Empirical study on the technical efficiency and total factor productivity of power industry: Evidence from Chinese provinces

Abstract: With government policy reviews of renewable energy, environmental regulation and climate change, the energy-based power industry has received much attention. To explore the inherent characteristics of technical efficiency and total factor productivity in Chinese power industry, we use DEA-BCC and DEA-Malmquist models to exam the regional disparities of energy efficiency in 30 provinces based on the Yearbook database from 1998 to 2017. The market technical efficiency and environment technical efficiency were compared from the power generation link, the power network link and the comprehensive performance, respectively. Although the empirical results indicate that the Chinese power industry presents the development pattern of "emphasizing market over environment", the green technology and renewable energy are the waves of future and the practices of environmental regulations have borne some fruit actually. In addition, the power market reform in power industry actually works out but lacks of long-term incentives for continuous progress. The research conclusions can ravel out the complex strong correlation system in power industry and help to make targeted efficiency promotion strategies, which is in line with other energy policy goals.

Keywords: energy technical efficiency; total factor productivity; Chinese power industry; DEA model

1. Introduction

Environmental deterioration, energy crunch and economic downturn can find are all countries in the same predicament. For the sake of carbon peaking and carbon neutrality goals, more vigorous policies and measures are put in China to build green energy markets. The power industry is the fundamental industry, affecting social stability and the people's livelihood. However, massive carbon dioxide emissions make the energy-based power industry one of the largest carbon-dioxide emitters [1]. The power system reform in 2021 works hard for the sustainable power industry. Meanwhile, *The Action Plan for Carbon Peaking Before 2030* points out that the applications of the green and low-carbon technologies should be scaled during the "14th Five-Year Plan" and the traditional energy mix should be optimized during the "15th Five-Year Plan". Energy conservation, pollution reduction and public health improvement are the important goals in the present and the future [2]. In the context of practical motivation and policy support, we attempt to answer the following questions: how has the efficiency of Chinese power system changed in the market reform? What about the efficiency after taking into account the environmental regulations? And what's the right direction and effective measure to the sustainable power industry?

The optimal state of Chinese power industry is keeping balance between industry development and environmental protection. Therefore, studying how to reconcile efficiency improvement and environmental protection in Chinese power industry is significant. Through the in-depth analysis of the power system, we can understand the evolutionary law of the technical efficiency (TE) in power system and identify the critical nodes which bring a considerable change and opportunity for the energy sector. More importantly, the effectiveness of the energy policy can be evaluated to some extent.

As for total factor productivity (TFP), the research on the TFP is rare when compared with the evaluation of the TE in power industry. The difference between TE and TFP is mainly reflected in the fact that the former belongs to static analysis, while the latter belongs to dynamic analysis. The flexible analysis of the TFP is conductive to dynamic tracking and performance evaluation in the power industry. In addition, the specific obstacles and contributors to the TFP can be obtained intuitively.

Data Envelopment Analysis (DEA) was originally presented by known operations researchers Charnes et al. [3]. It has been long serving as a method to evaluate the relative effectiveness of the comparable units. DEA model is suitable for multi-input and multi-output efficiency evaluation problems [4], which is consistent with the characteristic of the complex power industry. And one of the prominent virtues of the DEA model can be described as the convenience of no need to predetermine the weight of each indicator, which eliminates some subjective factors and makes the evaluation more efficient.

By reviewing relevant literature, the descriptive statistics indicate that the number of researches on the sustainable power industry keep increasing. Almost the literatures suggest the advanced technology and renewable energy have the potential to increase the power supply safety and improve the environmental sustainability [6][6]. Considering the efficiency is affected by a combination of multiple factors, Sartori used DEA specified with DDF to assess the sustainability performance of the Brazilian electricity power industry [7]. Mohsin used both DEA and DID to view the impact of energy reforms, which confirmed energy reform contribute much to energy efficiency promotion and energy consumption reduction [8]. Minimum input for maximum output is the ideal state, we explore the efficiency level in Chinese power industry during a long period to understand the evaluation trend and identify critical issue in both power generation and power network links.

To fill a knowledge gap about efficiency and productivity in the power industry, the efficiency of the power industry was evaluated from the power generation link, the power network link and the comprehensive perspective. Meanwhile, DEA-BCC and DEA-Malmquist index models are used to analyze the TE and TFP from both dynamic and static perspectives. One of the most important research results is that Chinese power industry presents a development pattern of "emphasizing market over environment", the power market reform in 2002 and 2013 actually work out but lacks long-term incentives for continuous progress. The contribution of green policy or effective incentives is insignificant for the sustainable power industry.

To some extent, this paper can academically make up for the deficiency of the sustainable power industry based on efficiency. At the same time, it facilitates further investigations in this field for other scholars. Turning the eyes from theory to practice, the research may have a practical guiding significance for the development and reformation of Chinese power industry. For governments and relevant departments, they can obtain insights about the development status and existing problems of the power industry, which can help them coordinate and control the whole industry from a macro perspective. Specifically, the research conclusions derived are applicable to electrovalence regulations, power market reform, power system mechanism.

The paper is structured as follows: part 1 is general introduction of the research, part 2 is a review of related literature, part 3 elaborates the chosen research method and data, the next part reports the empirical results in several tables and diagrams, part 5 provides a discussion and the last part sums up the main conclusions and puts forward policy recommendations.

2. Literature Review

The sustainable development is the eternal issue, scholars have launched lots of research in different industries, such as banking industry [9], the tourism industry [10]. Because the conflict in trying to promote efficiency and protect environment in power industry, the research on the sustainable power industry is long established and have gained much attention. In 2006, Hammons found European power generation link aggravated the greenhouse gas emissions and suggested developing clean technologies and promoting their large-scale use [5]. The sustainable, efficient, and renewable energy production are expected, Strik presented the green electricity production can be realized by living plants and bacteria in a fuel cell [6]. Many European countries relied on specific tax incentives and other supporting measures to encourage green electricity, especially quota obligations and price regulation [11]. Given the applied range of policy instruments can be restricted and unabiding, Gan affirmed the necessity to clarify policy objectives and improve capacity building [12].

It's not difficult to find most of the early research and practice experience came from Europe and other developed countries, which demonstrate their advances in renewable energy utilization and green production. Recently, given the purpose of net-zero emissions and the motivation of green policy, more and more scholars have started turning up in the sustainable power industry in developing countries. Gibadullin identified factors that impede the development of Russian renewable energy sources primarily come from technical, technological and economic aspects [13]. To assessment the different electricity supply technologies in Egypt scientifically, Shaaban implemented a systematic approach to identify and select major indicators [14]. Some other scholars shown that the smart technologies should be paid much attention, they believe only by constantly absorbing advanced technologies can all kinds of industries maintain meaningful results [15][16], including the power industry.

