ISSN 2004-2965 Energy Proceedings, Vol. 22, 2021

International Conference on Applied Energy 2021
Nov. 29 - Dec. 5, 2021, Thailand/Virtual
Paper ID: 471

Sensitivity Analysis between Influencing Factors and Clearing Price in Electricity Spot Market

Jianing Lin[1], Minglei Bao[2*], Yining Zhu[3], Ziyang Liang[2], Hengyu Hui[2], Yi Ding[2]

1 Polytechnic Institute, Zhejiang University
2 School of Electrical Engineering, Zhejiang University
3 School of Electrical Engineering, ZJU-UIUC Institute

ABSTRACT

With the expansion of electricity spot market, there have been more factors affecting clearing prices considering renewable energy, carbon emissions trading, and others. Assessing the impact of key factors on price is beneficial to the controllability and stability of electricity prices in spot markets. Therefore, this paper proposes a method to analyze the key factors influencing price based on sensitivity analysis. Firstly, an index system is constructed to evaluate the influence on clearing price, including factors from unit cost, unit operation and system operation. To study the specific impact of various factors, a spot market clearing model considering carbon emissions trading is introduced in this paper. Finally, the sensitivity analysis method is used to compare the influence of each factor on clearing price in markets with different ratios of renewable energy. In the case study, a 39-node system is used to verify the effectiveness of the method and loads in valley-load period is proved to be the most critical factor in the market with high ratio renewable energy.

Keywords: electricity spot market, clearing simulation, nodal price, influencing factor, sensitivity analysis

1. INTRODUCTION

As a typical pricing method in the electricity spot market, nodal prices have been widely used in power markets in the United States[1], Singapore[2], Australia[3] and other countries. Nodal prices of different nodes are varied[4]. Meantime, electricity price in spot market fluctuates over time. With the development of electricity spot market, there have been more uncertain factors influencing clearing price including high ratio of renewable energy, variation of fuel price and others. The uncertainty in clearing price grows in the future electricity spot market. Therefore, measuring the effect of key influencing factors on clearing price is important. The research can help to control the risk of price fluctuation and avoid the extremely high price. Also, the study can offer guidance for the improvement of market rules and decrease the risk of market decision.

There are several works endeavoring to analyze the influencing factors of the power market prices. Reference [5] analyzes the impact of unit operation constraints on market prices, including ramping constraints and unit output limit constraints. By comparing the market clearing results with or without considering the operational constraints of the transmission grid, the impact of transmission capacity on clearing prices is evaluated in reference [6]. A breaking down methodology directly to link each concerned factors to the nodal prices is proposed in [7], which describe the composition of the electricity price in detail. Reference [8] seeks to analyze the impact of privileged renewable electricity generation on spot market prices in Germany. Reference [9] uses sensitivity analysis to evaluate the influence of load, transmission line limit and generators output limit on nodal price separately.

These researches mostly studied the individual impact of each factor on clearing price. Moreover, a more detailed horizontal comparison is needed to identify the most critical factors that influence prices. Meanwhile the effect of renewable energy also needs to be considered. Therefore, this paper firstly constructs the comprehensive analysis of influencing factors on spot electricity price. Then the market clearing simulation model considering carbon emissions trading

Selection and peer-review under responsibility of the scientific committee of the 13_{th} Int. Conf. on Applied Energy (ICAE2021).

is established. Finally, the sensitivity analysis is used to identify the key factors in electricity spot market with different ratio of renewable energy.

2. CONSTRUCTION OF INFLUENCING FACTORS INDEX SYSTEM ON CLEARING PRICE IN SPOT MARKET

Based on the analysis of influencing factors of clearing price in the spot market, influencing factor index system are constructed, including operational cost, carbon emission cost, unit output upper bound, unit output lower bound, unit ramping rate, loads, operation reserve and transmission line capacity. The factors and classification that they belong to are shown in table 1.

