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An Operation Benefit Analysis and Decision Model of Thermal Power Enterprises in China against the Background of Large-Scale New Energy Consumption

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Abstract: With the continuous increase in new energy installed capacity, the slowdown in the growth of social power consumption, the pressure created by high coal prices, and the reduction in on-grid electricity tariffs, the challenges facing the survival and development of thermal power generation enterprises are becoming more severe. Hence, based on the cost–benefit analysis method, this paper proposes a diversified operating benefit analysis and decision model for thermal power generation enterprises that includes four profit models: power sales, peak load regulation (without oil), peak load regulation (with oil), and generation right trading. The opportunity cost of peak load regulation and generation rights trading was considered, and six scenarios were designed. An empirical analysis was conducted by selecting a thermal power enterprise in Ningxia, Northwest China, as an example, using scenario and sensitivity analyses. The results show that under the diversified business model, thermal power generation enterprises can more effectively avoid the risks when the external environment changes and significantly improve its economic benefits. The consumption of new energy can be promoted, and positive social effects will be achieved. Therefore, the findings will help the thermal power generation enterprises to face these challenges.

Keywords: new energy consumption; thermal power generation enterprises; deep peak load regulation; generation rights trading; diversified business model

1. Introduction

The global energy shortage has become an increasingly serious problem, and there is continual pressure to reduce carbon emissions [1]. In order to improve energy efficiency, countries around the world are actively taking countermeasures. With the deepening of energy supply-side structural reform in China, the survival and development of traditional thermal power generation enterprises will face more severe challenges. In terms of the macro-economy, China's is still under considerable downstream pressure, consumption growth is slowing, and the increase in electricity consumption of the entire society has been limited. The average increase in electricity consumption in China was only 4.9% from 2014 to 2018, as shown in Figure 1.

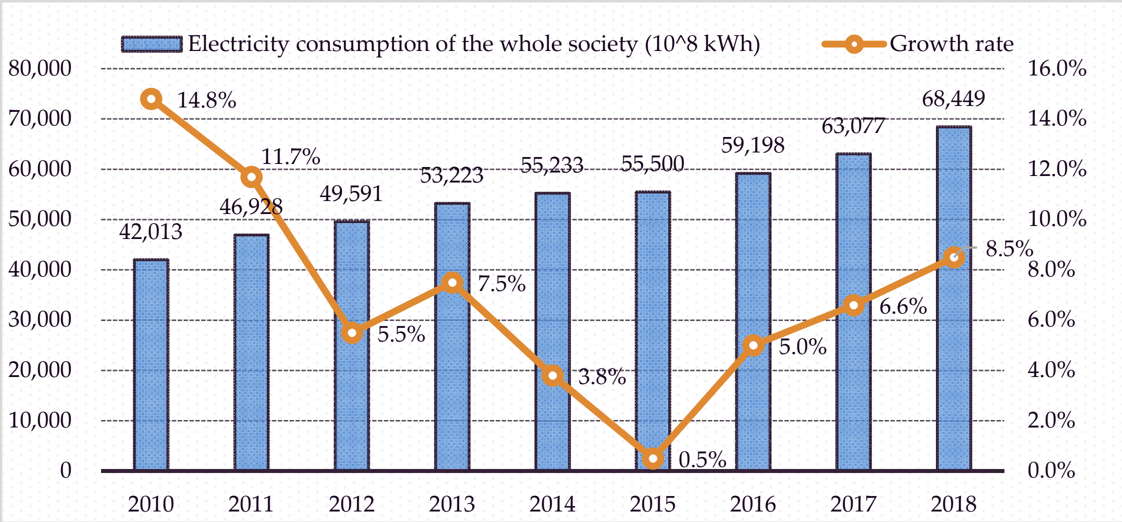


Figure 1. China's social power consumption growth from 2010 to 2018 (Data source: China electric power yearbook).

For power supply construction, by the end of 2018 the entire installed generation capacity in China was nearly 1.9 billion KW. Although the proportion and growth rate of installed capacity of thermal power generation has recently declined year by year, the installed capacity still accounts for 60.2%, as shown in Figure 2 [2].

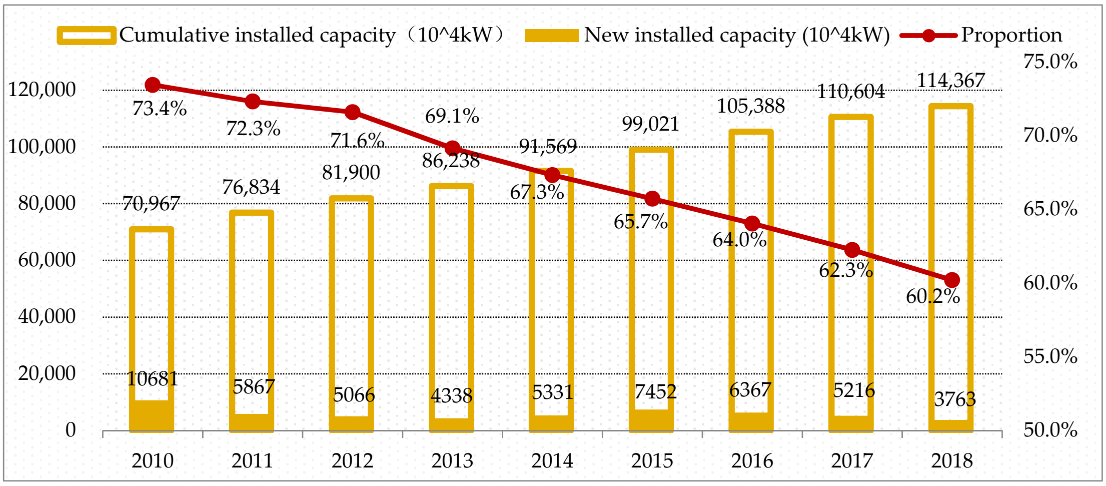


Figure 2. New installed capacity, cumulative installed capacity, and proportion of thermal power generation in China, 2010–2018 (Data source: China electric power yearbook).

The annual average thermal power equipment use is only 4361 h. This is far below 5500 h, which is the demarcation point for thermal power enterprises. The installed wind power and photovoltaic capacity is nearly 358 MW, with an average growth rate of 31.3% over five years, and the installed capacity ratio reached 18.9%, as shown in Figure 3 [3].