The consensus is the sustainable power industry requires the application of new energy technologies and the support of green policies. When it comes to China, there are much research put forward practical solutions based on the efficiency evaluation. And the commonly used method is DEA, which is a typical and operative nonparametric method that are fine for the power industry [17]. Wu et al. [18] and Yang et al. [19] applied DEA to investigate Chinese energy efficiency in different periods. With the enhancement of environmental regulations, the environmental technical efficiency (ETE) of the power industry receives extensive attention [20][21][22][23]. Some scholars incorporated carbon dioxide, sulfur dioxide, waste water and exhaust gas into the DEA model as undesirable outputs, which have broken through the research limitation of focusing on market technical efficiency (MTE) in the traditional efficiency evaluation model [24][25]. As the research moves along, the DEA-Malmquist model, the three-stage DEA model [26] and the meta-frontier DEA [27] were put forward and applied widely, which proves that scholars have carried out various degrees of innovation on the DEA model. Lam and Shiu used the Malmquist index to calculate the TFP growth between 1995 and 1996 in Chinese thermal power generation and found that technological promotion accounted for almost the growth [28].

In summary, the previous research on the sustainable power industry is mainly at a macro level and they believe the application of advanced technology and renewable energy is the way forward. Whether new technology or renewable energy, the ultimate purpose is efficiency promotion. Based on this, we study the TE of the power industry from power generation link and power network link to have a deeper understanding about the efficiency level and evaluate the TFP to identify the contributors. Actually, studying the performance of the power efficiency during a long term and explore the sustainable development path is evidence-based but has received less attention. To effectively enrich the previous research, complement and expansion are put forward from the following aspects: Firstly, we choose the panel data of Chinese 30 provinces and cities from 1998 to 2017. The long period involves the important power market reforms in 2002 and 2015, which is beneficial to explore the evolutionary trend and mutual interaction of the TE and TFP of the entire power industry in a relatively long period. Secondly, Given the new requests of the power industry under the new situation, such as economic and social development, raising efficiency and saving energy, environmental protection, etc., we study the efficiency from both market and environmental aspects. Thirdly, we choose indicators from multiple perspectives, which not only includes the desirable outputs such as power generation output, but also the undesirable outputs such as pollution emission index. Actually, various theoretical extensions have been developed in DEA methods, just as mentioned above. According to the research object and research purpose, we combine the DEA and DEA-Malmquist to explore the difference on the power efficiency from both dynamic and static perspectives, which can enrich the research content and diversify research perspectives.3. Method and Data

3.1. Method

When it comes to efficiency evaluation, Stochastic Frontier Analysis (SFA) are DEA are commonly mentioned together. The former is a parametric method, while the latter is a non-parametric method. Although SFA takes into account the existence of random errors, it can only measure the efficiency of one output and multiple input indicators, which is contrary to the industry characteristics of the power industry with complex and diverse inputs and outputs. While the DEA can just remedy the failure, and another advantage is the specific production function is needless [29]. Recent scientific research literatures have also devoted to deeper exploration of the prominent strength and extensive use DEA.

3.1.1. DEA-BCC Model

The CCR and BCC are the typical models of DEA. Given the presupposition of the CCR model is constant returns to scale, Banker et al. revised it and put forward the BCC model with the presupposition of variable returns to scale, making the efficiency measurement more effective [30]. The CCR model describes an idealized state of input and output increasing in equal proportions. Therefore, the CCR model is limited for the complex production situation in the power industry. While the BCC model takes into account the increasing or decreasing marginal benefit, it is more suitable to evaluate the efficiency in power industry practically.

Given the power industry manufacturers' operating behaviors of providing users with products and services depend on the market demand of economic and social development at that time. When studying the efficiency in power industry, it is more practical to calculate the minimum input for a certain output, and the input elements are easier to adjust and control than the output elements, so the input-oriented DEA model is selected. For any decision-making unit, the DEA-BCC model based on the input-oriented dual form can be described as the following format:

$$\min \theta$$
$$s.t.\begin{cases} \sum_{i=1}^{n} \lambda_i x_{ij} + s^- = \theta x_{0j} \\ \sum_{i=1}^{n} \lambda_i y_{ir} - s^+ = y_{0r} \\ \sum_{i=1}^{n} \lambda_i = 1 \\ \lambda_i \geq 0 \ ; \ s^+ \geq 0 \ ; \ s^- \geq 0 \end{cases} \tag{1}$$

where, $i = 1,2,\cdots,n$, $j=1,2,\cdots,m$, $r=1,2,\cdots,s$, n denotes the number of decision-making units, m and s denote the number of input and output variables respectively. x_{ij} denotes the input variable j of the decision-making unit i , y_{ir} denotes the output variable s of the decision-making unit n , θ denotes the effective value of the decision-making unit. The efficiency value calculated by the BCC model is the comprehensive technical efficiency value (TE). It can be further decomposed into the product of scale efficiency (SE) and pure technical efficiency value (PTE), namely $TE = SE \times PTE$.

3.1.2. DEA-Malmquist Model

The traditional model can only compare the same period efficiency between different decision-making units, while the DEA-Malmquist model is able to detect the dynamic evolutions at different periods. And there is no need to confirm the specific criteria in the decision-making units. Therefore, since the end of the 20th century, scholars have widely used the Malmquist index in the field of input-output research [31]. According to the unique advantages of the model and the characteristics of the power industry, we will study the TFP of the power industry from the dynamic perspective.

The mentioned Malmquist index is usually adopted to evaluate the dynamic changes of TFP [31]. Let (X_t, Y_t) and (X_{t+1}, Y_{t+1}) be the input-output relationship in the period t and t+1, respectively. The change in the input-output relationship from (X_t, Y_t) to (X_{t+1}, Y_{t+1}) is the change of productivity, which can be influenced by the change of technology level and technical efficiency. $D_c^t(x^t, y^t)$ is the distance function with constant returns to scale. The Malmquist productivity index from periods t and t+1 can be calculated by:

$$M_t(x^t, y^t, x^{t+1}, y^{t+1}) = \frac{D_c^t(x^{t+1}, y^{t+1})}{D_c^t(x^t, y^t)} \tag{2}$$

$$M_{t+1}(x^t, y^t, x^{t+1}, y^{t+1}) = \frac{D_c^{t+1}(x^{t+1}, y^{t+1})}{D_c^{t+1}(x^t, y^t)} \tag{3}$$

The Malmquist index from t to t+1 period is the comprehensive productivity index, expressed as:

$$\begin{aligned} M(x^t, y^t, x^{t+1}, y^{t+1}) &= (M_t \times M_{t+1})^{1/2} \\ &= \left[\frac{D_c^t(x^{t+1}, y^{t+1})}{D_c^t(x^t, y^t)} \cdot \frac{D_c^{t+1}(x^{t+1}, y^{t+1})}{D_c^{t+1}(x^t, y^t)} \right]^{1/2} \end{aligned} \quad (4)$$

The comprehensive productivity index can be further decomposed into:

$$\begin{aligned} & M(x^t, y^t, x^{t+1}, y^{t+1}) \\ &= \frac{D_v^{t+1}(x^{t+1}, y^{t+1})}{D_v^t(x^t, y^t)} \times \left[\frac{D_v^t(x^t, y^t)}{D_v^{t+1}(x^t, y^t)} \cdot \frac{D_v^t(x^{t+1}, y^{t+1})}{D_v^{t+1}(x^{t+1}, y^{t+1})} \right]^{1/2} \times \\ & \left[\frac{D_c^t(x^{t+1}, y^{t+1}) / D_v^t(x^{t+1}, y^{t+1})}{D_c^t(x^t, y^t) / D_v^t(x^t, y^t)} \cdot \frac{D_c^{t+1}(x^{t+1}, y^{t+1}) / D_v^{t+1}(x^{t+1}, y^{t+1})}{D_c^{t+1}(x^t, y^t) / D_v^{t+1}(x^t, y^t)} \right]^{1/2} \\ & \overset{\text{denote as}}{=} PEch \times TEch \times SEch \end{aligned} \quad (5)$$

