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# Analysis on Energy Saving Potential for Pumped-storage and Two-shift Peaking of Coal-fired Units

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**Abstract**. North China power grid is mainly a thermal power system, so it is hard to meet increasing need of difference between peak and valley loads and the demand of peak-load regulation. Units peaking mode is directly related to the peaking economy, this paper set up a mode and appropriate economic assessment model for pumped storage and coal-fired power units two-shift peaking. Comprehensive consideration of pumped storage capacity and the factors influencing the load time, the evaluation method was proposed. The application indicates that the method is effective in a peaking cycle. The evaluation method can reasonably reflect the situation of the turbine peaking economy in the coal-fired power plants, and brings the benefits for pumped storage and 300MW coal-fired power units. It provides a reference for energy-saving dispatching. Pumped-storage and coal-fired power units can be used as basis for decision making of peaking shaving mode.

## 1. Introduction

With the sustained and rapid development of the national economy in North China, the demand for power grids in North China has shown an accelerated growth trend, and the peak-to-valley difference in electricity consumption has increased (Yang et al., 2013). In particular, the installation capacity of 300MW coal-fired units and 600MW coal-fired units accounts for about 94% of the total installation capacity for thermal power-based power grids in northern areas. According to the actual situation of power supply in North China Power Grid, tapping the peak-shaving capacity of existing power plants in the network and preparing for the technical and economic analysis of expanding peak-shaving capacity is a better solution to enhance the peak-shaving capability of the power grid. Currently, according to numerous documents (Abila, 2010), it is feasible to regulate peak load of power grids by means of two shifting between 320MW coal-fired units and 200MW coal-fired units (Li, 2012). In addition, the successful implementation of two shifting between 125MW coal-fired units and 200MW coal-fired units demonstrates that it is theoretically practical for 300MW coal-fired units and 600MW coal-fired units to undergo two shifting (Qi, 2013, Yang and Zhang, 1989). Therefore, in view of the current large-scale unit in North China and the increasing peak-to-valley difference of power grid load, it is of great significance to analyze and study the economics of the peak-shaving operation mode of large generating units for comparing and evaluating the peak-shaving operation mode.

As power shaving power sources, the pumped storage power stations have two characteristics (Zhang, 2007): 1. peak clipping and valley filling. The daily load curve of the power system is changing, the night load is reduced, and the power system is required to reduce the power supply, forcing the thermal power plant to reduce the output operation, which is disadvantageous for the operation of the thermal power plant. During periods of high load demand, the stored water is released to produce electric power, helping increase electrical supply capacity at the peak state and also reduce start and stop times, fuel demand, maintenance costs, and pollutant emission(Zhang,2007), and bringing great benefits for thermal power plant consumption reduction and social environment. 2. Rapid start, flexible operation, high reliability, quick reaction to dramatic load change, self-starting ability, and access to such demands as frequency regulation, phase regulation, emergency standby, and black start (Wan, 1997).

This paper proposes a two-shift combined peak-shaving method for thermal power units and pumped storage units(hereinafter referred to as 'TSTP-PS peak-shaving' method). Taking the North China regional power grid as an example, under the same peak-to-valley load, comprehensive consideration of pumped storage capacity and the peaking period factors, respectively calculate and compare the low load peaking mode and the peaking coal consumption of the 'TSTP-PS peak-shaving' method mode, and the 'TSTP-PS peak-shaving' method can effectively reduce the peak coal consumption, and the coal saving effect is obvious. To provide positive reference for in-depth power grid peaking and energy saving and tapping work.

