Research on evaluation index system of the operation efficiency in electricity market

Yuzhuo Zhao¹, Yanchi Zhang¹,³*, Xinlin Zhang¹, He Li¹, Dong Chen¹ and Da Xie²

¹School of Electrical Engineering, Shanghai Dianji University, 201306 Shanghai, China;
²School of Electronic Information and Electrical Engineering, Shanghai Jiaotong University, 200240 Shanghai, China
³Email: zhangyc@sdju.edu.cn

Abstract. In order to ensure the efficient and stable operation of the electricity market, it is very important to set indexes to measure the market efficiency. In this paper, Herfindahl Hirschman Index (HHI) and social welfare index are used to measure the market efficiency. The article improves the traditional HHI. The HHI and social welfare index are standardized by min-max, and applied to a certain electricity market. The calculating results of each index and the result curve after standardization are given by example analysis.

1. Introduction

In June 2020, the National Development and Reform Commission, the National Energy Administration officially issued a new version of ‘the Basic Rules for Medium - and Long-Term Electric Power Trading’, which provides a useful reference for all kinds of market players to participate in market transactions. With the deregulation of energy and the massive demand for electricity in society, to ensure the stable operation of power system and promote the sustainable development of electricity market, it is very necessary to set appropriate evaluation indicators for the electricity market. Suitable evaluation index should be based on market efficiency, which can be measured using its impact factors as well as social welfare.

The market share of power generation subjects in China's electricity market is relatively concentrated, so the electricity market is close to oligopoly market. Power generation enterprises with a large share have the power to exercise market power [¹], that is, they can adjust the price to a level higher than the average competition level to obtain excess profits. As long as a power generation enterprise can influence the market equilibrium point, it has certain market power [²]. The existence of market power, however, will reduce social welfare and even produce power supply crisis [³], thus affecting market efficiency. The market power is therefore an important influencing factor of market efficiency. Appropriate indexes must be set to evaluate market power. In the electricity market, market concentration is an important method to measure market power, that is, to select the measurement index according to the market structure. Literature [⁴] introduced the basic theory of HHI and its advantages and disadvantages. It pointed out that HHI could not reflect the elasticity of demand and was a static measurement method. After by setting indicators to evaluate market power, we can roughly screen for performing market power generation the main body and use various methods to weaken the market power. Examples include encouraging more suppliers to enter the market, limiting
the market share of individual suppliers, expanding the transmission network, entering into long-term trading contracts and promoting demand-side bidding.

In addition to the market power index, the social welfare index can simply and directly measure the operation efficiency of the electricity market. The realization of the maximum social welfare can ensure the stable and efficient operation of the power market [5]. Literature [6] proposed an algorithm for individual welfare maximization and pointed out that individual welfare maximization depended on the optimal flow solution of social welfare maximization.

The general idea of this paper is to use the market power indicators and the social welfare indicators to measure the market efficiency in order to better manage the electricity market. In this paper, Improved Herfindahl Hirschman Index (IHHI) is proposed to solve the shortcoming that the market concentration index HHI cannot reflect the real-time running status of the system. In other words, according to the different demands, the local HHI is firstly derived, and then the system HHI is calculated. The evaluation indicators of social welfare and its associated producer surplus share indicator are proposed. The calculation and comparison of the traditional HHI and improved HHI are based on electricity data from a local electricity market. Finally, several indicators were min-max normalized to synthesize the power data.

2. Construction of evaluation index system

2.1. Market power evaluation index

2.1.1. The traditional HHI index. Usually the first step in measuring market power is to assess the market structure, that is to study the market share of generators. Market concentration is a good indicator to summarize market share. There is a nonlinear and positive relationship between market concentration and market power. The higher the degree of market concentration, the higher the market power will be. With monopoly power gradually replacing competitive power, while when the concentration is high, market competition has almost disappeared. At this point if the concentration is increased again, it will not have too much impact on market power. According to the above views, the relationship between market concentration and market power is shown in the S-shaped curve below.

\[
\text{HHI} = \sum_{i=1}^{n} (100p_i)^2
\]  

where \( p_i \) is the share of generator \( i \) in the market, \( n \) is the number of generators in the market.