It can be simplified as:

$$TFPch = PEch \times TEch \times SEch \quad (6)$$

$$TFPch = Effch \times TEch \quad (7)$$

Where, $PEch$ denotes the change of pure technical efficiency, i.e., the change of technical efficiency under the presupposition of variable returns to scale; $TEch$ denotes the change of technology, which reflects the contribution of the movement of production frontiers to the change of productivity; $SEch$ denotes the change of scale efficiency, which is the ratio of the technical efficiency value corresponding to the constant returns to scale and the variable returns to scale, it can reflect the impact of scale economy on productivity. $Effch$ denotes the change of technical efficiency, which is the product of $PEch$ and $TEch$. The comprehensive productivity will increase if $TFPch$ is greater than 1, otherwise the comprehensive productivity level will decrease in different degree. When the change ratio of an index that constitutes the $TFPch$ index is greater than 1, the index accounts for the productivity enhancement, otherwise it lowers the productivity [32].

3.2. Data Description

To make research more convincing, we conduct the research based on 30 Chinese provinces excluding Tibet because of data unavailability, so there are 30 evaluated DMUs. According to the evaluation system, we identified and selected 10 input and output indicators. *Chinese Electricity Statistics Yearbook, Chinese Statistics Yearbook, Chinese Environment Statistics Yearbook* and *Chinese Statistics Database* are the main data sources for each variable and the time span of the dataset is from 1998 to 2017.

3.2.1. Evaluation System

The separation of production and transmission and distribution is an inevitable course of Chinese power market reform. Therefore, a two-link vertical production structure diagram is constructed to reflect the multiple links and their internal interactions in the power system. As the initial link, the generation link plays a decisive role in power industry chain. The terminal electricity consumption comes from power generation enterprises. As the supply link, the performance of transmission and distribution network has a great influence on the power efficiency. The generation link will be caught in "save power" when the power sources and the power networks is in non-compatibility. The subsequent consequences are idle power generation equipment and even depressed power generation efficiency. Meanwhile, the output electricity of the power generation enterprises acts as the input electricity in the supply link, which is an intermediate variable. To be specific, the input of the supply link depends primarily on the generation efficiency, the electric energy production relies on the transmission capacity of the supply link, conversely. The coordinated development of the two links is crucial for the power industry, as demonstrated in Figure 1.

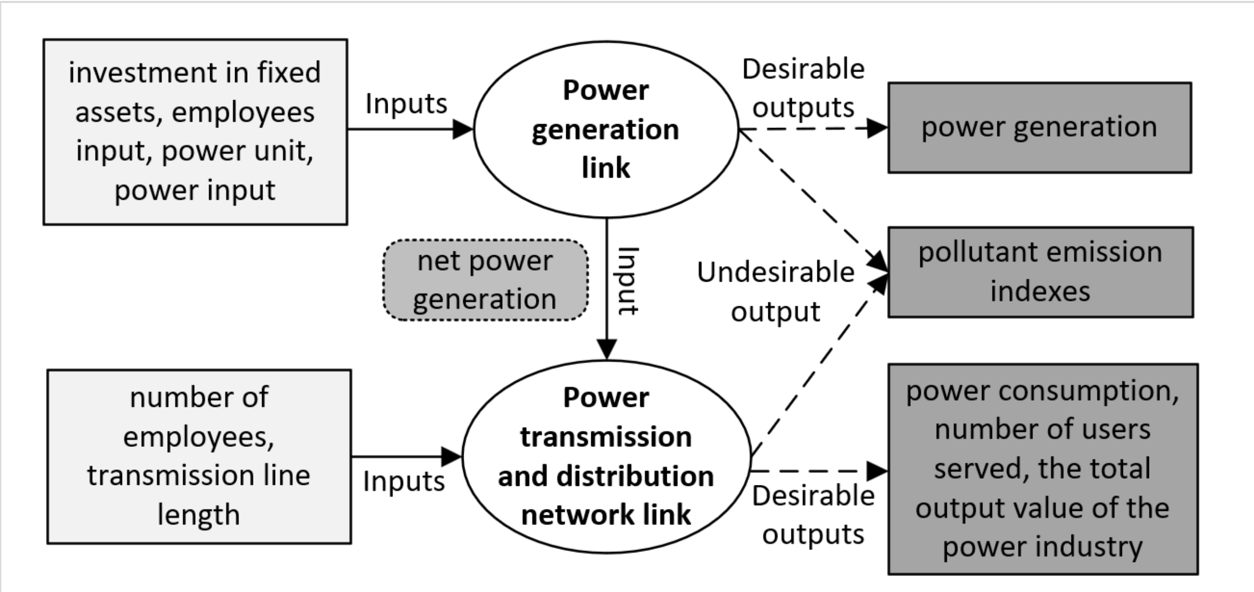

Figure 1. Diagram of power system production structure.

3.2.2. Variable Selection

The portfolio of input and output elements are critical, which should conform to the principles of importance and relevance, refer to the relevant literatures and consider the availability of data. Given the chain production mode of the power system, a corresponding input-output indicators system is constructed, as illustrated in Table 1.

There are four types of employed inputs and outputs from the labor, raw materials, capital, and technology aspects [33]. The physical production factors are chosen for the empirical study including investment in fixed assets, plant power consumption rate, equipment utilization hours, and transmission line length etc. The power generation is an intermediate variable, which is not only the output of the power generation link but also the input of the power network link [34]. The net power generation is represented by the difference between the power generation and plant power consumption [35]. Among the indicators of desirable outputs, the electricity sales represent the actual electricity provided by the local power network to users [36]. To reflect the influence of cross-region electricity trading on the MTE in regional power industry, the electricity sales and the total output value of the power industry are selected as the desirable outputs. The pollutant emission index is merged from the four indicators of wastewater, sulfur dioxide, soot and solid waste by the entropy weight method to represents the undesirable output of the ETE, which reflects the sustainable goal of emission reduction and energy saving in power industry [37].

Actually, the existing literatures usually select various input and output variables based on their research question and research objective, sometimes it is unrealistic to incorporate all inputs and outputs into empirical models in same article. As this study focuses on studying the energy efficiency in new period, we taken economic, social and environmental factors into consideration in variables selection process.

Table 1. Input-output indicators system of technical efficiency in power industry.

Evaluation type	Evaluation link	Input	Desirable outputs	Undesirable outputs
the market/ environmental technical efficiency in power industry	Power generation link	number of employees, coal consumption for power generation, investment in fixed assets, plant power consumption rate, equipment utilization hours	power generation (Intermediate variable)	pollutant emission index (waste water, exhaust gas, soot and solid waste)
	Power transmission and distribution network link	net power generation (Intermediate variable) transmission line length	electricity sales, served users, the total output value of the power industry	

Note: The indicators adopted for the MTE in the power industry do not include "pollutant emission indexes"; The indicators adopted for the ETE in the power industry does not include "total output value of the power industry".