2.1 Unit Cost Factors

The impact of unit cost on clearing price is reflected by the bidding behavior of power producers. Under the same load level, nodal prices increase as the unit cost goes higher. Under the mechanism of limiting carbon emissions, fossil energy generators will need to purchase carbon emissions in the carbon market to get access to electricity generation. At this point, the operating cost of the unit would include not only the traditional cost of fuel, but also the cost of carbon emissions. For this reason, the cost of carbon emissions for generators will also have an impact on the market clearing price[10].

2.2 Unit Operation Factors

The output bound and ramp rate of units could influence the available output of units that further affect the nodal prices in market clearing. For the unit output upper bound, when a unit with lower bidding decreases its output upper bound, the market has to call the unit with a higher bidding to meet the load, resulting in a higher clearing price[11]. For the unit output lower bound, more renewable energy can be called on when output lower bound of thermal power unit decreases. And the clearing price decreases as the marginal cost of renewable energy is zero. For unit ramping rate, as the unit ramp capacity changes, the marginal unit that determines the nodal price will also change, thus affecting the market price.

2.3 System Operation Factors

In the power spot market, prices are also affected by system operation factors, such as the level of loads and operation reserves. For example, the ISO needs to dispatch the units with higher bidding prices to ensure the balance when the loads increase, resulting in the increase of clearing prices. Besides, the growth of loads causes the congestion of transmission line and increase the congestion cost. Meanwhile, as the boundary condition of the clearing model, operation reserve affects nodal price by influencing the balance of supply and demand[12].

Besides, the capacity of the transmission line has an impact on the clearing results. On the one hand, the shadow price of the transmission line is part of the nodal price. Changes in transmission capacity will lead to changes in shadow price[13]. On the other hand, the capacity of the transmission line influences the output of the units. For example, units with lower bidding prices are not dispatched due to the congestion, resulting in the need for electricity to be supplied by units with higher costs, which ultimately leads to an increase in clearing prices.

3. ELECTRIC SPOT MARKET CLEARING SIMULATION CONSIDERING CARBON EMISSIONS TRADING

3.1 Objective Function

In this paper, the total cost of the generator set is composed of carbon emissions trading cost and operational cost. The cost of carbon emissions trading can be expressed as follows[14]:

$$\rho_{co2i}(t) = \alpha(\varepsilon_i P_i(t) - \kappa P_i(t)) \tag{3-1}$$

where α is the transaction price of CO2 per ton in the carbon market. ε_i is the carbon emission coefficient of unit *i*. κ is the carbon quota base.

Table 1. Influencing Factor Index System on Clearing Price in Spot Market[10]-[12]

Factor Classification	Specific Factor
Unit Cost Factors	Operational Cost
	Carbon Emission Cost
Unit Operation Factors	Unit Output Upper Bound
	Unit Output Lower Bound
	Unit Ramping Rate
System Operation Factors	Loads
	Operation Reserve
	Transmission Line Capacity

By integrating the carbon emission cost and the operational cost, the complex cost curve of the generator set can be expressed as follows:

$$C_i = a_i\left(P_i(t)\right)^2 + b_iP_i(t) + c_i + \alpha(\varepsilon_iP_i(t) - \kappa P_i(t)) \quad (3\text{-}2)$$

where a_i, b_i, c_i represents the cost coefficients of the unit operational cost.

The original cost function needs to be linearized to form the block bidding, and the objective function can be expressed as follows:

$$minF = min\sum_{t=1}^{T}\sum_{i=1}^{NG}\left[\sum_{j=1}^{m}k_i^j\Phi_i^j(t)\right] \quad (3\text{-}3)$$

$$\text{S.T} \quad \Phi_i^1(t) + \Phi_i^2(t) + \cdots + \Phi_i^m(t) = P_i(t) \quad (\mathrm{i} = 1,2\ldots,NG) \quad (3\text{-}4)$$

where k_i^j and Φ_i^j respectively represent the bidding and bid-winning capacity of section j of unit *i*. *m* and *NG* respectively represent the number of the bidding block and total unit in the system.