When the market is monopolistic, that is, there is only one generator in the market, its share is 100% and the HHI reaches a maximum of 10000. When the market is perfectly competitive, that is, there are enough generators in the market, HHI approaches zero. Range of market concentration based on HHI indicators given by the Energy Regulatory Commission, when the HHI>1800, the market is highly
concentrated. When 1000<HHI<1800, the market is moderately concentrated. When HHI<1000, the market is normal.

Since HHI is determined by the market share of each generator, it is a static indicator, whereas market power is a dynamic issue. The supply and demand of the market changing over time. HHI cannot reflect the elasticity of demand and cannot measure the effect of changes in supply and demand on the level of market power.

2.1.2. Improved HHI index (IHHI). In times of severe blockages, the load is often higher. There is less capacity available at this point. To increase the demand for load, it is necessary to provide power from unscheduled units. In the unscheduled units, there will be generators with large capacity, which will have a certain market power. The market concentration indicators will therefore vary between different operating conditions at different times in the electricity market.

Taking full account of the influence of transmission congestion, elasticity of demand and other factors, IHHI provides a comprehensive measure of the market structure and sets reasonable indexes according to the different positions of generators in the electricity market under different operating conditions. The calculation method of IHHI is to first divide the power market into several local markets based on the actual situation. For a given hour, calculating the generation of each generator as a percentage of the generation of the sub-network, leading to the local HHI (LHHI):

\[ LHHI = \frac{\sum_{i=1}^{x} \left( \frac{P_{Gi}}{Total_{L}} \right) \times 100}{2} \]

where \( x \) is the number of generators, \( P_{Gi} \) denotes the amount of electricity generated by generator \( i \), \( Total_{L} \) represents the total power generation in the local electricity market.

After calculating the local HHI, the share of the transmission power of the sub-network in the total power of the system is taken as the coefficient, and the HHI of the whole system (SHHI) is calculated by weighting each part of HHI:

\[ SHHI = \sqrt{\sum_{j=1}^{y} \left( \frac{P_{Gj}}{Total_{S}} \times LHHI_{j} \right)^{2}} \]

where \( y \) is the number of generators, \( P_{Gj} \) represents the power generation of the JTH subsystem, \( Total_{S} \) represents the generation capacity of the entire system, \( LHHI_{j} \) represents the HHI index of the JTH subsystem.

This calculation reflects the market concentration during transmission congestion. It gives market power indicators for different periods and operating conditions in the electricity market. Compared with the traditional HHI index, it is more dynamic.

2.2. Social welfare evaluation index

Social welfare is the sum of consumer surplus and producer surplus, considering the market transaction cost. It can measure the efficiency of operation of the whole electricity market. Consumer surplus is the benefit received by consumers from using electricity minus the cost incurred in purchasing it. The producer surplus is the revenue received from selling electricity minus the cost of supplying it. As follows:

\[ \sum (B_{i} - E_{i}) + \sum (-C_{j} + R_{j}) \]

where \( i \) refers to demand, \( j \) refers to supply, \( B_{i} \) refers to profit, \( E_{i} \) refers to expenses, \( C_{j} \) refers to cost, \( R_{j} \) refers to revenue.

In the electricity market, a rise in price provides an incentive to increase supply. As supply increases, the marginal cost of production rises, forcing producers to charge higher prices. So the supply curve slopes up to the right with a positive slope. Conversely, the demand curve slopes down to the right with a negative slope. Social welfare is greatest when market efficiency is highest.

However, such an ideal situation does not exist in the electricity market. Actual social welfare will be partially lost due to market transaction costs and transmission congestion costs. The actual size of
social welfare should therefore be reduced by the maximum value of social welfare minus the portion of welfare lost. As follows:

$$W = W_{\text{max}} - W_{\text{loss}}$$  \hspace{1cm} (5)

where \(w\) is the actual social welfare, \(W_{\text{loss}}\) is the loss of social welfare. The market transaction cost is composed of the costs incurred in the construction and operation of the electricity trading platform. Different pricing mechanisms will be used to manage transmission congestion during operation, which will result in different market transaction costs. Regardless of the type of transmission blockage management used, the cost will be accounted for in the social welfare. The cost is mainly due to the increase in the cost of generating electricity and the reduction of electricity consumption by costumers due to the elasticity of demand. Figures 2 and 3 show the ideal social welfare curve and the actual social welfare curve respectively.

![Figure 2 Ideal social welfare](image1)

![Figure 3 Actual social welfare](image2)

Curves S and D in the figure are supply curve and demand curve respectively. The area on the left half is social welfare. The maximum social welfare is the largest area, and the maximum social welfare is \(W_{\text{max}}\).