4. Results

To have a more comprehensive understanding in the power efficiency and develop several actionable recommendations for sustainable industry accordingly, the energy efficiency in different regions of China are examined from two aspects of the market and the environment, and the TE and TFP are explored from the power generation link, the power network link and the comprehensive perspective.

4.1. Technical Efficiency in Power Industry

The TE in power industry describes an optimal allocation between input elements and output elements. One of the significant targets for power market reform is promote efficiency, which concludes both the MTE and ETE. Therefore, studying the Chinese power efficiency can help to understand the current efficiency level.

On the whole, the annual average of the MTE and ETE in Chinese power industry are at a medium level from 1998 to 2017, and they can be improved and promoted further, as shown in Table 2.

Table 2. National mean of technical efficiency in Chinese power industry from 1998 to 2017.

year	The market technical efficiency			The environmental technical efficiency		
	The entire power industry	**Power generation link**	**Power transmission and distribution network link**	**The entire power industry**	**Power generation link**	**Power transmission and distribution network link**
1998	0.808	0.832	0.783	0.784	0.851	0.717
1999	0.819	0.850	0.787	0.802	0.887	0.716
2000	0.781	0.765	0.796	0.762	0.822	0.702
2001	0.776	0.816	0.735	0.764	0.864	0.663
2002	0.784	0.852	0.715	0.771	0.890	0.652
2003	0.791	0.838	0.744	0.800	0.883	0.716
2004	0.748	0.838	0.658	0.758	0.887	0.628
2005	0.757	0.812	0.701	0.783	0.878	0.687
2006	0.768	0.845	0.691	0.785	0.892	0.677
2007	0.724	0.763	0.684	0.761	0.847	0.675
2008	0.689	0.721	0.657	0.736	0.841	0.631
2009	0.684	0.758	0.609	0.740	0.901	0.578
2010	0.861	0.738	0.984	0.945	0.906	0.983
2011	0.886	0.787	0.984	0.955	0.926	0.983
2012	0.693	0.780	0.606	0.747	0.935	0.559
2013	0.715	0.799	0.631	0.755	0.919	0.591
2014	0.692	0.762	0.622	0.740	0.915	0.564
2015	0.741	0.832	0.649	0.771	0.954	0.587
2016	0.695	0.762	0.628	0.762	0.954	0.570
2017	0.650	0.702	0.598	0.718	0.893	0.542
mean	0.753	0.793	0.713	0.782	0.892	0.671

The TE in power industry can be analyzed from different links and perspectives. For the links of power generation and power network, both the MTE and ETE in the power generation link is better than power network link in Chinese power system by 11.22% and 32.94%, respectively. The general situation of "emphasizing power generation over power transmission and distribution" in Chinese power industry can be confirmed through empirical results. From the perspectives of market and environment, the ETE in the power generation link exhibits an overall upward trend, while the MTE declines with fluctuation. It's worth noting that the average value of the MTE and ETE in power network link shows a trend of fluctuating downward. It's very urgent to improve operational and managing level in power networks for the sake of higher efficiency. When comes to the energy efficiency from a comprehensive perspective, the 2003 can be seen an important turning point. The MTE was higher than the ETE before 2003, which presented a situation of "emphasizing economy over environment". But the situation was reversed after 2003, the ETE was improved under the effect of environmental constraint index, such as "encourage large projects and discourage small energy-inefficient power plants", “desulfurization and denitrification”. The enhanced environmental regulations promoted the management intensity and technical level, thereby improving the overall ETE. And it proved the effectiveness of the power system reform in 2002 in terms of environmental regulations.

For Chinese 30 provinces, the efficiency level varies significantly among provinces, as shown in Table 3. The favourable geographical locations, developed economies and superior resource endowments lead to the high overall power efficiency in Shanghai, Guangdong, Jiangsu, Zhejiang etc., especially Shanghai has achieved the highest power efficiency. The above results are consistent with Wu's results in reference [20]. While Xinjiang, Gansu, Shanxi, Shanxi, Jilin and other provinces have lower efficiency, which can be attributed to the limited management level and the ignorance of environment protection. As centralized power output regions, Shanxi, Hebei, Inner Mongolia, Yunnan, Guizhou and other regions often have low efficiency in supply link, which exemplifies the existence of the regional "resource curse". Regarding the MTE, Guangdong (0.997) and Beijing (1.000) have the highest-efficiency level in power generation link and supply link, respectively. While regarding the ETE, Qinghai (1.000) and Beijing (1.000) have the highest-efficiency level in power generation link and supply link, respectively. On the whole, Beijing has achieved the optimal allocation of input-output resources, indicating that the city performs well in supply link. Furthermore, Beijing can elaborate driving effect for the transmission and distribution networks of neighboring areas.

To make a thorough inquiry of the regional disparities in power efficiency, we divide China into six major regional power networks based on the classification standards of regional power networks, i.e., Northeast, North China, Central China, East China, South China, and Northwest. The regional efficiency level of MTE and ETE from high to low is East (Central) China, Central (East) China, South China, North China, Northeast and Northwest, and the conclusion has been confirmed by other studies [38]. It shows that the ranking of MTE hardly changes after the inclusion of environment constraints, as shown in Table 3 and Figure 2. The coal resource reservation and economic development degree have an important influence on TE. As a coal-inputting region, the East China Power Grid has the highest efficiency value, and the TE in power generation link is as high as 0.931, which may due to its highly-developed economy. However, the Northwest Power Grid with rich coal resources ranks the lowest in efficiency. The poor technology and equipment make it difficult to realize full utilization of the existing resource endowment advantages and optimal resource allocation. For the supply link, the MTE is better than ETE, while the ETE in power generation link performs well than the power network link. How to achieve the balance between MTE and ETE in different links of the six major regional power networks, as well as the optimal dispatch among regions, are issues that need to be solved urgently.

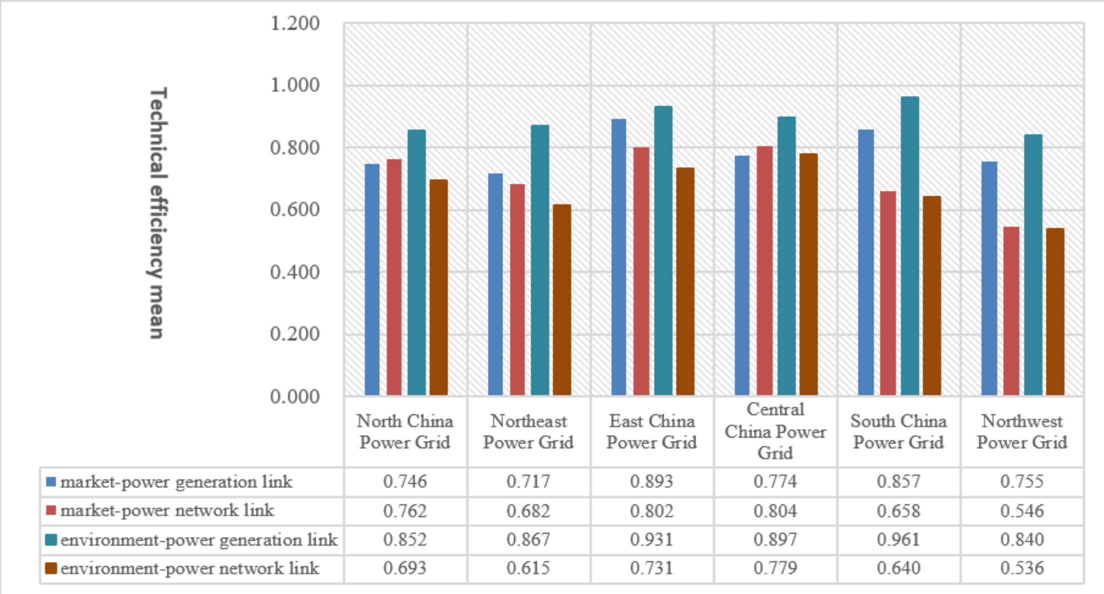

Figure 2. Annual mean trend diagram of technical efficiency of power industry in six major regions.