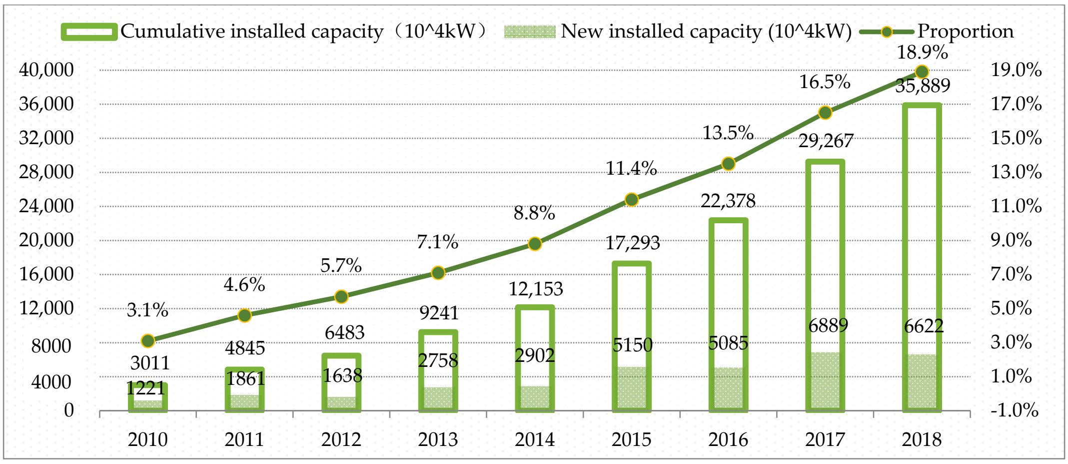


Figure 3. New installed capacity, cumulative installed capacity, and proportion of wind and photovoltaic power in China, 2010–2018 (Data source: China New Energy Power Generation Analysis Report).

The growth rate of the installed capacity in China has been higher than that of the electricity consumption of the whole society in recent years, and China still faces the problem of excess power supply. With continuous advances in new energy technology and the rapid decline in installed cost, the parity era of China's new energy generation is coming. With the implementation of a renewable power consumption responsibility weight system, the market share of thermal power generation enterprises will be further negatively affected. Therefore, given the background of various restrictive pressures (such as high coal prices, environmental protection requirements, low thermal power generation hours, power market reforms and other constraints), avoiding policy dependence, adjusting profit models to face market competition, and improving their viability as soon as possible have become worthy issues for thermal power enterprises to explore.

Some scholars have acknowledged the dilemma facing the development of Chinese thermal power enterprises, and have comprehensively reviewed and analyzed the development of the thermal power industry in China. They have focused on the cost and benefits of thermal power [4], as well as analyzing and forecasting the low-carbon development of the Chinese thermal power industry to achieve emission reductions and the sustainable development of China's thermal power industry [5]. From the literature, the research on the thermal power enterprises benefits has been mainly conducted from two aspects: social benefits and economic benefits.

Thermal power enterprises provide social benefits to indicate social responsibility and promote energy conservation and emission reduction. The studies on social benefits mainly include the reduction of CO_2 emissions, energy savings, and environmental protection. In terms of improving social benefits, the ongoing power transformation within the framework of global sustainable transformation has been studied in-depth based on the low-carbon development goals, reflecting the influence of technological progress and incentive policies on power generation enterprises from an economic perspective [6]. The carbon dioxide trading mechanism affects the cost structure and price model of thermal power enterprises, further affecting the production decisions of the enterprises. To mitigate the environmental problems caused by thermal power enterprises, the performance of power generation enterprises has been evaluated according to the environmental cost and other factors that can guide decision-makers to formulate appropriate future production programs to improve their business performance [7,8].

Thermal power enterprises aim to improve their economic benefits to increase their viability in the current and future market environment. The existing studies on economic benefits were mainly conducted from the perspectives of reducing production costs, participating in peak load regulation, trading power generation rights, etc.

From the aspect of reducing production costs, some scholars studied the technological transformation of thermal power enterprises. The urgent task for thermal power enterprises is developing low-carbon and efficient units, as they are going to become the main forces driving the sustainable development of coal-fired power generation industry [9]. In response to the problems with the operation of coal-fired power plants, methods to improve and upgrade coal-fired power plants have been proposed [10–12]. The economic decision to transition toward flexible coal power transformation in China is determined by the compensation standards and the time and the depth of peak load regulation. With a certain depth of peak regulation at suitable times, the power plants that have reasonable compensation standards are willing to undergo coal power flexibility transformations [13]. A multi-generation system based on the integrated three-effects refrigeration system was proposed to substantially improve thermal power efficiency [14]. Other scholars researched the fuel cost of thermal power enterprises, which is the central link of production control and economic calculation of the enterprises [15]. A hybrid fuzzy multi-attribute decision-making approach (fuzzy entropy-TOPSIS) was proposed to select the best green supplier [16]. Thermal power enterprises can ensure a long-term stable source of coal by selecting suitable coal suppliers [17]. To optimize transportation and storage in regional coal distribution planning, a feasible model was introduced that minimizes regional transportation and storage costs [18]. Considering the coal safety inventory demand of coal-fired power enterprises, fluctuations in coal demand, and the uncertainty of coal prices and coal inventory replenishment, with maximizing corporate profits as an optimization goal, coal-fired coal inventory was optimized [19].

To participate in deep peak load regulation, the flexibility of thermal power enterprises is valuable for power systems that have a high share of renewable energy [20], so participation in peak load regulation is also a business path for thermal power enterprises [21]. The peak load regulation cost of coal-fired thermal power units was comprehensively analyzed considering their coal consumption costs, fuel consumption costs, loss costs, and environmental costs. A mathematical model of the peak load regulation cost of coal-fired thermal power units was reported [22]. On this foundation, a new multi-target commitment method was proposed, and a thermoelectric cost model was developed to accurately determine different peak regulation schemes [23]. The market rules of Northeast China's graded deep peak shaving were studied. Considering the cost and compensation under different loads and the impact of coal price on peak shaving income, for thermal power units in the Northeast of China, Zhang et al. [24] constructed an optimal economic strategy for grading and deep peak load regulation. Regarding the peak shaving compensation of cogeneration units, the bidding strategies and payment of corresponding strategies for various thermal power plants were discussed in different compensation scenarios [25]. By optimizing the peak shaving compensation price, and the distribution strategy of peak load shaving income in the thermal system, cogeneration units were encouraged to fully participate in peak shaving to improve power system peak flexibility [26].

Power generation rights trading between thermal power enterprises and wind power plants is an efficient method to meet the demands of wind power development, which can considerably improve the consumption of new energy and improve thermal power units for the greater good [27]. Power generation rights trading among new energy and self-generating stations is effective [28]. The profits of thermal power enterprises in power generation rights trading can be obtained through subsidy coefficients and sharing coefficients [29]. Based on different optimization goals, many scholars have studied the process of power generation rights trading in which thermal power enterprises participate. As the risk of power generation rights trading is having an increasingly significant influence on the profits of power plants, the impact of power generation rights trading on profits has been discussed by setting different risk rates for the sellers and buyers in transactions [30]. From the perspective of coal consumption and the system network loss of generating units, a model that maximizes energy savings after trading was proposed [31]. A multi-objective optimization model that can realize the comprehensive optimization of load margins and generator output costs considering carbon emission constraints was proposed to guide thermal power enterprises when they participate in power generation rights trading [32].

Other researchers comprehensively evaluated the benefits of thermal power enterprises. Starting from the characteristics of the costs–benefits of thermal power enterprises, the benefits were evaluated based on an index system established from three aspects: economic benefits, environmental benefits, and social benefits [33]. Considering flexibility, economy, reliability and technical standards, Li and Chen et al. [34] proposed a hybrid multi-criteria decision-making model to evaluate the sustainable development level of China's coal-fired power plants.