3.2 Constraint Conditions

DC power flow is used to model the power system constraints in this paper[15]. The detailed constraints are as follows.

1) Power balance constraints

$$\sum_{i=1}^{NG}P_i(t) = d(t) \quad (3\text{-}5)$$

where $\sum_{i=1}^{NG}P_i(t)$ and $d(t)$ represents the total output of unit and load during period t respectively.

2) Operation reserve constraints

$$\sum_{i=1}^{NG}\left(\overline{P_i} - P_i(t)\right) \geq \overline{R}(t) \quad (3\text{-}6)$$

$$\sum_{i=1}^{NG}\left(P_i(t) - \underline{P_i}\right) \geq \underline{R}(t) \quad (3\text{-}7)$$

where $\overline{P_i}$and$\underline{P_i}$ represent unit output upper and lower limit. $\overline{R}(t)$ and $\underline{R}(t)$ represents spinning reserve capacity.

3) Unit Output limits constraints

$$P_i(t) \leq \overline{P_i} \quad (3\text{-}8)$$

$$P_i(t) \geq \underline{P_i} \quad (3\text{-}9)$$

4) Unit ramping limits constraints

$$P_i(t) - P_i(t-1) \leq \Delta_i \quad (3\text{-}10)$$

$$P_i(t) - P_i(t-1) \geq -\Delta_i \quad (3\text{-}11)$$

where Δ_i is the maximum output that unit *i* can increase or decrease in each period.

5) Transmission line limits constraints

$$P_l(t) \leq \overline{P_l} \quad (3\text{-}12)$$

$$P_l(t) \geq \underline{P_l} \quad (3\text{-}13)$$

where $P_l(t)$ represents interface power flow at period *t*. $\overline{P_l}$ and $\underline{P_l}$ represent upper bound and lower bound of capacity.

4 ANALYSIS OF THE INFLUENCE OF FACTORS ON CLEARING PRICE

4.1 Sensitivity Analysis of Clearing Price to Influencing Factors

To horizontally compare the influence of different factors on the clearing price in the electricity spot market and find out the key factors affecting the clearing price, this paper adopts the finite difference method to calculate the sensitivity of clearing price to operational factors[16]. The sensitivity coefficient of electricity price and each factor can be obtained to measure the influence between different factors quantitatively.

Since the dimensions of different factors are inconsistent, it is necessary to normalize the factors to make a unified comparison of data. the normalization formula is as follows:

$$\Delta x = \frac{x_{after} - x_{original}}{x_{original}} \quad (4\text{-}1)$$

where x_{after} is the changed value of the factor, $x_{original}$ is the ground state of the factor.

The corresponding sensitivity analysis can be calculated by using the following formula:

$$F_k = \frac{\Delta A}{\Delta k} \quad (4\text{-}2)$$

where ΔK and ΔA is the normalized change of influencing factors and average nodal price.

4.2 Selection of the Key Influencing Factors

The specific process is as follows:

Firstly，Divide the whole day into high load period, mid load period and low load period according to load level. Subsequently, the sensitivity was compared in different periods

Then， on the basis of the initial state, heuristic method is used to find the upper and lower limits of influencing factors that both make the clearing model solvable and make the change of the factor has an obvious influence to clearing price. Six different factor's scenarios are generated by taking six groups of the influencing factor in the range of lower limit and upper limit with the same step. The sensitivity calculation formula is used to calculate six groups of sensitivity of the clearing price to this factor shown as follows：

$$F_{k1} = \frac{\Delta A_1}{\Delta k_1}, F_{k1} = \frac{\Delta A_1}{\Delta k_2}, \ldots, \; F_{k6} = \frac{\Delta A_6}{\Delta k_6} \quad (4\text{-}3)$$

Finally, assign scores to the original sensitivity data based on a suitable score criteria which is shown in table 2. The average assigned score can be used for unified comparison, and the key influencing factors of the electric spot market can be finally determined.