Table 3. Annual mean and ranking of technical efficiency by province/region from 1998 to 2017.

Provinces and cities	**The market technical efficiency**			**The environmental technical efficiency**		
	The entire power industry	**Power generation link**	**Power transmission and distribution network link**	**The entire power industry**	**Power generation link**	**Power transmission and distribution network link**
Beijing	0.731	0.462	1.000	0.906	0.811	1.000
Tianjin	0.798	0.675	0.921	0.733	0.770	0.695
Hebei	0.707	0.781	0.632	0.715	0.821	0.609
Shanxi	0.662	0.877	0.446	0.681	0.916	0.446
Shandong	0.873	0.935	0.810	0.828	0.941	0.716
North China Power Grid	0.754**(4)**	0.746	0.762	0.772**(4)**	0.852	0.693
Inner Mongolia	0.720	0.919	0.520	0.727	0.933	0.520
Liaoning	0.714	0.736	0.692	0.725	0.854	0.596
Jilin	0.659	0.608	0.710	0.764	0.874	0.655
Heilongjiang	0.705	0.605	0.806	0.749	0.808	0.690
Northeast Power Grid	0.699**(5)**	0.717	0.682	0.741**(5)**	0.867	0.615
Shanghai	0.917	0.841	0.994	0.954	0.942	0.965
Jiangsu	0.894	0.993	0.796	0.835	0.993	0.677
Zhejiang	0.868	0.956	0.780	0.832	0.977	0.688
Anhui	0.772	0.781	0.764	0.782	0.815	0.748
Fujian	0.786	0.896	0.677	0.752	0.926	0.578
East China Power Grid	0.848**(1)**	0.893	0.802	0.831**(2)**	0.931	0.731
Jiangxi	0.728	0.597	0.859	0.823	0.805	0.840
Henan	0.831	0.861	0.802	0.841	0.909	0.774
Hubei	0.812	0.979	0.645	0.781	0.988	0.575

Hunan	0.788	0.722	0.854	0.871	0.907	0.835
Chongqing	0.727	0.509	0.946	0.854	0.777	0.931
Sichuan	0.848	0.979	0.718	0.858	0.998	0.718
Central China Power Grid	0.789**(2)**	0.774	0.804	0.838**(1)**	0.897	0.779
Guangdong	0.921	0.997	0.844	0.875	0.997	0.752
Guangxi	0.747	0.790	0.704	0.822	0.940	0.704
Hainan	0.672	0.669	0.675	0.834	0.993	0.675
Guizhou	0.719	0.883	0.555	0.735	0.916	0.555
Yunnan	0.731	0.949	0.514	0.736	0.958	0.514
South China Power Grid	0.758**(3)**	0.857	0.658	0.800**(3)**	0.961	0.640
Shanxi	0.624	0.589	0.660	0.673	0.718	0.628
Gansu	0.613	0.739	0.488	0.669	0.851	0.488
Qinghai	0.721	0.987	0.456	0.728	1.000	0.456
Ningxia	0.701	0.812	0.591	0.710	0.829	0.591
Xinjiang	0.594	0.651	0.537	0.659	0.802	0.516
Northwest Power Grid	0.651**(6)**	0.755	0.546	0.688**(6)**	0.840	0.536
mean	0.753	0.793	0.713	0.782	0.892	0.671

Note: The values in parentheses are the ranking order.

4.2. Evolution and Decomposition of Total Factor Productivity in Power Industry

The above exploration on the MTE and ETE in power industry is to examine the relative efficiency level of each decision-making unit from a static perspective. To understand the dynamic evolutionary trend of the power efficiency, we use the DEA-Malmquist index model to calculate the TFPch of the power industry, and try to understand the dynamic evolutions from the power generation link, the power network link and the comprehensive perspective. It further decomposes TFPch into TEch, PEch and SEch to reflect the factors that promote or inhibit the TFPch in the power industry. This part will study the space-time variation trend of TFP in the power industry from three perspectives of the nation, province, and region, as demonstrated in Figure 3, Figure 4, and Table 4, respectively.

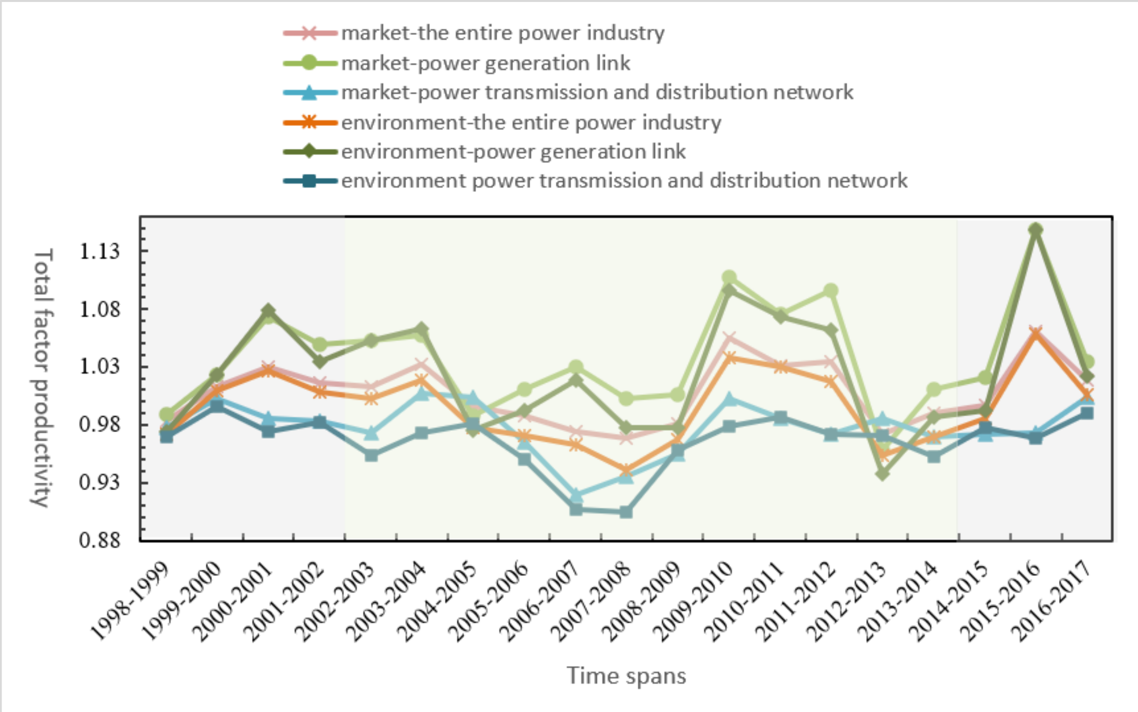

Figure 3. Trend diagram of China's total factor productivity from 1998 to 2017.