The studies mentioned above were mainly conducted from two aspects: By furthering energy conservation and emission reduction to improve social benefits, and by focusing on fulfilling the social responsibility of thermal power generation enterprises. However, studies on improving the viability of thermal power enterprises are lacking, and aimed at improving the efficiency of thermal power enterprises from individual aspects (such as saving production costs, participating in peak load regulation, and trading power generation rights), without comprehensively considering these business models. Against the large-scale clean energy consumption background, studies about the diversified business model of thermal power enterprises are required.

Given this background, we analyzed the costs and benefits of thermal power enterprises during operation based on the cost–benefit analysis method from the perspective of thermal power enterprises, and analyzed the diversified operation benefits and decision-making model of thermal power enterprises. Combined with the actual operation of the current electricity market, six possible business scenarios were designed, including four profit scenarios of electricity sales, power generation rights trading, peak load regulation (without oil), and peak load regulation (oil). The opportunity cost of peak load regulation and power generation rights trading loss was also considered. Finally, using a thermal power enterprise in Ningxia, Northwest China, as an example of an empirical analysis. Through scenario analysis and sensitivity analysis, we verified that thermal power enterprises could more effectively avoid the risk of external environment changes and significantly improve the economic benefits of the enterprise in a diversified business scenario. Power generation rights trading and in-depth peak load regulation can also effectively promote the consumption of renewable energy.

The rest of this paper is arranged as follows: Section 2 describes analysis and setting of the six business scenarios, Section 3 describes the analysis model, Section 4 outlines the empirical case study, Section 5 provides the result discussion and scenario analysis, and Section 6 is the conclusion and proposes future research.

2. Scenario Setting

For thermal power generation enterprise, power sales revenue is the most basic profit model. With the deepening of the reform of the power system and the increasing pressure for environmental emissions reduction, the consumption of clean energy must be further increased, alternative production of clean energy power generating units must be encouraged, and the goals of social energy conservation, emissions reduction, and efficient resources use must be achieved. Power generation rights trading can generate incremental profits for both parties simultaneously. Therefore, thermal power generation enterprises should actively engage in power generation rights trading with clean energy power generation enterprises, which can further expand the source of revenue.

The installed capacity of renewable energy, such as wind energy and solar energy, has grown rapidly in recent years. Due to the impact of intermittent and anti-peak load regulation characteristics of renewable energy power generation and climate change, the peak valley difference of the power grid continues to increase, resulting in increasing pressure for peak load regulation of the power grid. According to the existing auxiliary service market operation rules, thermal power generation enterprises can actively participate in peak load regulation auxiliary services, which can reduce the apportionment cost of the auxiliary service market and produce certain economic compensation to increase operating income.

Therefore, in the context of this external environment, to better illustrate the applicability of the methods and the differences in the benefits of thermal power generation enterprises in different business scenarios, we examined the possible combination of multiple business scenarios based on four revenue modes, i.e., power sales revenue, power generation rights trading revenue, peak load regulation service revenue (without oil), and load regulation service revenue (with oil); six specific business scenarios are proposed for comparative analysis. The specific scenario combinations are listed in Table 1.

Table 1. Scenarios for the business model of thermal power generation enterprises.

Scenario	Business Model
A	power sales
B	power sales + generation rights trading
C	power sales + peak load regulation (without oil)
D	power sales + generation rights trading + peak load regulation (without oil)
E	power sales + peak load regulation (without oil) + peak load regulation (with oil)
F	power sales + generation rights trading + peak load regulation (without oil) + peak load regulation (with oil)

3. Model Description

The profit model literature for thermal power generation enterprises in China is mainly concentrated on power trading, and the profit model of thermal power generation enterprises is relatively simple. Most business in power sales is settled through the power grid—and the other part involves signing contracts with large power users and contract settlement. Therefore, thermal power generation enterprises must actively expand their business paths and continuously reduce their production costs to strengthen capacities and achieve sustainable development.

3.1. Income Analysis of Diversified Operation

3.1.1. Income of Power Sales

The thermal power generation enterprises mainly consider power as their product, and sell power to energy customers to earn effective income, which can be expressed as the product of on-grid power and on-grid electricity price:

$$R_{og}(P) = Q_{on\text{-}grid}(P) \times \omega_{on\text{-}grid} \tag{1}$$

where $R_{og}(P)$ is the income of power sales; $Q_{on\text{-}grid}(P)$ is the on-grid electricity power quantity, which refers to the power input from the thermal power generation enterprise to the power grid enterprises at the on-grid power metering point, that is, the power sold by the power plants to the power supply enterprises; and $\omega_{on\text{-}grid}$ is the unit on-grid electricity price, which represents the calculation price of electric power (purchased by power grid enterprises) when the power generation enterprises connect to the main grid [35].

3.1.2. Income of Peak Load Regulation

The main participants in the peak load regulation auxiliary market are grid-connected power plants (including public thermal power plants, wind power plants, photovoltaic power plants, and hydropower stations with an installed capacity of 50 MW and above), electricity storage consumers, and interruptible load consumers (who have been admitted to enter the market). Peak load regulation service falls into two categories: basic (obligatory) peak load regulation, and paid peak load regulation. Paid peak load regulation is traded on the electricity auxiliary service market, including real-time deep peak load regulation, mediation standby transactions, interruptible load transactions, and electricity storage transactions. We mainly studied deep peak load regulation. The income generated by thermal power units participating in deep peak shaving can be expressed as the product of the trading electricity quantity and the clearing electricity price:

$$R_{plrs,i}(P) = \sum_{i=1}^{n} [Q_{plrs,i}(P) \times \omega_{plrs,i}] \quad (2)$$

where $R_{plrs,i}(P)$ is the income of deep peak load regulation, $Q_{plrs,i}(P)$ is the trading electricity quantity of the thermal power units taking part in deep peak load regulation at i level in a certain period, and $\omega_{plrs,i}$ is the clearing electricity price in the market corresponding to the i level in a certain period.

3.1.3. Income of Generation Rights Trading

Power generation rights trading refers to the transaction behavior of power generation enterprises transferring contracts power (basic electricity contracts and priority electricity contracts) to other power generation enterprises through the trading platform built in the electricity market with marketization methods such as bilateral negotiation, centralized bidding and listing. Due to the difference in generation costs between the buyers and the sellers, the transaction of generation rights can produce incremental profits for both parties simultaneously. At this point, the cost of new energy power generation is much lower than the cost of thermal power generation, and no carbon emissions are generated during new energy power generation. Therefore, given excessive coal prices, thermal power generation enterprises can transfer power generation rights to obtain corresponding benefits. When participating in the trading of power generation rights, the income of thermal power generation enterprises can be expressed as:

$$R_g = Q_g \times (\omega_s - \omega_e) \quad (3)$$

where R_g is the income of generation rights trading, Q_g is the trading electricity quantity of power generation rights transferred by thermal power generation enterprises to efficient units and environmentally friendly units, ω_s is the benchmark power price of the region, and ω_e is the clearing price in the power generation trading market [36].