## 2. Energy consumption analysis of typical peak load regulation schemes

According to the actual operation of coal-fired units in China, the main peak-setting methods for coal-fired units are: 1) low load operation. In order to increase the units' adjustable output, the units are operated as far as possible at the lowest allowable load. At present, some power plants in China have already developed and implemented related measures such as blending and plasma mixing during low-load operation, which can ensure that the unit will not operate with oil at 50% of the rated load to achieve the purpose of deep peak shaving (Wang et al., 2012). For this scheme, peak load regulation of thermal power units can be done regardless of energy consumption and pollutant emission amounts. In this regard, the units with small installation capacity and high energy consumption may possibly operate during periods of low load for a long time, while the units with large installation capacity and low energy consumption may suffer low utilization rate. Such conditions, if happened, will lead to low utilization rate of primary energy and even serious environmental pollution. 2) Two shifting, or start-stop peak load regulation. For this scheme, units operate according to the daily load curve. After the nighttime peak load time, the units will be shut down to the state of hot spare, waiting for a startup for the following daytime peak load the next day. Compared to scheme 1, in spite of the requirement of a frequent start-stop operation with heavy workload, this scheme is characterized by the large amount of available electricity supply and the ability to reach 100% load capacity, thus posing a more prominent effect to peak load regulation of power grids. As the coal-fired units witness upgraded operation and automation levels with improved and reasonable support services of main units and auxiliary units, the more and more obvious energy-saving superiority of two shifting operation renders this scheme to be safe, practical and reliable. It has become the fundamental measure with regard to peak load regulation of power grids (Yao, 1982).

### *2.1. Energy consumption for low load operation*

Under low load operation, any deviation from rated working conditions would dictate the increase of energy consumption for thermal power units. If the difference of coal consumption when the load changes is neglected, $B_L$, the coal consumption at low load, can be estimated according to the following equation:

$$B_L = \sum_{i=1}^{\Omega} Z_i \cdot N_i \cdot b_0^i \cdot \tau_L^i \times 10^{-3} \quad (1)$$

Where:

$Z_i$ is the number of units of the i-th unit for the low-load operation, set; $N_i$ is the load for the i-th unit, MW; $b_0^i$ is the coal consumption rate for the i-th unit at low load, g/(kW·h); $\tau_L^i$ is the duration of the low-load operation of the unit, h.

*2.2. Energy consumption for two shifting operation*

There is frequent start-stop operation for the two shifting scheme. The start-stop loss decides whether the two shifting scheme is economical or not, and can be calculated through either experimentally or theoretically. With certain constraints, the experimental calculation always fail to represent real loss. The method of linear factors is usually used for theoretical calculation. Its basic thought is: the start-stop loss (H) during the whole start-stop process is divided into k phases, with m influential factors corresponding to each of the k phases. The loss amounts are calculated according to the characteristics and the influential factors of each phase. The corresponding expression is:

$$H = \sum_{i=1}^{k}\sum_{j=1}^{m} K_i^j \tau_i^j \quad (2)$$

Where: $\triangle B_L = -74.63\ln\left(\frac{N}{N_n}\right) + 315.1 \qquad N < 220MW$ is the linear loss factor caused by the j-th factor in the i-th phase, t/h; $\triangle B_L = -28.98\ln\left(\frac{N}{N_n}\right) + 332 \qquad N \geq 220MW$ is the time at which the j-th factor acts in the i-th phase, h.

A whole start-stop process is usually partitioned into several phases, namely load off, shutdown, unit shutdown, boiler ignition preparation, boiler ignition, boost, turn on, grid connection, load up, and thermal stability. The calculation method of loss at each stage is detailed in the literature (Zhang, 1988).

## 3. The establishment of the 'TSTP-PS peak-shaving' models

'TSTP-PS peak-shaving' models which are intended for the currently thermal power-based power grids, and in combination with characteristics of unified peak load regulation between pumped storage and thermal power units. the optimized models aim at minimizing the total coal consumption during the periods of peak load regulation and further reducing the pollutant emission amounts from electricity generation.

*3.1. Coal consumption characteristics of thermal power units*

The coal consumption characteristic of a thermal power plant refers to the relationship between the fuel consumption B and the output electric power P during stable operation. The fuel consumption characteristics of the unit can be expressed as B = B (P), which is usually approximated by a quadratic curve.

$$B_i(P) = a_i P^2 + b_i P + c_i \quad (3)$$

Where: $a_i$, $b_i$, $c_i$ are the coefficient of relationship between unit coal consumption and power P, respectively.