4.2.1. Annual Evolution of Total Factor Productivity in Chinese power industry

From 1998 to 2017, the TFP of the entire power industry, power generation link and power network link fluctuated on the whole, as shown in Figure 3. At the aspects of market and environment, the average values of the three are 1.007, 1.037, 0.977 and 0.9945, 1.024, 0.965, respectively. Among them, the TFP of the power network link is the lowest, inhibiting the development of the entire power industry. And the TFP at the market level is higher than the environmental level, which indirectly reflects the unsustainable development status of "emphasizing market over environment" in Chinese power industry. Regardless of the market or the environmental levels, the TFP of power generation link is superior to power network link, which still reflects the fact of "emphasizing power generation over transmission and distribution" in China's power construction. Taking the two power system reforms in 2002 and 2015 as the time nodes, the TFP first increased and then decreased before 2002. From 2002 to 2015, the change trend of TFP showed an inverted "S"-shape. After 2015, it first increased and then decreased. The average TFP of the entire industry in three stages is 1.0104, 1.0023, and 1.0400, respectively, and the third stage has the highest average annual growth rate of 4%. The statistical evidence demonstrates that during the current research period, the power system reform in 2015 achieved better results compared with that in 2002, and the power system reform in 2002 failed to achieved the improvement of enterprise management and productivity level. From 2002 to 2015, the fluctuations in TFP were more obvious. Under the macro background of global economic crisis and the economy downward pressure, the continuous shrinking of the domestic market has made an obstacle for the efficiency improvement in power generation link and power network link to a certain extent. Although the "Circular NO. 5" is committed to promote the power market reform by improving efficiency and optimizing resource allocation, which is insufficient to establish an efficient and organized power market system.

4.2.2. Evolution of Total Factor Productivity by Province

The annual average values of the TFP in Chinese 30 provinces in the entire power industry, the power generation link and the power network link are 1.00075, 1.0305, and 0.971, respectively, as shown in Figure 4. The power network showed a negative growth rate of 2.9%, which lowered the productivity in the entire power industry. The promotion of the production and the management of related enterprises in the transmission and distribution link should be paid more attention. For the comprehensive perspective, the MTE and ETE are both higher than the average value of the entire power industry in 11 provinces including Tianjin, Shanxi, Inner Mongolia, Shanghai, Jiangsu, Zhejiang, Hubei, Guangdong, Sichuan, Yunnan, and Ningxia. There are only 36.7% coverage rate, which indicates that few provinces have a positive development room of the production growth rate. Benefited from highly-developed economies or optimized allocation of existing resources, Shanghai, Jiangsu, Zhejiang, Guangdong, Sichuan, Yunnan, etc. have higher growth rates, which can play an exemplary role. For the power generation and transmission and distribution network, about 90% of provinces have higher TFP in the power generation link than the supply link, and the TFP at the market level is over the environmental level, which is in line with above results on TE. Through comparison, it is found that the provinces with high static power efficiency tend to have slower or negative growth in dynamic efficiency, such as Beijing, Shandong, etc. On the contrary, the provinces with middle or low technical efficiency in static analysis have better performance in dynamic analysis, such as Shanxi, Sichuan, Guizhou, Yunnan, etc., indicating that the regional "catch-up effect" appears at efficiency level.

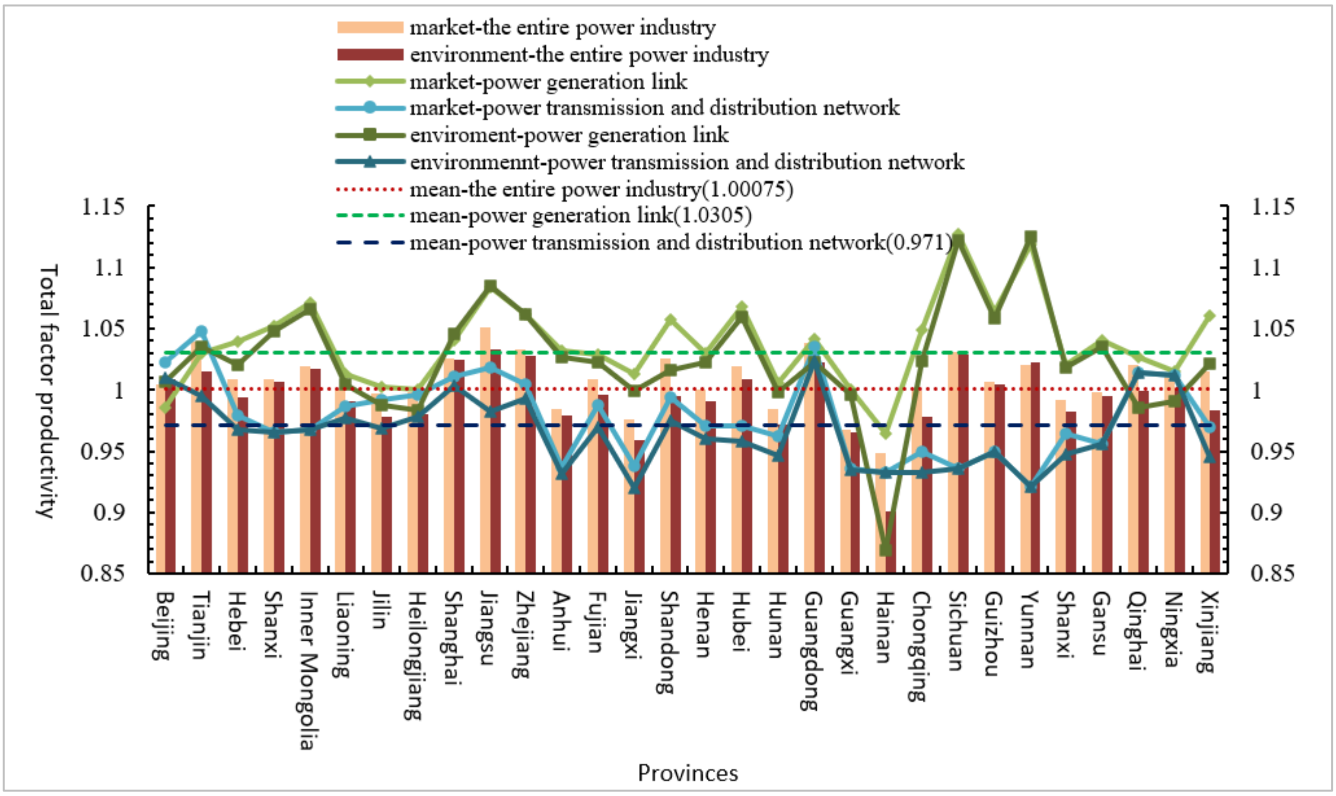

Figure 4. Diagram of annual total factor productivity evolutions of each province in China.

4.2.3. Evolution of Total Factor Productivity by Region

Malmquist results can be explained into integrated Effch and TEch. Therefore, we can try to understand which part ultimately makes for the decline or rise of the efficiency, thus putting forward some practical advice. And the exact results are demonstrated in Table 4.