3.2. Cost Analysis of Diversified Operation

3.2.1. Cost of Power Production

We focused on the benefit analysis of thermal power generation enterprises under the diversified business model. According to the variable cost analysis method, regardless of the business model, other costs change less with the output except for production costs. Therefore, the cost of power generation is usually represented by the energy consumption characteristic curve of thermal power generating units:

$$C_{og}(P) = \sum_{P=P_{min}}^{P_{max}} \left(F(P) \times T_{p,k}\right) \times \omega_{coal} + \sum_{P=P_{min}}^{P_{max}} \left(F(P) \times T_{p,k}\right) \times C_{other} \quad (4)$$

where

$$F(P) = aP^2 + bP + c \quad (5)$$

where $C_{og}(P)$ is the power generation cost and $F(P)$ is the energy consumption characteristic curve function of thermal power generating units. At present, the coal consumption characteristic curves of thermal power units are mainly obtained from the performance parameters or thermal test data provided by the manufacturer, and these curves remained unchanged for a long time. However, the actual operation of the units is affected by many factors, such as operation mode, coal quality, equipment status, operator's technical level, etc., which makes the curves quite different from actual operation. Therefore, some scholars used intelligent algorithms to refit the coal consumption characteristic curves in the actual operation and obtained the quadratic function curve, which may be closer to the original data point and can more accurately depict the coal consumption operation performance of each unit [37]. P is the actual output of the units when participating in peak load regulation; a, b and c are the consumption characteristic coefficients of thermal power generating units, their values are associated with the types and characteristics of the thermal power units [37]; ω_{coal} is the price of standard coal; $T_{p,k}$ is the corresponding operating time of thermal power generating units at different power P; and C_{other} are other unit costs except for the coal cost.

When thermal power enterprises participate in deep peak load regulation, as the load rate continues to decrease, the deep depressurization output adds excessive thermal stress to the units' rotor system. Excessive alternating thermal stress can cause low cycle fatigue life loss and creep loss, which can result in the severe deformation and fracture of the unit body and reduce unit life. Therefore, there will be additional unit loss costs, which are as follows:

$$C_{co}(P) = \beta S_{unit}/2N_t(P) \tag{6}$$

where $C_{co}(P)$ is the unit loss cost when the thermal power generating units are involved in deep peak load regulation; β is the actual operating loss coefficient of thermal power generating units; S_{unit} is the purchase cost of thermal power units; and N_t is the rotor cracking times of thermal power unit at time t, and its value is related to P, which is the power of thermal power generating units [38].

When the units participate in deep peak load regulation, they are not able to maintain stable operation because the combustion stability of the boiler and the safety of the hydrodynamic working conditions decrease rapidly. As a result, oil injection is required to guarantee the units' safe operation. The oil consumption cost is:

$$C_{oil}(P) = Q_{oil}(P) \times \omega_{oil} \tag{7}$$

where $C_{oil}(P)$ is the cost of using oil for the low load operation of thermal power units, $Q_{oil}(P)$ is the amount of oil needed for thermal power units with low load operation, and ω_{oil} is the oil price for the season [39].

3.2.2. Loss Cost of Less Power Generation When Units Participate in Deep Peak Load Regulation

$$C_{plrsog}(P) = \sum_{i=1}^{n} Q_{plrs,i}(P) \times \omega_{on\text{-}grid} - \sum_{P=P_{min}}^{P_b} \left(F(P) \times T_{p,i}\right) \times \omega_{coal} - Q_{plrs,i}(P) \times C_{other} \tag{8}$$

where $C_{plrsog}(P)$ is the loss of less power generation (due to the participation in peak load regulation), $Q_{plrs,i}(P)$ is the trading electricity quantity of the thermal power units participating in the deep peak service at i level in a certain period, $\omega_{on\text{-}grid}$ is the on-grid electricity tariff for thermal power, ω_{coal} is the price of standard coal, P_b is the benchmark load value of thermal power generation enterprises participating in deep peak load regulation, and $T_{p,i}$ is the time required for the units to produce electricity with $Q_{plrs,i}(P)$ production under different power P [40].

3.2.3. Apportioned Cost When the Units Do Not Participate in Peak Load Regulation

The compensation cost for paid peak load regulation is apportioned by thermal power enterprises, wind power plants and photovoltaic power plants, whose load rate is higher than or equal to the benchmark load rate of deep peak load regulation. Thermal power generation enterprises are divided into different grades based on the actual peak regulation rate to apportion the cost with the "ladder" quotation. Therefore, if the thermal power generation enterprises do not participate in deep peak load regulation, the cost can be expressed as follows:

$$C_{plrc} = \frac{Q_{re}}{Q_{re} + Q_{others}} \times W_{total} \tag{9}$$

where

$$Q_{re} = \sum_{j=1}^{n} (Q_{g,j} \times k_j) \tag{10}$$

where C_{plrc} is the apportioned cost when the units do not participate in peak load regulation, Q_{re} is the electricity quantity corrected by the power generation enterprise during peak load regulation period, Q_{others} is the corrected total electricity quantity of all wind farms and photovoltaic power plants in the region, W_{total} is the total amount of peak shaving compensation, $Q_{g,j}$ is the power generation quantity when the units' load rate ranges at j level, and k_j is the correction coefficient when the load rate range is at j level.

3.2.4. Loss Cost of Less Power Generation When the Generation Rights Are Traded

$$C_g(P) = Q_g \times \omega_{on\text{-}grid} - \omega_{coal} \times F(P) \times T_s - Q_g \times C_{other} \tag{11}$$

where $C_g(P)$ is the cost of less power generation when the generation rights are traded, Q_g is the trading electricity quantity of power generation rights transferred by thermal power generation enterprises to efficient units and environmentally friendly units, $\omega_{on\text{-}grid}$ is the on-grid electricity tariff for thermal power, ω_{coal} is the price of standard coal, and T_s is the time required for thermal power generating units to produce electricity with Q_g production at a certain power P_s [41].

3.3. Objective Functions and Constraints

To summarize, the operating income of thermal power generation enterprises in the diversified business model can be expressed as:

$$R_T = \begin{cases} R_{og}(P) + R_g & P_b \le P < P_{max} \\ R_{og}(P) + R_{plrs,1}(P) & P_a < P < P_b \\ R_{og}(P) + R_{plrs,2}(P) & P_{min} < P \le P_a \end{cases} \tag{12}$$

The operating cost of thermal power enterprises in the diversified business model can be expressed in sections. It includes the cost of power production, the increased unit loss cost, the oil consumption cost, and the loss cost of less power generation when the units participate in deep peak shaving, and the generation rights are traded. It can be expressed as:

$$C_T = \begin{cases} C_{og}(P) + C_{plrc} + C_g(P) & P_b \le P < P_{max} \\ C_{og}(P) + C_{co}(P) + C_{plrsog}(P) & P_a < P < P_b \\ C_{og}(P) + C_{co}(P) + C_{oil}(P) + C_{plrsog}(P) & P_{min} < P \le P_a \end{cases} \tag{13}$$

According to the income function and the cost function of the thermal power generation enterprise established in the diversification model, taking the maximum operating benefit of the units as the objective function, it is expressed as follows:

$$maxL = R_T - C_T = \begin{cases} R_{og}(P) + R_g - C_{og}(P) - C_{plrc} - C_g(P) & P_b \le P < P_{max} \\ R_{og}(P) + R_{plrs}(P) - C_{og}(P) - C_{co}(P) - C_{plrsog}(P) & P_a < P < P_b \\ R_{og}(P) + R_{plrs}(P) - C_{og}(P) - C_{co}(P) - C_{oil}(P) - C_{plrsog}(P) & P_{min} < P \le P_a \end{cases} \tag{14}$$

where L is the diversified operating profits of thermal power generation enterprises, $R_{og}(P)$ is the income of power sales, $R_{plrs}(P)$ is the income of peak load regulation, R_g is the income of generation rights trading, $C_{og}(P)$ is the power generation cost of thermal power enterprises, $C_{co}(P)$ is the unit loss costs when units participate in deep peak load regulation, $C_{oil}(P)$ is the cost of oil consumption when the thermal power units operate with low load, C_{plrc} is the apportioned cost when the units do not participate in peak load regulation, $C_{plrsog}(P)$ is the cost of less power generation (due to participating in peak load regulation), and $C_g(P)$ is the cost of less power generation when the generation right is traded.