*3.2. The relationship between Power and time*

The relationship between the power and the time is:

$$P_i = s_i \times N_0^i \times t_i / 60 \quad (4)$$

Where: $P_i$ is the power generated by unit i, MW; $S_i$ is the climbing rate of unit i, %; $N_0^i$ is the rated power of unit i, MW / h. $t_i$ is the climb time of unit i, min.

### *3.3. The establishment of the 'TSTP-PS peak-shaving 'models*

#### *3.3.1. The model of peak load working conditions*

During peak hours (from $T_1$ to $T_2$), the two-shift thermal power units start up and generate electricity under the peak-shaving state. At the same time, the pumped storage units help produce electric power, thus reducing the workload of corresponding m thermal power units. Then, the total coal consumption ($B_P$) of the two shifting units during peak hours is expressed as:

$$B_P = \int_{T_1}^{T_2} \sum_{i=1}^{m} \left[ \mu_{P,\ i}^{t} B_{P,\ i} \left( P_{P,\ i}^{t} - V_{P,\ i}^{t} \right) + \mu_{P,\ i}^{t} \left( 1 - \mu_{P,\ i}^{t-1} \right) \left( H_{P,\ i}^{t} + W_{P,\ i}^{t} \times t \right) \right] dt \quad (5)$$

Where: $T_1, T_2$ are the system peak load start time and end time, respectively, h; $\mu_{P,\ i}^{t}$ is the operating state of the i-th unit in the peak load period t, $\mu_{P,\ i}^{t} = 1$ is the indicating operation, $\mu_{P,\ i}^{t} = 0$ is the indicating outage; $V_{P,\ i}^{t}$ is the replacing the generating capacity of the thermal power unit i for the pumped storage unit ; MW / h; that is $V_P^t = \sum_{z=1}^{k} V_{P,\ z}^{t}$ ; $H_{P,\ i}^{t}$ is the peak start-up period t the unit start and stop coal consumption, t standard coal; $W_{P,\ i}^{t}$ is the peak load period t unit i shutdown standby unit time coal consumption, t standard coal / h.

#### *3.3.2. The model of valley load working conditions*

During valley hours (from $T_3$ to $T_4$), off-peak electric power of thermal power plants is used to run the pumps, thus increasing the workload of these units. Assuming that water is pumped from $T_3$ to $T_4$, and there is a total of n thermal power units running the pumps, the total coal consumption ($B_v$) of the two shifting units during valley hours is expressed as:

$$B_V = \int_{T_3}^{T_4} \sum_{j=1}^{n} \left[ \mu_{V,\ j}^{t} f_{P,\ j} \left( P_{V,\ j}^{t} + V_{V,\ j}^{t} \right) + \mu_{V,\ j}^{t} \left( 1 - \mu_{V,\ j}^{t-1} \right) \left( H_{V,\ j}^{t} + W_{V,\ j}^{t} \times t \right) \right] dt \quad (6)$$

Where: $T_3$, $T_4$ are the system valley load start and end time, respectively, h; $\mu_{V,\ j}^{t}$ is the operating state of the j-th unit in the valley load period t; $\mu_{V,\ j}^{t} = 1$ indicates the operation, $\mu_{V,\ j}^{t} = 0$ indicates the outage; $V_{V,\ j}^{t}$ is the thermal power unit j in the valley load period t bears the pumped storage unit electricity consumption; MW/h, e. g $V_V^t = \sum_{z=1}^{k} V_{V,\ z}^{t}$ ; $H_{V,\ j}^{t}$ is the inherent start-stop coal consumption of unit j during the valley load period t, t standard coal; $W_{V,\ j}^{t}$ is the valley unit load period t unit j shutdown standby unit time coal consumption, t standard coal / h .

