is a structural model established to predict the dynamic behavior of the system in various cases, analyze the structure, behavior and causality of the system by applying the principle of system dynamics, and simulate the dynamic changes of the system. These models usually describe the evolution of a system based on the interactions between various elements in the system (e.g. mass, inertia, friction, etc., in a physical system, or population, resources, rules of behavior, etc.).

System dynamic models are widely used in the field of energy economy. By establishing mathematical equations to describe the interaction between various factors in the energy system, these models help decision makers better understand the complexity of the energy system, predict the future development trend, and formulate corresponding policies and strategies to achieve the goal of sustainable energy development and economic growth. The basic formula of system dynamics model usually uses differential equation or difference equation to describe the dynamic behavior of the system. Differential equations apply to continuous time systems, while difference equations apply to discrete-time systems.

(1)Differential equation form

$$\frac{dx}{dt} = f(x, u, p) \tag{4}$$

Where, $\frac{dx}{dt}$ represents the change rate of state variable x with time, represents the state equation of the system, describes the change law of variable x with time, u is the control input variable of the system, p is the parameter vector of the system.

(2)Difference equation form

$$x_{t+1} = f(x_t, u_t, p) \tag{5}$$

Where, x_t represents the state vector of the system at time t, x_{t+1} represents the state vector of the system at time t+1, $f(x_t, u_t, p)$ represents the equation of state of the system, describes the change of the system in time step, u_t represents the control input vector of the system at time t, and p is the parameter vector of the system.

We can establish a system dynamics model through several main steps, which is used to study and analyze the dynamic behavior and development trend of various complex systems. The model building process is shown below (Figure 4).

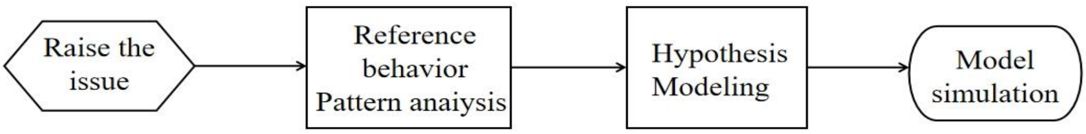


Figure 4: Flowchart of system dynamics modeling

3.2 Model construction and data explanation

Referring to the research idea of system dynamics model in the study by Wang Jiawei [8], this paper applies the system dynamics method to establish the radiation factor model of negative electricity price in Shandong Province, and the influence relationship chain of negative electricity price is analyzed from the perspective of each factor of negative electricity price radiation. The model shown below is established through the software Vensim PLE (Figure 5). Because the negative electricity price has a wide range of radiation areas and many types of influencing factors, the research on the radiation influencing factors of negative electricity price plays an important role in the effective understanding and control, and has certain guiding significance for the realization of carbon neutrality and carbon peak as soon as possible.

Summarized from the study by Li Li-Min[9] and ZHAO Li Yun [10], among others, it is obtained that the direct and affected factors of negative electricity price are mainly: electricity consumption, electricity sales revenue, energy policies and subsidies, power generation cost. Therefore, this paper simplifies the system dynamics model into four parts: electricity consumption and income module, power generation and cost module, policy and subsidy module, and carbon emission impact module.