Table 2. Assigned Score Criteria of Sensitivity

Sensitivity	0	(0,0.5]	(0.5,1]	(1,3]
Score	0	1	2	3
Sensitivity	(3,5]	(5,7]	(7,9]	(9,11]
Score	4	5	6	7
Sensitivity	(11,13]	(13,15]	(15,17]	(17,+∞)
Score	8	9	10	10

5 EXAMPLE ANALYSIS

5.1 Basic State of Electricity Spot Market

In this paper, the 39-node system is adopted to analyze the key influencing factors of the clearing price in the electricity spot market. The specific configuration of the 39-node system is given in [17] and the system predicted load is taken from reference [18]. The positive and negative reserve capacity are both 100MW, unit ramping rate is 30MW/min, and the clearing price is the weighted average node-price of the load side in the whole grid. The carbon quota base of this market is 7.838 tons/10,000KWH, and the transaction price of the carbon market is 41.5 RMB/ton CO2. The comprehensive 4-paragraph bidding of each unit is shown in table 3.

5.2 Sensitivity Analysis of key influencing factors in the market without renewable energy

According to the load level, the whole day is divided into peak-load (including period 11, 16, 17, 19, 20), valley-load (including period 4-7) and mid-load period (the rest period).

According to Equation (4-3), the forward difference method is used to calculate six groups of sensitivity of clearing price to factors. Assign scores based on suitable score criteria shown in table 2 for the original sensitivity data. The correlation between influencing factors and the clearing price can be obtained for further comparison, as shown in figure 1. Obviously, it can be found that the key influencing factor under varied load level is different.

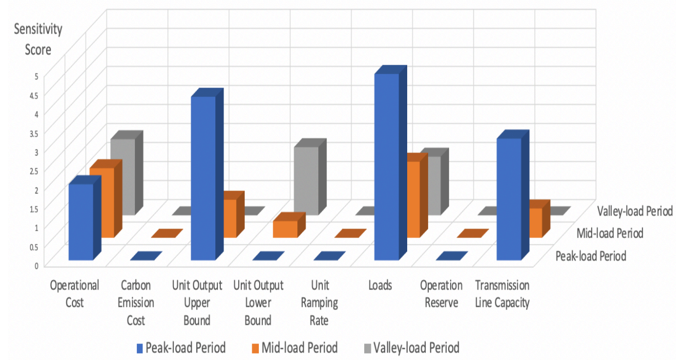

Figure 1. Sensitivity score of clearing price on influencing factors without renewable energy

From the horizontal comparison, in peak-load period, loads has the most obvious impact on nodal price. Unit output upper bound has the secondary impact on clearing price.

From the longitudinal comparison, the influence degree of loads, line transmission capacity and unit output upper bound on nodal price during peak-load period is significantly higher than that during off-peak load period. Whereas the effect of unit output lower bound on nodal price in valley period is higher.

Over the whole view, when the demand of system is far beyond the supply, the transmission congestion of the system is more serious too. So inaccurate load prediction will have a huge impact on clearing price. Meantime, the bidding strategy of not declaring full

Table 3. Basic State of Unit Bidding Data

Unit	Bid/ (¥/(MWh))	Cap /MW	Bid/ (¥/(MWh))	Cap /MW	Bid/ (¥/(MWh))	Cap /MW	Bid/ (¥/(MWh))	Cap /MW
1	137.34	416	224.7	624	312.06	832	399.42	1040
2	87.57	258	141.75	387	195.93	516	250.32	646
3	97.65	290	158.55	435	219.45	580	280.35	725
4	105.63	260	142.8	390	197.4	520	252.42	652
5	88.2	204	113.4	306	156.24	408	202.23	508
6	70.56	276	151.2	414	209.16	552	266.49	687
7	93.24	232	128.1	348	176.82	464	225.54	580
8	79.38	226	124.95	339	172.41	452	219.66	564
9	77.49	346	187.95	519	260.61	692	333.27	865
10	115.29	440	237.3	660	329.7	880	422.1	1100

capacity with higher price can significantly increase the nodal price as well.