To sum up, assuming that the indicator of actual market efficiency is \(P\), the calculation formula is given in the following equation:

$$P = \left( \frac{W}{W_{\text{max}}} \right) \times 100\% = \left( \frac{W_{\text{max}} - W_{\text{loss}}}{W_{\text{max}}} \right) \times 100\%$$  \hspace{1cm} (6)

2.3. Standardisation of indicators

Since social welfare includes producer surplus and consumer surplus, the attributes and dimensions of social welfare indicators are different from those of producer surplus ratio and consumer surplus ratio. In order to make a more accurate comprehensive evaluation and measure the market efficiency, this paper takes HHI, social welfare and producer surplus ratio as three quantitative indicators and standardises them min-max.

For social welfare indicators, the higher the value is, the better the performance will be, which is a positive indicator. While the opposite is true for HHI indicators, which are negative indicators. Producer surplus ratio is an intermediate index. So it is necessary to conduct min-max standardization for these three different types of quantitative indicators. Min-max standardization scales the original data so that the results lie between \([0,1]\). The unit limitation of the index is avoided, and the indicator data is transformed into dimensionless pure value. It is easy to compare and weight indicators of different units or orders of magnitude. The following formula shows three different treatments:

$$k_1 = \frac{x - x_{\text{min}}}{x_{\text{max}} - x_{\text{min}}}$$  \hspace{1cm} (7)
\[ k_2 = 1 - \frac{2 \times \left| x - \frac{x_{\text{max}} + x_{\text{min}}}{2} \right|}{x_{\text{max}} - x_{\text{min}}} \]  

Equations (7), (8) and (9) above show the normalisation of positive, intermediate and negative indicators respectively. Where \( x \) is the original data of the indicator, \( x_{\text{max}} \) is the maximum value of the indicator, \( x_{\text{min}} \) is the minimum value of the indicator. The use of this standardisation approach ensures the reliability of the results. If the analysis is carried out directly with the original data, it will highlight the role of higher value indicators in the comprehensive analysis, while weakening the role of lower value indicators.

3. The example analysis

In this paper, the actual data of electricity transactions in a local electricity market from January to December 2019 are selected measure and analyse three indicators of HHI, social welfare and producer surplus ratio. The HHI is based on the traditional HHI formula and the improved HHI formula respectively.

![Figure 4 Traditional HHI curve](image)

![Figure 5 Improved HHI curve](image)

![Figure 6 Social welfare curve](image)

![Figure 7 Producer surplus curve](image)
HHI is a negative indicator with a value range of 0-10000. As can be seen from the graph, the traditional HHI index is unable to capture market changes in a timely manner as it does not take into account factors such as transmission blockages and elasticity of demand. The curve is therefore flatter and less accurate in its measurement.

Social welfare is a positive indicator, generally taking a positive value, without limiting the range. Producer surplus ratio is a medium-sized indicator with a value range of 0-1.

When the median value is 0.5, it indicates that the market is fair and consumers and producers receive the same benefits.

The curves of the three indicators after min-max standardization are shown as follows:

![Figure 8 Curve of min-max standardization results](image)

It can be intuitively seen from the trend of the above curve that the HHI varies between 1000-1800. It indicates that the electricity market here is basically in a moderate state of concentration. The overall social welfare curve shows an upward trend. The producer surplus ratio is always close to 1, that is, the market transaction price is always close to the declared price on the user side. This is due to certain market power in the market. The trend in the curves normalised for these three indicators appears to show that the market is performing well overall. The social welfare curve, although volatile, is on an upward trend. This indicates that under the established market rules, market players play with uncertainty. However, after familiarisation with the rules, market equilibrium is reached and market efficiency is improved.

4. Conclusion

This paper summarises the traditional calculation method of HHI and its shortcomings. An improved HHI index calculation method is proposed according to the dynamics of the market. It analyses the social welfare evaluation indicators. The three indicators of HHI, social welfare and producer surplus ratio were standardized by min-max. Finally, the three indicators are measured and analysed based on the actual electricity transaction data of a local electricity market from January to December 2019. Major contributions include the improvements to the traditional HHI and the selection of three indicators with different attributes and magnitudes to measure market efficiency. The three indicators are also standardised and applied to the local electricity market.

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