From the market perspective, the TFP of the entire industry in six major power networks is ranked from high to low, i.e., East China Power Grid, North China Power Grid, Northwest Power Grid, Northeast Power Grid, Central China Power Grid, and South China Power Grid. The fastest-growing power grid is East China Power Grid, which is 2.06%, while South China Power Grid showed a negative growth. All power networks have positive production growth rates in the power generation link. The East China Power Grid has the highest growth rate of 4.94%, and the Northeast Power Grid has the lowest growth rate, which is only 2.15%. Except the North China Power Grid, all power networks have negative production growth rates in the supply link, which inhibits the growth of TFP in the entire power industry. The Central China Power Grid has the highest negative growth rate of 4.55%. From the environmental perspective, the TFP of the entire industry in six major power networks is ranked from high to low in East China Power Grid, North China Power Grid, Northwest Power Grid, Northeast Power Grid, Central China Power Grid, and South China Power Grid. East China Power Grid has the fastest growth rate of 1.22%, but it is lower than the market level (2.06%), manifesting that the supply link is weaker than the power generation link. All the six major power networks in the power generation link have positive growth rates, while all of them have negative growth rates in power supply link. It suggests that power enterprises often ignore the relevant users when conducting power transmission and distribution business, such as the number of served users is insufficient or redundant. On the whole, there is a phenomenon of a “catching-up” effect in the overall power efficiency among various regions. The East China Power Grid has the fastest growth rate, which can play a leading role. TEch accounts for the TFP improvement in power industry, and Effch is the main constraints. The growth rate of overall market efficiency is faster than the overall environmental efficiency, and there is a phenomenon of "emphasizing market over environment".

Table 4. Decomposition results of total factor productivity in six major power network regions.

Regions			Nort China Power Grid	Northeast Power Grid	East China Power Grid	Central China Power Grid	South China Power Grid	Northwest Power Grid
Market	The entire power industry	TFP	1.0173	1.0036	1.0206	1.0017	0.9963	1.0080
		Effch	0.9862	0.9896	0.9876	0.9833	0.9789	0.9911
		TEch	1.0316	1.0143	1.0331	1.0187	1.0174	1.0168
	Power generation link	TFP	1.0328	1.0215	1.0494	1.0488	1.0378	1.0328
		Effch	0.9814	0.9890	0.9920	0.9850	0.986	0.996
		TEch	1.0526	1.0328	1.0574	1.0648	1.0520	1.0370
	Power transmission and distribution network link	TFP	1.0018	0.9858	0.9918	0.9545	0.9548	0.9832
		Effch	0.9910	0.9903	0.9832	0.9815	0.9718	0.9862
		TEch	1.0106	0.9958	1.0088	0.9725	0.9828	0.9966
Environment	The entire power industry	TFP	1.0038	0.9916	1.0122	0.9898	0.9833	0.9924
		Effch	0.9907	0.9990	0.9925	0.9885	0.9835	0.9913
		TEch	1.0130	0.9926	1.0197	1.0008	0.9999	1.0009
	Power generation link	TFP	1.0252	1.0103	1.0484	1.0375	1.0142	1.0100
		Effch	0.9944	1.0033	0.9968	0.9985	0.9926	0.9990
		TEch	1.0310	1.0073	1.0518	1.0388	1.0222	1.0112
	Power transmission and distribution network link	TFP	0.9824	0.9730	0.976	0.9422	0.9524	0.9748
		Effch	0.9870	0.9948	0.9882	0.9785	0.9744	0.9836
		TEch	0.9950	0.9780	0.9876	0.9628	0.9776	0.9906

Note: TEch is the product of PEch and SEch.

Based on the empirical results, we analyzed the overall TE and TFP, and explored them further by provinces and regions. Through analysis, the efficiency level of the power industry in different dimensions can be demonstrated more clearly, which is also the focused research questions. To make the empirical results more convincing, we changed the specific inputs and outputs to run multiple tests. The empirical results show that it passes the robustness test as expected and the research results are credible.

5. Discussion and Applications

High energy consumption and high emissions can be stated as the typical characteristic of the power industry. Existing studies have paid much attention on the sustainable power industry. By reviewing the relevant literatures, we can easily find that there is a shift from the early studies focused on the best practice sharing from developed countries to the exploration of efficiency promotion and green production measures in developing countries. Besides, the research methods have changed from the single qualitative method to the multivariate quantitative method, just as shown in Table 5. The main optimization paths from them are the renewable energy sources, advanced technologies application and green policies support. However, some scholars ignored the existing efficiency levels, which caused the recommendations are too ambiguous to implement. Appropriate measurement of TE and TFP can provide reference for policy making and process modification. Therefore, we provide the policy recommendations based on the detailed efficiency evaluation. We take two links of the power industry into account and conduct a dynamic and static analysis of the TE and TFP from the power generation link, the power network link and the comprehensive power industry. The results are rich and can be divided into two aspects. From the static perspective, the power efficiency shows a downward trajectory of "East, Mid, West". The efficiency of the power generation link performs well than supply link. From the dynamic perspective, the TFP fluctuates significantly with the two power system reforms in 2002 and 2015 as the time nodes. The promotion of TFP rest with Tech mainly, and the "catch-up effect" appears among regions.

Table 5. Comparison of related researches.

Study	Research Object	Methodology	Main Conclusions
Hammons (2006) [5]	Russia, Greece, Italy	critical analysis	There are still much fossil fuel dependence in power generation technologies. The promotion and application of the clean technologies should be emphasized.
Cansino (2010) [11]	EU-27 countries	case studies	Tax incentives (tax exemptions, lower tax rates) can promote green electricity. The legislative changes or high administrative barriers are the difficulties.
Zhou (2015) [39]	China	comparative analysis	Present five-aspect suggestions to further promote energy conservation and emissions reduction International collaboration and cooperation can help to achieve sustainable power industry.
Sartori (2017) [7]	Brazilian	DEA with DDF	It perceives the strength of economic indicators specially. The greenhouse gas emissions were highlighted to sustainability performance. It founds the problem of the inefficiency companies.
Li (2020) [40]	China	bottom-up analysis	The total CO2 emissions keeps increasing through 2020, but the rate of growth decelerated. The penetration of renewable generation and the large-scale application of CCS can reduce carbon emissions.
Mohsin (2021) [8]	48 countries	DEA and DID	The implementation of electricity reforms changed the original situations obviously. The electricity reforms gave a 13.2% promotion in energy efficiency.

Due to the multi-perspective and multi-aspect exploration, the results drawn from the research are of great academic and practical significance. At the academic level, the paper can enrich existing researches on this field to some extent and provide reference for other scholars. The next step is to guide practice with theory. The results and findings can give empirical support for the sustainable power industry. Above all, the paper provides an access to know about the evaluation laws and practical predicament of the TE in power industry, so the governments can "prescribe the right medicine" in industry management. Furthermore, all links of power industry are involved, the relevant departments can have a clear understanding of the efficiency level and determine the goals for development in next phase. Only through the detailed efficiency evaluation and feasible efficiency promotion measures can the Chinese power industry close to the sustainable development targets.

The outbreak of COVID-19 has made the efficiency problems of Chinese power industry more obvious. Narrowing the gap among different regions and contributing to the sustainable power industry under the guidance of theory is positive for dealing with major crises such as COVID-19.