The constraints of thermal power generation enterprises in the diversified business model are mainly the power constraints of the thermal power units, the declared price constraints of deep peak load regulation, the declared electricity quantity constraints of deep peak load regulation, and the constraints on the electricity quantity in generation rights trading:

$$\begin{cases} P_{min} \leq P \leq P_{max} \\ \omega_{plrs,min} \leq \omega_{plrs,i} \leq \omega_{plrs,max} \\ 0 \leq Q_{plrs,i}(P) \leq Q_{plrs,max}(P) \\ 0 \leq Q_g \leq Q_{g,max} \end{cases} \tag{15}$$

where P_{max} is the maximum output power of the units; P_{min} is the output power of the given minimum operating mode of the units, that is, the limit load value of the thermal power units participating in deep peak regulation; $\omega_{plrs,min}$ is the lowest quotation; $\omega_{plrs,max}$ is the highest quotation; $Q_{plrs,max}(P)$ is the maximum electricity quantity when thermal power units participate in deep peak load regulation; and $Q_{g,max}$ is the maximum electricity quantity in generation rights trading.

4. Empirical Study

We analyzed the diversified business model of the thermal power generation enterprise in the Ningxia Autonomous Region of Northwest China, which has a high proportion of new energy installed capacity.

4.1. Background Introduction

The thermal power enterprise has built two 600 MW supercritical surface indirect air-cooled coal-fired units to complete the in-depth replacement of fossil energy with clean energy from the Northwest Power Grid and Ningxia Power Grid as soon as possible. According to the requirements of the State Grid Corporation of China (SGCC) for the doubling of new energy power generation and its proportion, and double reduction of abandoned new energy power and its rate, the enterprise completed a flexibility retrofit project for supercritical thermal power units to further improve the comprehensive performance of the units and their competitiveness in the auxiliary service market. At present, the transformed units have achieved a minimum technical output of 30%, the NO_X emission of the units by 30–50%, the boiler maximum continue rate (BMCR) operating conditions are less than or equal to 50 mg/Nm^3, and the average load response rate is greater than or equal to 2.0%/min. The units' fast start-stop capability has reached a relatively advanced level among similar units, so the enterprise is competitive in terms of deep peak load regulation.

4.2. Model Parameters

The data used in the empirical analysis were analyzed with 600 MW thermal power units. The unit cost of the thermal power units was 3646 yuan/kW. In accordance with the boiler parameters and the unit performance test results, the value of a was 0.000169, the value of b was 0.27601, and the value of c was 11.46196 in the energy consumption curve function of the coal-fired units.

According to the actual 2018 operating data, the thermal power units were annually used for 5108.2 h, and the unit price of standard coal was 514.15 yuan/ton. Moreover, the on-grid electricity tariff of thermal power was 259.5 yuan/MWh, the electricity quantity brought by power generation rights trading was 312,000 MWh, and the average price difference of power generation rights trading was 50 yuan/MWh. $Q_{plrs,max}(P)$, which represents the maximum electricity quantity when thermal power units participate in deep peak load regulation, was 25,374 MWh, in which the power quantity of deep peak load regulation accounted for 88% when the units' average load rate P fit the range (P_a, P_b), whereas the power quantity of deep peak load regulation accounted for 12% when P fit the range $(P_{min}, P_a]$.

According to Notice on operation rules (Trial) of Ningxia electric power auxiliary service market [42], the ladders quotation method is adopted for deep peak shaving transactions. The bid quotation is $\omega_{plrs,1}$ when P (the units' average load rate) fits the range (P_a, P_b) and $\omega_{plrs,1}$ ranges between

0 and 0.38 yuan/kWh. The bid quotation is $\omega_{plrs,2}$ when P fits the range $(P_{min}, P_a]$ and when $\omega_{plrs,2}$ ranges between 0.38 and 0.95 yuan/kWh, where P_{max} is the maximum output power of the units; P_{min} is the output power of the units with given minimum operating mode, that is, the limit load value of the thermal power units in the state of deep peak regulation; P_a is 40%; and P_b is 50%. The process of thermal power enterprises participating in deep peak load regulation is illustrated in Figure 4.

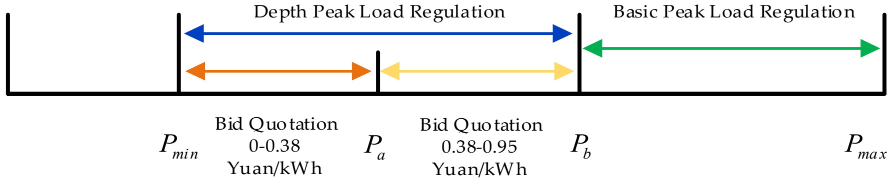


Figure 4. The process of thermal power enterprises participating in deep shaving service.

The operating loss coefficient () is 1.2 when units participate in deep peak load regulation (without oil), whereas β is 1.5 when units participate in deep peak load regulation (with oil). The oil consumption of the units is 4.8 t/h, and the price of oil is 6130 yuan/ton. The relationship between N (the rotor cracking times) and P (the units' load rate) during the deep peak load regulation is as follows [43]:

$$N(P) = 0.005778P^3 - 2.682P^2 + 484.8P - 8411 \tag{16}$$

When the thermal power enterprise does not participate in deep peak load regulation, its apportioned cost is graded with different load rate intervals. If the load rate is higher than the baseline of paid peak load regulation but less than 70%, it is categorized as the first level; if the load rate is between 70% and 80%, it is the second level; and if the load rate is higher than 80%, it is the third level. The correction coefficients corresponding to the three levels are $k_1 = 1$, $k_2 = 1.5$ and $k_3 = 2$, respectively.

According to the Notice on announcing the compensation allocation of Ningxia electric power auxiliary service market (NCERB), the corrected quantity of electricity was 5,829,820 MWh and the total apportioned cost was 113.79 million yuan for one year since the peak load regulation market began operation in May 2018 [44]. The monthly data of the corrected electricity quantity and the peak shaving cost-sharing are shown in Figures 5 and 6. Model detail parameters can be seen in Table A1.