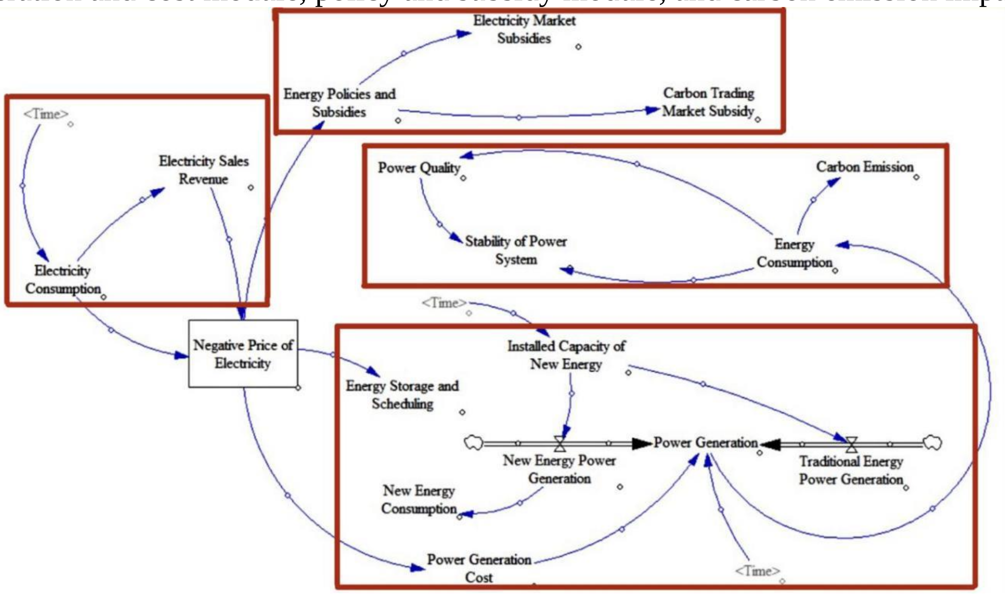


Figure 5: System Dynamics Model Diagram

3.2.1 Electricity consumption and revenue module

The electricity consumption and income module consists of electricity consumption and electricity sales revenue. With the change of time, electricity consumption will also change, and the electricity consumption of residents and enterprises will have an impact on the electricity sales revenue. This model mainly collects the electricity consumption data of Shandong Province from 2011 to 2023, as shown below. (Table 2)

Table 2: Electricity consumption data

year	2011	2012	2013	2014	2015	2016	2017
electricity consump-tion(twh)	3635	3795	4083	4224	5182	5391	5430
year	2018	2019	2020	2021	2022	2023	
electricity consump-tion(twh)	5917	6219	6940	7383	7559	7768	

3.2.2 Power generation and cost module

The power generation and cost module is directly affected by the four main factors of new energy generation, traditional energy generation, power generation cost, energy storage and scheduling.

With the change of time, the installed capacity of new energy changes, which leads to the change of the proportion of new energy generation, and indirectly affects the traditional energy generation. Power generation also affects the cost of power generation, and storage and scheduling affect the amount of new energy consumption. The new energy installed capacity data collected by this model from 2011 to 2023 are shown below (Table 3). In addition, by searching the data, the selected new energy consumption rate of the province is 98.2%, the independent energy storage scale is 1.976 million kilowatts, and the distribution energy storage scale is 854,000 kilowatts.

Table 3: New energy installation data

year	2011	2012	2013	2014	2015	2016	2017
new energy installed capacity (10000kw)	452	464	534	745	1120	1581	2329
year	2018	2019	2020	2021	2022	2023	
new energy installed capacity (10000kw)	2853	3624	4541	5849	7204	8031	

3.2.3 Policy and subsidy module

The Policy and subsidy module mainly shows the impact of negative electricity prices on energy policies and subsidies, and thus on electricity market subsidies and carbon trading market subsidies. The negative electricity price will affect the new energy generation, and the subsidy of new energy generation is related to its power generation, so the change of negative electricity price will also have a certain impact on energy policies and subsidies. The subsidies of the new energy policy are mainly reflected in two aspects: carbon market subsidies and electricity market subsidies.

3.2.4 Impact module on carbon emissions

The impact module on carbon emissions is mainly centered on energy consumption, and the change of energy consumption will have an impact on carbon emissions, power quality and power system stability. Among them, the most important is the change of carbon emissions, which has an important significance for the realization of the carbon peak goal. Carbon emissions can be measured by multiplying energy consumption by the energy's carbon factor.

3.3 Model results and analysis

3.3.1 Model Checking

Two model verification methods are used in this study. One is to use the "check model" function of Vensim PLE software to check whether the model has running errors. The second is to carry out historical verification. Four core variables including electricity consumption, electricity sales revenue, energy policy and subsidy intensity, and power generation cost are selected, and the simulated values produced by the model from 2011 to 2023 are compared with the historical data for comparison and verification.

The above two model verification methods show that the system dynamics model is correct.

3.3.2 New energy generation

Through the analysis of model data, it can be seen that in recent years, with the continuous increase in the installed capacity of renewable energy, the power generation of new energy is also increasing, resulting in the phenomenon of negative electricity prices becoming more and more serious (Figure 6 and Figure 7). Conversely, in the future, the rising frequency of negative electricity prices will inhibit the growth of new energy output, promote the increase of the proportion of traditional fossil energy output, and reduce the installed capacity of new energy. At the same time, since the subsidies enjoyed by new energy power generation are related to its power generation, the rise in the frequency of negative electricity prices will also lead to the decline of subsidies enjoyed by new energy, and the increase in power generation costs, power generators may be forced to reduce or stop the generation of new energy to avoid greater losses. Therefore, the development of negative electricity price for the development of new energy industry is very unfavorable, the new energy industry and the relevant government departments need to take corresponding measures to ensure the healthy development of new energy. As a market signal valued by government and energy industry decision makers, the phenomenon of negative electricity prices will prompt them to take measures to address the imbalance between supply and demand or adjust the market mechanism to avoid frequent negative electricity prices.