5.3 Sensitivity Analysis of Key Influencing Factors in the Market with Renewable Energy

In this section, the sensitivity analysis between influencing factors and clearing price in power spot market with renewable energy is further studied. The output of renewable energy is called based on predicted value. The sensitivity score of clearing price on each influence factor with 5% and 20% renewable energy ratio are shown in figure 2 and figure 3 respectively.

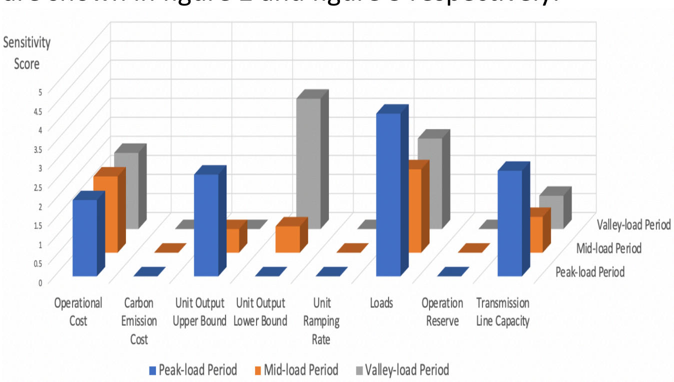

Figure 2. Sensitivity score of clearing price on influencing factors with 5% renewable energy ratio

The result of sensitivity analysis with 5% renewable energy can be summarized as follows. In peak-load period, loads has the most obvious impact. In valley-load period, unit output lower bound has key influence on clearing price as well.

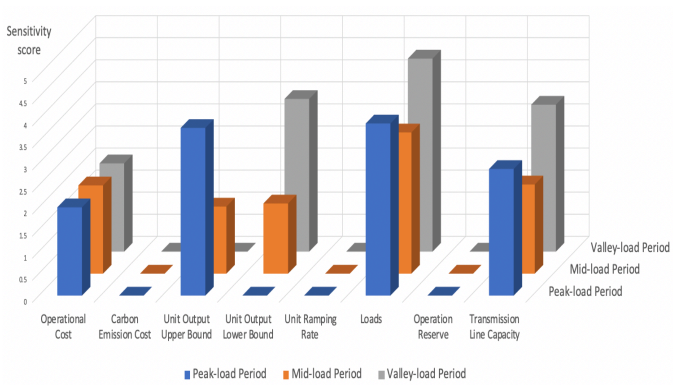

Figure 3. Sensitivity score of clearing price on influencing factors with 20% renewable energy ratio

The result of sensitivity analysis with 20% renewable energy can be summarized as follows. In valley-load period, loads has the most critical influence. In peak-load period, loads and unit output upper bound have the secondary impact on clearing price.

5.4 Comparison of Sensitivity between Influencing Factor and Price with Different Renewable Energy Ratio

From figure 1-3, it can be found that effect of certain influencing factors including unit output lower bound, loads and transmission line capacity on price changes with the increasement of renewable energy ratio.

Figure 4-6 shows comparison of sensitivity between above factors and clearing price with different renewable energy ratio respectively.