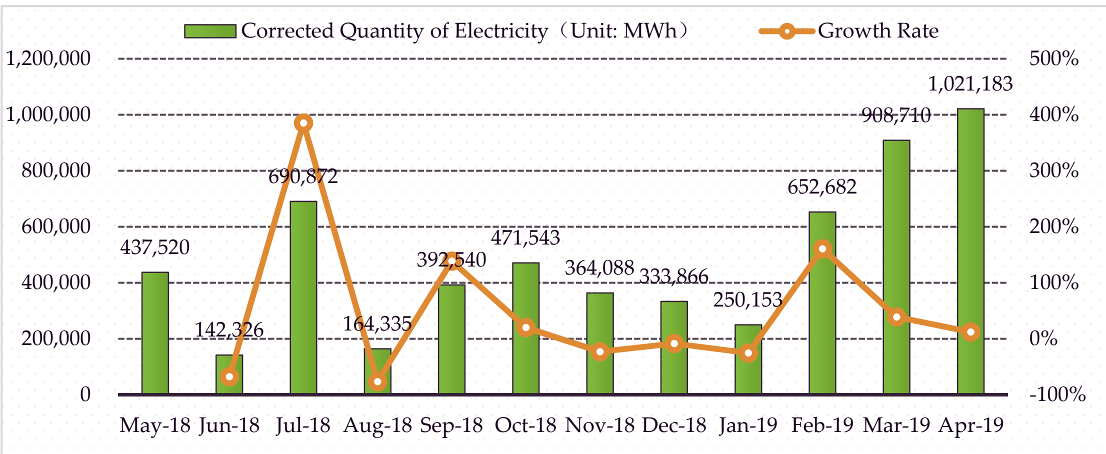


Figure 5. The corrected electricity quantity of Ningxia auxiliary service market from May 2018 to April 2019. (Data source: Northwest China Energy Regulatory Bureau of National Energy Administration of the People's Republic of China).

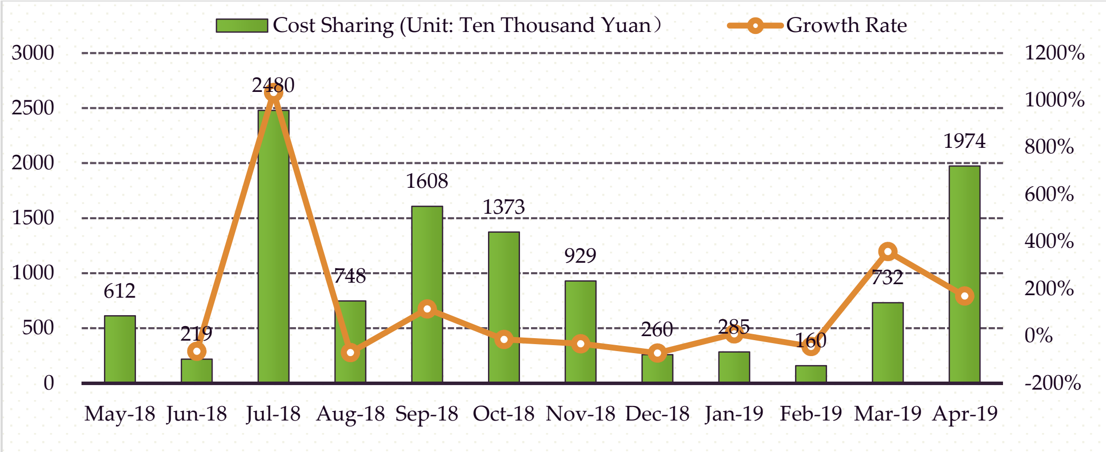


Figure 6. The peak shaving cost-sharing of Ningxia auxiliary service market from May 2018 to April 2019. (Data source: Northwest China Energy Regulatory Bureau of National Energy Administration of the People's Republic of China).

4.3. Simulation Results

4.3.1. Scenario A

The thermal power generation enterprise only carries out a single business model. It generates electricity for sales to earn income, and does not participate in the trading of power generation rights and in-depth peak load regulation. The units' actual output value P fits the range $[P_b, P_{max})$, so the enterprise has to share the apportioned cost. According to the equations in Section 3.3, the profits under scenario A are calculated as 17.4592 million yuan.

4.3.2. Scenario B

Because the unit price of coal for production is too high, the thermal power generation enterprise not only sells electricity, but also actively engages in generation rights trading with clean energy power generation enterprises to further expand the sources of income. However, they still do not provide in-depth peak load regulation under scenario B. The units' actual output value P is within the range $[P_b, P_{max})$ when they participate in peak load regulation, so the compensation cost must be shared for not participating in peak load regulation services. Based on the equations in Section 3.3, the profits under scenario B were calculated as 31.1432 million yuan.

4.3.3. Scenario C

In addition to selling electricity, thermal power generation enterprises provide peak load regulation to reduce the peak load compensation cost-sharing expenses. During in-depth peak load regulation, the units' actual output value P is within the range (P_a, P_b), so oil is not required to maintain combustion. However, the continuous reduction of the units' load rate will generate additional units' loss costs. Therefore, according to the equations in Section 3.3, the profits under scenario C were calculated as 25.392 million yuan.

4.3.4. Scenario D

The thermal power generation enterprise sells electricity, actively trades power generation rights, and participates in peak load regulation simultaneously. The units' actual output value P is within the range (P_a, P_b) when they participate in peak load regulation, so oil is not required to maintain combustion. However, the continuous reduction of the units' load rate generates additional units' loss costs. Therefore, according to the equations in Section 3.3, the profits under scenario D were calculated as 39.0782 million yuan.

4.3.5. Scenario E

The thermal power generation enterprise participates in deep peak load regulation while selling electricity, but it does not trade power generation rights. During the peak load regulation period, the units' actual output value P is within the range (P_a, P_b) without oil to maintain combustion, where P is within the range $(P_{\min}, P_a)$, so oil is required to maintain combustion and units' loss cost is generated. Therefore, according to the equations in Section 3.3, the profits under scenario E were calculated as 25.5674 million yuan.

4.3.6. Scenario F

In addition to the normal production of electricity, the thermal power generation enterprise also actively trades power generation rights and provides in-depth peak load regulation concurrently. During in-depth peak load regulation, oil is not required to maintain combustion when P is within (P_a, P_b), and oil is not required to maintain combustion when P is within $(P_{\min}, P_a)$, while generating t unit loss costs in different stages. Therefore, according to the equations in Section 3.3, the profits under scenario F were calculated as 39.2513 million yuan.

The profits value of each scenario is shown in Figure 7.