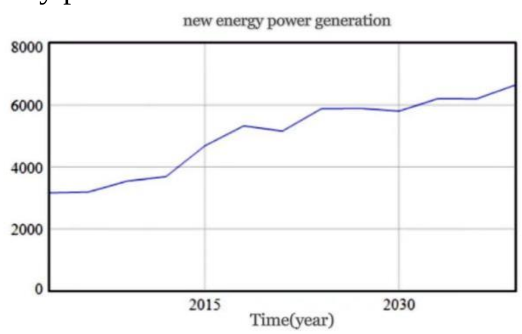


Figure 6: New energy generation chart

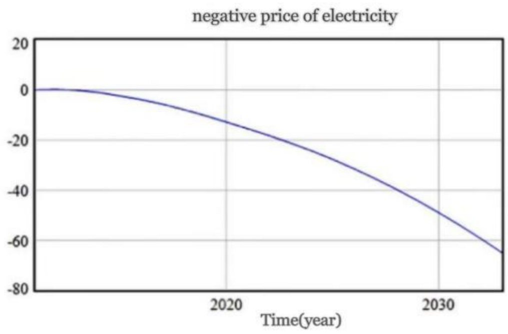


Figure 7: Negative electricity price trend

3.3.3 Carbon emission

In the radiation impact of negative electricity price, carbon emissions are also one of the important influencing variables. The development of negative electricity price will have a certain impact on the power generation of new energy units, thus affecting the change of carbon emissions. Under the background of "dual carbon", it is of great significance to study the impact and development of negative electricity price for the control of carbon emissions and the realization of carbon peak target. If the negative electricity price is not well controlled, the installed amount of new energy will decline, the power generation of new energy will also decrease accordingly, and the carbon emissions will continue to increase. Then the carbon peak target should be achieved later than 2030, which increases a certain obstacle to the realization of China's established commitment. Through the model, we obtain the trend diagram of the impact of the continuous development of negative electricity price on carbon emissions (Figure 8), which also verifies the above corresponding statements. Therefore, reasonable control of the frequency of negative electricity price can better help China achieve the goal of carbon peak and carbon neutrality as soon as possible, which has long-term strategic significance under the background of "dual carbon".

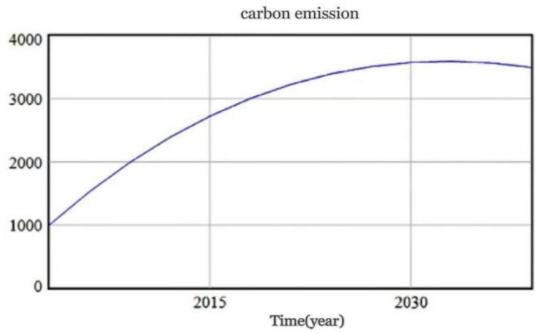


Figure 8: Carbon emissions trend

4. Recommendations for improvement

In the process of power marketization, negative prices in the spot market should be viewed and accepted in a normalized way.

4.1 Building large-scale energy storage capacity

Negative electricity prices reflect the new energy power grid consumption problems, highlighting the importance of the energy storage system, which will prompt a variety of energy storage technologies to accelerate the coexistence of development, different energy storage technologies in different scenarios to play their respective advantages. Therefore, in the planning and design stage of the power system needs to fully consider the demand and potential of energy storage, energy storage as an important part of system flexibility and stability. At the same time, the integration and synergistic operation of the power system and energy storage facilities should be strengthened to maximize the benefits and capabilities of energy storage.

4.2 Grid Intelligent Informationization

The new generation of energy system, including new energy storage and grid intelligent informationization, is centered on electricity, with the grid as the backbone, covering all kinds of energy production, transmission, use, storage and conversion devices.

4.3 Power users actively regulate their own production organization

Negative electricity prices appear frequently, the price of electricity up and down, will mobilize power users to use the law of price to regulate their own production organization behavior, pay more attention to the production process and energy consumption levels, take active measures to achieve cost reduction, enhance their competitiveness and economic efficiency. Users can adjust the behavior of electricity consumption according to the market price of electricity, improve process technology, use more electricity in low electricity prices, negative electricity prices to reduce electricity expenses, increase the scale of their participation in demand response, and through the construction of distributed power supply, energy storage, virtual power plants, etc., to further strengthen the ability to participate in market competition.

5. Conclusions

Negative electricity price is an unsustainable normal phenomenon in the electricity market, the frequent occurrence of negative electricity price phenomenon will be an obstacle to the increase in installed capacity of new energy, thus reducing new energy power generation, increasing carbon emissions, hindering the realization of China's peak carbon goals. Therefore, this state is unsustainable, both for new energy such as photovoltaic, or for new energy subsidies in the context of the policy of traditional thermal power companies in the negative electricity price , there is a continuous emergence of strong signals, which also signals: market participants need to be more rational to participate in the market; new energy industry needs to pay attention to the phenomenon of negative electricity prices and the implementation of the corresponding countermeasures to regulate the development of negative electricity prices, to ensure that new energy power generation industry stability of the new energy power generation industry. At the same time, the emergence of negative electricity prices is also related to the insufficient allocation of energy storage, the future design of the power system to put the commercialization of energy storage on the agenda.

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