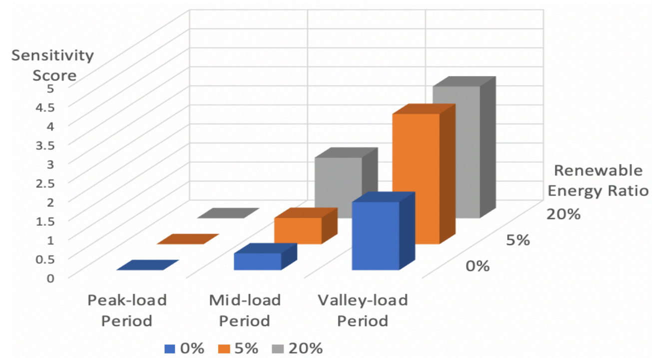

Figure 4. Sensitivity score of clearing price on unit output upper bound with different renewable energy ratio

Figure 4 shows that the effect of unit output lower bound on price increases with the increasement of renewable energy ratio in all load level period. when the lower limit of unit output decreases by the same amount, as the proportion of renewable energy increases, the clearing output of renewable energy in priority increases, and thus the degree of decrease in clearing price adds.

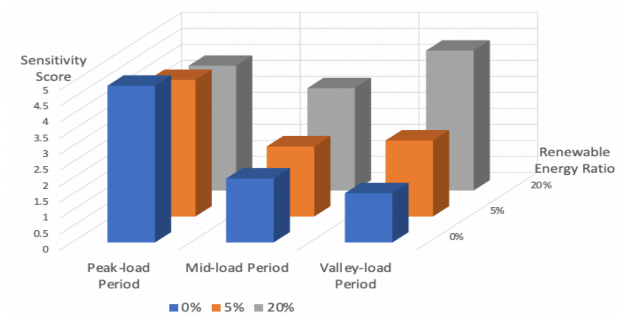

Figure 5. Sensitivity score of clearing price on loads with different renewable energy ratio

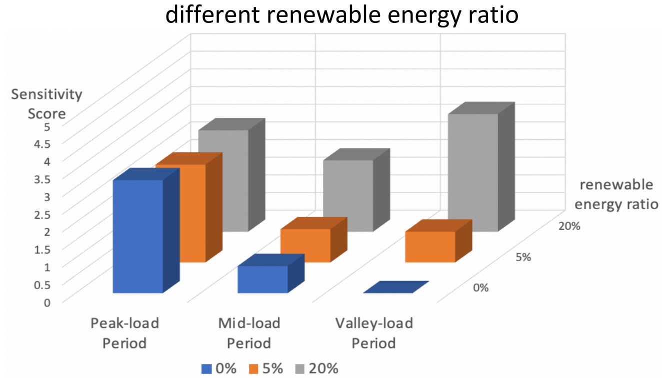

Figure 6. Sensitivity score of clearing price on transmission line capacity with different renewable energy ratio

Figure 5-6 shows that with the increasement of renewable energy ratio, both effect of loads and transmission line capacity on price decreases in peak-load period and increases in off-peak period. In high ratio of renewable energy market, the system may does not need to call on extra unit output with higher bidding in peak-loal period. However, during valley-load period, when the loads adds or the transmission capacity decreases, the line associated with the node where the renewable energy unit are located may change from non-congestion to congestion, thus increasing the price greatly.

In summary, the key factor in the market with different ratio of renewable energy is shown in table 4. In the system with no renewable energy, the key factor is loads in peak-load period. In low ratio of renewable energy system, loads in peak-load period and unit output lower bound in valley-load period are the most critical factors. loads in valley-load period is the most critical factor. In high ratio of renewable energy system, loads in valley-load period is the key factor.

Table 4. Key Factor in Market with Different Ratio of Renewable Energy

Renewable Energy Ratio	Key Factor
0%	Loads in peak-load period
5%	Loads in peak-load period, unit output lower bound in valley-load period
20%	Loads in valley-load period

6 CONCLUSION

This paper proposes a method to analyze the key influencing factors of clearing price in power market by sensitivity analysis. As a result, in high ratio of renewable energy system, loads in valley-load period is the most critical factor. In low ratio of renewable energy system, loads in peak-load period and unit output lower bound in valley-load period are the key factors. In the market without renewable energy, the key factor is loads in peak-load period. Meantime, as the ratio of renewable energy increases, the effects of loads, unit output lower bound and transmission line capacity in off-peak period increases.