6. Conclusions and Policy Recommendations

6.1. Conclusions

The TE and TFP of Chinese power industry were measured and evaluated from dynamic and static perspectives by using the DEA model and the 1998-2017 panel data of Chinese 30 provinces and cities. The TE and TFP of the entire power industry, power generation, transmission and distribution network links in different provinces and cities are analyzed from both market and environmental levels, as well as their differences. On the one hand, the paper analyzed the efficiency evolution trend in power industry during a long period, the fluctuation has attested to the effectiveness of the power market reform in 2002 and 2015 and the policies of "encourage large projects and discourage small energy-inefficient power plants", "desulfurization and denitrification". The conclusions can provide important reference for the further amelioration of the power system reform and policy formulation. The specific findings and conclusions are as follows.

6.1.1. Technical Efficiency of the Power Industry from a Static Perspective

(1) The comprehensive level of TE in Chinese power industry is not reaching the expected status and there is a gap between different provinces and cities. The high-efficiency provinces are mostly distributed in the eastern or coastal areas with developed economies and resource-oriented regions. (2) When added the environmental factors on the power system, the MTE and ETE in power industry trades off with 2003 as the demarcation node. (3) The Chinese power efficiency in power generation link is better than the supply link,

which presents the development pattern of "emphasizing power generation over transmission and distribution" in the construction of Chinese power industry. Monopolistic operating system and improper management of damaged lines can be related to the low TE in power network link. The efficiency of supply link in regions with centralized power output is generally low, which exemplifies the existence of regional "resource curse". (4) The comprehensive TE of the regional power industry shows a downward trend of "East, Mid, West" and be listed from higher to lower as East China (0.839), Central China (0.813), South China (0.779), North China (0.763), Northeast (0.705), and Northwest (0.659).

6.1.2. Total Factor Productivity of the Power Industry from a Dynamic Perspective

(1) Taking the two power system reforms in 2002 and 2015 as the time nodes, the TFP first increases and then decreases before 2002. From 2002 to 2015, it showed an inverted "S"-shape, and, it showed an escalating trend and then a downward trajectory after 2015, suggesting that the new round of power system reform in 2015 performs better than in 2002. (2) No matter from the market and environment level, the overall TFP of the six major power networks is ranked from high to low in East China Power Grid (1.0164), North China Power Grid (1.0105), Northwest Power Grid (1.0002), Northeast Power Grid (0.9976), Central China Power Grid (0.9957), and South China Power Grid (0.9898). However, the “catching-up” phenomenon among various regions appears in the power generation and power network links. The East China Power Grid has the fastest growth rate（1.64%）, which can play a positive demonstration and driving role. (3) Through comparison, it is found that the provinces with the highest static power efficiency tend to have slower or negative growth in dynamic efficiency, while the provinces with static technical efficiency at a normal or lower level have better performance in the dynamic analysis, indicating regional “catch-up effect” appears in the efficiency level. (4) TEch is a motivator for the improvement of TFP in the power industry, while Effch is the constrains. The MTE growth rate is faster than the ETE generally, and there is a phenomenon of "emphasizing market over environment".

6.2. Policy Recommendations

For the sustainable power industry, this paper puts forward several corresponding policy recommendations from the power generation link, the power supply link and the comprehensive perspective.

For Chinese power industry, firstly, strengthen the inter-regional power technical exchange and cooperation to narrow the gap between regions. The longstanding regional disparity can not be improved effectively by benign "catch-up effect" in power efficiency. It is necessary for high-efficiency provinces to take maximum advantage to their leading part through technical cooperation to promote the development of low-efficiency provinces, which can further improve the overall TE of Chinese power industry. Secondly, keep deepening the power system reform and boost the energy efficiency. After the introduction of the reform policies in 2002, "separation of government and enterprise, separation of power plant and network, and separation of main and auxiliary" was the new direction in the foreseeable future. Although power generation companies have achieved market competition in a certain degree, the monopoly situation has not changed fundamentally. The power system reform in 2015 contains the construction of the electricity market, the reform of transmission and distribution price and other content. Although the effect of power system reform in 2015 with an even better fashion, the lagging and imperfect policies make it more difficult to achieve the desired results. In the future, we should keep deepening the reform further, try to separate the transmission and distribution and determine reasonable electricity prices, etc. Thirdly, accelerate the progress of power marketization nationwide and construct the reasonable resource allocation system. Traditionally, the power in various regions is self-sufficient, but there is an imbalance between power demand and supply. The absonant resource allocation caused the relatively low efficiency among regions. In a later work, an effective electricity trading chain should be formed according to the power demand of various regions and their power generation capabilities. The reasonable resource allocation system based on market mechanism is helpful to promote the power efficiency.

For the power generation link, firstly, adjust the energy mix of the power generation link and increase the proportion of new energy. The long-term coal-based power structure system has made the ETE generally low. It suggests that the high partial new energy power generation usually brings high TE, but the average value of new energy generation is only 22.37% from 1998 to 2017. The proportion of new energy generation of Qinghai, Hubei, Sichuan, Yunnan, Guangxi and other places is well above average levels, and their ETE of the power generation link is also at a higher level. It can be foreseen that the better performance in new energy generation can help to make the economy growth and environment protection develop in a more balanced way. Secondly, strengthen environmental regulations and construct a logical pollution compensation mechanism. For the insufficient utilization of existing resources and insufficient environmental governance, some provinces rich in coal but have lower ETE. The realistic situation confirms the existence of the regional "resource curse" and "pollution paradise". On the one hand, the planning and management of coal resources should be strengthened to reasonable mining; on the other hand, a complete pollution compensation mechanism should be improved to reduce the environmental governance costs of regional power generation enterprises.

For the transmission and distribution network link, firstly, increase the application scale of UHV grid transmission technology and strengthen the construction of large-scale, long-distance and high-efficiency transmission line channels. The standardized and unified power networks can reduce the electricity loss in supply link. The optimized power network resources allocation and the reasonable economic benefits distribution are the higher goals. Energy bases and load centers in China are farther apart in each place, which makes the difficulty in electricity transmission and distribution. Moreover, there is an inextricable contradiction between supply and demand in China, more than four out of five coal power base, hydropower base, wind power base, etc. are mainly located in northwest, and southwest, but less than 30% demand for electricity at the corresponding places. Therefore, it is particularly significant to enhance the planning and optimization of the whole power networks. Restricted by technology, capital and other factors, the implementation of Chinese power networks programme is unpromising. The realistic problems are mainly manifest the lagging construction of UHV grid transmission channels from energy bases to load centers and the insufficient trans-regional power transmission capacity. Secondly, enact a scientific power price mechanism and resource price compensation mechanism. The state-promoted UHV power grid project can overcome the shortcomings of traditional power production and avoid the "localization" phenomenon of electricity generation and consumption. In addition, the centralized electricity generation and centralized electricity transmission can effectively improve the optimal configuration of the power network resources. However, the implementation of the process requires a matched electricity price mechanism and resource price compensation mechanism, which can increase the enthusiasm for power generation.

6.3. Limitations and Further Study

We have to say there are some limitations to the paper. One the one hand, the latest data is still lacked. Because we do not have access to the latest data, there is a certain time lag in this paper. On the other hand, the study put forward sustainable strategies based on efficiency evaluation, but the feasibility hasn't been verified with the specific data. In addition, effective prediction of future trends can also guide practice to some extent, we will deal with these issues in the future study.

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