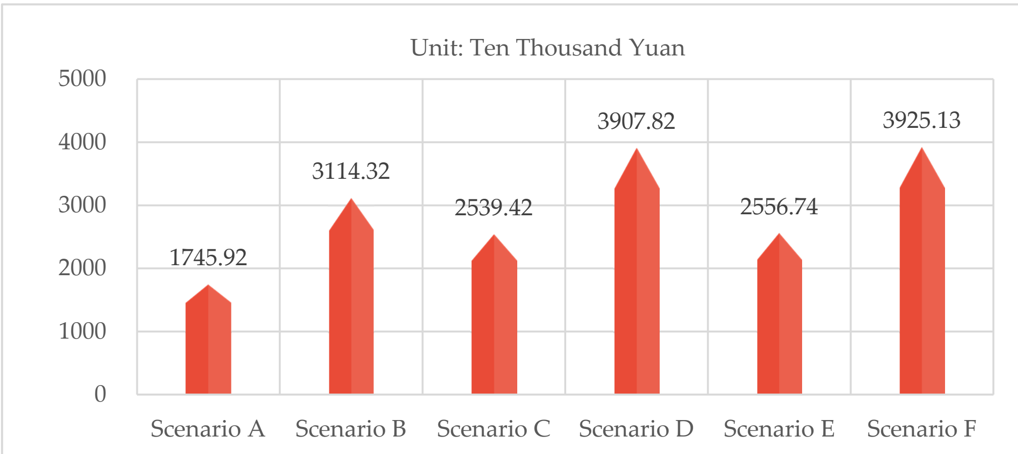


Figure 7. Profits of thermal power generation enterprise in different scenarios.

5. Discussion and Scenario Analysis

Under the same external boundary conditions, the profits of thermal power generation enterprise varied considerably in the different scenarios, as shown in Figure 7. Scenario A, with a single profit mode of power sales, produces the least profit, where L is 17.4592 million yuan.

When the unit price of coal is too high, in addition to power sales, the thermal power generation enterprise actively engages in power generation rights trading with clean energy power generation enterprises in scenario B. Due to the low production cost of clean energy, the transaction price difference is much larger than the price difference between the on-grid electricity prices and the unit production cost of thermal power enterprise, which produces considerable incremental revenue for the thermal power generation enterprise.

The thermal power generation enterprise participates in peak load regulation in scenarios C and E. The difference is that the thermal power enterprise participates in two stages of deep peak load regulation (with oil and without oil) simultaneously in scenario E, which reduces the sharing cost and increases the compensation income of peak load regulation. The profits in scenario E increase by

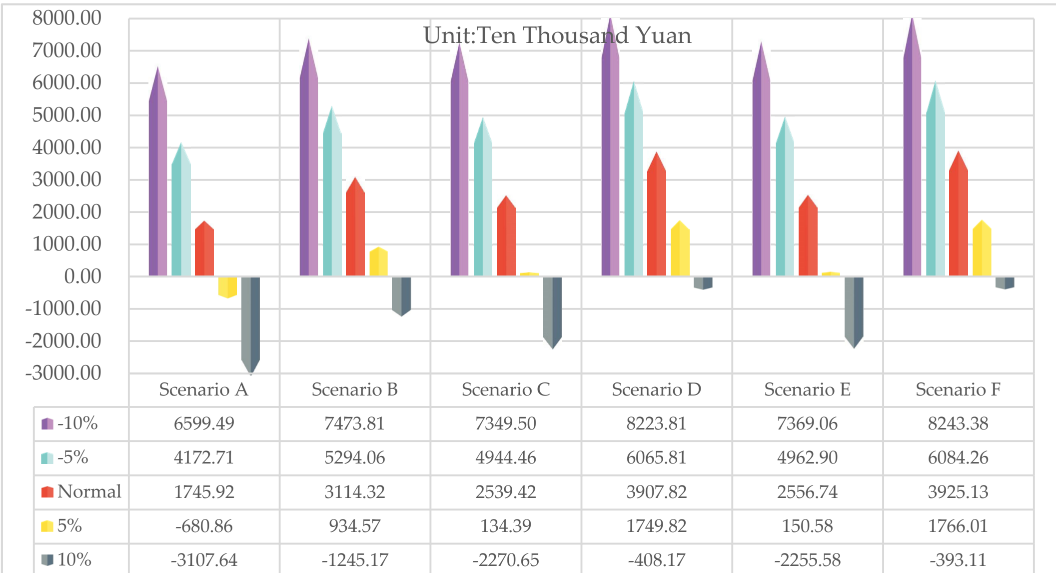
0.1731 million yuan compared with scenario C. In the in-depth peak load regulation stage, where oil injection is required to maintain combustion, although the oil injection cost and unit loss cost increase further, the compensation price for peak load regulation is higher when P is within $(P_{\min}, P_a)$, which can compensate for the increased cost of deep peak load regulation, and even produce a small amount of profit.

Scenario D assumes that Scenarios B and C occur concurrently. The thermal power enterprise participates in power generation rights trading and deep peak load regulation (without oil) in scenario D; its profit is higher than in scenarios B and C. The diversified business model creates higher profits for the thermal power generation enterprise.

Scenario F produces the most profit. Compared with scenario A, the profit of the two business models differs by 21.7921 million yuan. Therefore, the thermal power generation enterprises receive higher profits with a diversified business model.

To better illustrate the adaptability of the various business models proposed in this article to changes in the external environment, we conducted a sensitivity analysis of the profits in different scenarios. Sensitivity analysis is an uncertainty analysis method commonly used in economic decision-making. By measuring the change range of the decision-making goal caused by the change in one or more uncertain factors, the degree of influence of various factors on achieving the desired goal can be determined. Since about 70% of the costs of the thermal power generation enterprise is due to coal burning, the profits are sensitive to the price of coal. The fluctuations in on-grid electricity tariff also affect the profits of thermal power generation enterprise. Therefore, the unit price of standard coal and on-grid electricity tariff were both selected as uncertain factors to analyze the impact on profits for a thermal power generation enterprise.

Firstly, assuming other factors were unchanged, the impact of coal unit price changes on profits was analyzed. We selected the change proportions of the unit price of standard coal as −10%, −5%, 5% and 10%, and then the profit value in each scenario with different coal prices was calculated using the equations in Section 3.3. The result is shown in Figure 8.

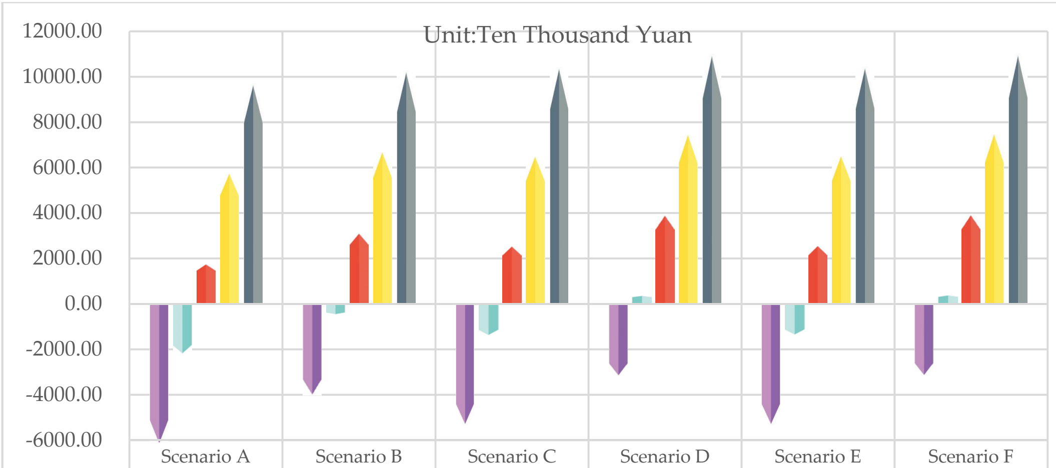


	Scenario A	Scenario B	Scenario C	Scenario D	Scenario E	Scenario F
-10%	6599.49	7473.81	7349.50	8223.81	7369.06	8243.38
-5%	4172.71	5294.06	4944.46	6065.81	4962.90	6084.26
Normal	1745.92	3114.32	2539.42	3907.82	2556.74	3925.13
5%	-680.86	934.57	134.39	1749.82	150.58	1766.01
10%	-3107.64	-1245.17	-2270.65	-408.17	-2255.58	-393.11

Figure 8. The impact of changes in the unit price of standard coal on the profits in different operating scenarios.