REFERENCE

[1] Roberto F. Paliza, The Midwest ISO Market Design. [EB/OL] [2000-04-12].www.miso-pjm-spp.com.

[2] F. Lu and H. Gan, "National electricity market of Singapore," in Proc. 7thInt. Power Eng. Conf., vol. 29, Dec. 2005, pp.1007–1012.[M]. Proc 7thInt Power Eng Conf. Dec. 2005: 1007-12.

[3] PLEXOS for Power Systems, Drayton Analytics, Adelaide,Australia,2007.[Online].Available:http://www. plexossolutions.com.

[4] LI F, WEI Y, ADHIKARI S. Improving an unjustified common practice in Ex Post LMP calculation: An expanded version; proceedings of the IEEE PES General Meeting, F 25-29 July 2010, 2010 [C].

[5] Shi Xinhong, Zheng Yaxian, Xue Bike, et al. Effect Analysis of Unit Operation Constraints on Locational Marginal Price of Unit Nodes [J]. Power System Technology, 2019, 43(08): 2658-65(in Chinese).

[6] WANG Z Y. A Novel Evaluation Method of Transmission Grid Performance in Power Spot Market [J]. Ieee Access, 2019, 7(181178-83).

[7] LUONAN C, SUZUKI H, WACHI T, et al. Components of nodal prices for electric power systems [J]. IEEE Transactions on Power Systems, 2002, 17(1): 41-9.

[8] SENSFUS F, RAGWITZ M, GENOESE M. The merit-order effect: A detailed analysis of the price effect of renewable electricity generation on spot market prices in Germany [J]. Energy Policy, 2008, 36(8).

[9] ABY A T, KARTHIKEYAN S P, BHATTACHARYA T, et al. Sensitivity assessment on Locational Marginal Price under deregulated electricity market; proceedings of the 2016 IEEE Region 10 Conference (TENCON), F 22-25 Nov. 2016, 2016 [C].

[10] M. Lu, "Research on enterprise strategy in carbon market from allocation of quota," 2016 International Conference on Management Science and Engineering (ICMSE), 2016, pp. 697-701.

[11] LIU Ximei. Analysis of electricity commodity property based on perspective of generalized virtual economy[J]. Smart Power,2019,47(7):19-23,28.

[12] H. Wang, Z. Lin, F. Wen and J. Huang, "A comprehensive evaluation index system for power system operation," International Conference on Sustainable Power Generation and Supply (SUPERGEN 2012), 2012, pp. 1-6.

[13] F. Li, J. Pan and H. Chao, "Marginal loss calculation in competitive spot market", Proc. 2004 IEEE Int. Conf. Deregulation Restructuring and Power Technologies (DRPT), vol. 1, pp. 205-209, Apr. 2004.

[14] R. Zhou, Y. Li, J. Sun, H. Zhang and D. Liu, "Low-Carbon Economic Dispatch considering carbon capture unit and demand response under carbon trading," 2016 IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC), 2016, pp. 1435-1439.

[15] N. I. Nwulu, "Modelling locational marginal prices using decision trees," 2017 International Conference on Information and Communication Technologies (ICICT), 2017, pp. 156-159.

[16] CONEJO A J, CASTILLO E, MINGUEZ R, et al. Locational marginal price sensitivities [J]. IEEE Transactions on Power Systems, 2005, 20(4): 2026-33.

[17] ENGINEERING TEXAS A&M UNIVERSITY. IEEE 39-Bus System[M].[EB/OL].[2021-09-15]. https://electricgrids.engr.tamu.edu/electric-grid-test-cases/ieee-39-bus-system/.

[18] Zhou Baolong, Zhao Wenmeng, Xuan Peizheng, et al. Research on the Key Influencing Factors of Electricity Spot Market Locational Marginal Price [J]. Guangdong Electric Power, 2020, 33(02): 86-92(in Chinese).