Figure 8 proves that the change in the unit price of standard coal has a reverse relationship with profits, and increases in the price of coal produce a sharp decline in the profits of thermal power generation enterprises. When the unit price of standard coal increases by 5%, the thermal power generation enterprise in scenario A, with a single power sales mode, begins to lose money, and the profits in other scenarios are still positive.

We then analyzed the impact of changes in on-grid electricity tariff on profits by assuming that other factors were unchanged. The on-grid electricity tariff was also obtained with change proportions of −10%, −5%, 5%, and 10%, and the profit value in each scenario with different change proportions of on-grid electricity tariff were calculated using the equations in Section 3.3. The result is shown in Figure 9.



	Scenario A	Scenario B	Scenario C	Scenario D	Scenario E	Scenario F
-10%	-6207.54	-4029.51	-5348.20	-3170.16	-5330.88	-3152.85
-5%	-2230.81	-457.60	-1404.39	368.83	-1387.07	386.14
Normal	1745.92	3114.32	2539.42	3907.82	2556.74	3925.13
5%	5722.66	6686.23	6483.24	7446.81	6500.55	7464.13
10%	9699.39	10258.15	10427.05	10985.80	10444.36	11003.12

Figure 9. The impact of changes in on-grid electricity tariff on the profits in different operating scenarios.

Figure 9 shows that a positive relationship exists between the change in on-grid electricity tariff and the change in profits. The decline in on-grid electricity tariffs produces a significant decline in profits. When the on-grid electricity tariff decreases by 5%, the thermal power generation enterprise suffers losses under scenarios A, B, C, and E, while the profit values are still positive under scenarios D and F. This shows that the diversified business model proposed in this paper has a better ability to resist risks than the single business model. The sensitivity coefficient analysis in Table 2 shows that the average sensitivity coefficient of the profit to coal price is 16.93 and the average sensitivity coefficient of the on-grid price is 27.76, indicating that it was reasonable to select coal price and on-grid electricity price as uncertainty factors for analysis.

Table 2. Sensitivity coefficient analysis.

Scenario	Sensitivity Coefficient of Profit to Coal Price	Sensitivity Coefficient of Profit to On-Grid Electricity Price
A	27.80	45.55
B	14.00	22.94
C	18.94	31.06
D	11.04	18.11
E	18.82	30.85
F	11.00	18.03
Average	16.93	27.76

Therefore, due to the continuous increase in new energy installed capacity, as well as slow growth of society's power consumption, high coal prices, encouragement to protect the environment, and the reduction of power generation, thermal power generation enterprises have to change their traditional single business model. We suggest a change into a diversified business model, involving power sales, generation rights trading, and peak load regulation—which is more conducive to mitigating the risks of external environmental changes, improving the operating efficiency, and achieving sustainable development of thermal power generation enterprises.

6. Conclusions

With the continuous increase in new energy installed capacity, the slowdown of social power consumption growth, the high coal prices, and the reduction of on-grid electricity tariff, we used the cost–benefit analysis method to analyzed the costs and benefits of thermal power enterprises in the operation process in detail. This established an operation benefit analysis and decision model for thermal power enterprises that includes four profit models: power sales, peak load regulation (without oil), peak load regulation (with oil), and generation right trading. The opportunity cost of peak load regulation and generation rights trading was considered. To demonstrate the applicability of the methods proposed in this paper and the differences in the benefits of thermal power generation enterprises under different business models, we combined the current operation of the power market, aiming at the possible combination of business models, and introduced six specific business models for comparative analysis. Finally, an empirical analysis was conducted by selecting a thermal power enterprise in Ningxia, Northwest China, as an example, which verified that the diversified business model is better than the single power sales operation model for thermal power enterprises.

Thermal power generation enterprises with diversified business models can receive an incremental income of 21.7921 million yuan in one year, which significantly improves the economic benefits of the enterprises. This model is conducive to the sustainable development of the thermal power industry. Thermal power generation enterprises participating in power generation rights trading can promote new energy consumption, and thermal power units conducting deep peak load regulation can reduce the amount of abandoned wind power. This can promote new energy consumption of 337,473 MWh, and the annual carbon dioxide emission can be reduced by 186,900 tons, producing social benefits. This will also play a positive role in energy conservation, emission reduction, and environmental protection.

We used sensitivity analysis to analyze the impact of the change in external uncertainty factors, such as coal price and on-grid electricity tariffs, on enterprise profits. The calculation results showed that the diversified business model could help thermal power generation enterprises to more effectively mitigate the risks of external environment change and achieve sustainable development.

Finally, the shortcoming of this model is that it only considers the combined scenarios of four business models: power sales, peak load regulation (without oil), peak load regulation (with oil), and generation rights trading. However, with advancing technology and the development of the external power market, other business paths need to be solved in the future work, such as thermal energy sales, energy saving, and consumption reducing service. In further research, we will continue to consider more business paths in the diversified business model to produce more profits, and support sustainable development for thermal power enterprises.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Parameters setting details.

Parameter	Value	Details
a	0.000169	Citing references [43]
b	0.27601	
c	11.46196	
β_1	1.2	
β_2	1.2	
$N(P)$	$0.005778P^3 - 2.682P^2 + 484.8P - 8411$	
Unit price of standard coal	514.15 yuan/ton	Market price in 2018
On-grid electricity tariff of Thermal power	259.5 yuan/MWh	Market price in 2018
Price of oil	6130 yuan/ton	Market price in 2018
The average price difference of Power generation rights trading	50 yuan/MWh	Unit operation data
$Q_{plrs,max}(P)$	25,374 MWh	Unit operation data
Q_g	312,000 MWh	Unit operation data
$\omega_{plrs,1}$	0–0.38 yuan/kWh	*Notice on operation rules (Trial) of Ningxia electric power auxiliary service market*
$\omega_{plrs,2}$	0.38–0.95 yuan/kWh	*Notice on operation rules (Trial) of Ningxia electric power auxiliary service market*
P_a	40%	*Notice on operation rules (Trial) of Ningxia electric power auxiliary service market*
P_b	50%	*Notice on operation rules (Trial) of Ningxia electric power auxiliary service market*
The corrected quantity of electricity	5,829,820 MWh	Northwest China Energy Regulatory Bureau of National Energy Administrator of the People's Republic of China. http://xbj.nea.gov.cn/website/Aastatic/news-list-100300-100301.html
The total apportioned cost	113.79 million yuan	

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