For pumped storage units, the amount of electricity stored during pumping is $V_P^t = \sum_{z=1}^{k} V_{V,\ z}^{t} \cdot \eta$ , $\eta$ is the overall efficiency of the pumped storage unit; %, usually take 75%.

#### *3.3.3. Objective functions and constraints*

According to the above analysis, it can be obtained that within a daily peak load regulation period, the total coal consumption (B) is equal to the sum of $B_p$ and $B_v$. Considering that the unified peak load regulation aims at minimizing the total coal consumption during the whole periods of peak load regulation, the objective is then optimized as:

$$\min B = B_P + B_V \tag{7}$$

Corresponding constraints are:

$$\sum_{i\in\Omega_G} P_i = P_P \tag{8}$$

$$\sum_{i\in\Omega_G} P_i = P_V \tag{9}$$

$$\mu_{p,\ i}^{t} P_{i,\ min} \le P_{p,\ i}^{t} \le \mu_{p,\ i}^{t} P_{i,\ max} \tag{10}$$

$$\mu_{v,\ i}^{t} P_{i,\ min} \le P_{v,\ i}^{t} \le \mu_{v,\ i}^{t} P_{i,\ max} \tag{11}$$

$$\Delta P_i^{-} \le P_i^{t} - P_i^{t-1} \le \Delta P_i^{+} \tag{12}$$

## 4. Examples and analysis

### *4.1. System example introduction*

The North China Power Grid is a power grid based on thermal power. As of 2009, the installed capacity is 170,780.15MW, including 300 MW, 600 MW wet cooling, 600 MW air cooling and 1000 MW units as the main units, with 219 units, 77 units，31 units and 6 sets respectively, as well as 2,530MW of pumped storage unit, the time and loss of each stage of the known 300MW and 600MW units are shown in Table 1(Zhang et al., 2016). The relationship between load and coal consumption of different types of units is as follows:

The load and coal consumption characteristics of the 300MW coal-fired unit are:

$b = -0.0003 \cdot P^2 - 0.0446 \cdot P + 363.49$

The load and coal consumption characteristics of the 600MW (WC) coal-fired unit are: $b = 0.0001 \cdot P^2 - 0.2088 \cdot P + 379.26$

The load and coal consumption characteristics of the 600MW (AC) coal-fired unit are:

$b = 0.0003 \cdot P^2 - 0.3567 \cdot P + 434.85$

Tab.1 Start-stop loss factor of 300MW and 600MW coal-fired power units/t/h

| item | | Start-stop phase | | | | |
|---|---|---|---|---|---|---|
| | | unit shutdown | boiler ignition preparation | boiler ignition, boost, turn on, and grid connection | load up | thermal stability |
| Time/h | 300 MW | —— | 0.50 | 0.83 | 0.82 | 1.00 |
| | 600 MW | —— | 0.50 | 0.67 | 0.75 | 1.00 |
| 300MW units | | 1.15 | 7.69 | 23.75 | 1.82 | 2.34 |
| 600MW units(WC) | | 2.29 | 14.01 | 64.69 | 6.55 | 4.68 |
| 600MW units(AC) | | 2.30 | 14.32 | 64.98 | 7.94 | 4.68 |

The calculated grid selected a peak load of 137,828 MW, a valley load of 73,529 MW, a peak-to-valley difference of 64,299 MW, and a peak-to-valley difference of 46.7%. In order to meet the peak-to-valley difference above the balance, according to the current peak-shaving mode of the power grid for low-load peak-shaving, the units in the network must participate in peak-shaving under 55% rated load conditions. In the case of ensuring that the peak shaving capacity of the power grid remains unchanged, if the ‘TSTP-PS peak-shaving’ method is adopted to participate in peak shaving, the options are as follows:

Option 1: 300MW coal-fired units in the network are all regulated by two-shift. The 600MW and 1000MW coal-fired units all participate in peak shaving at rated full load.

Option 2: The 600MW coal-fired units in the network are all regulated by two- shift. The 300MW and 1000MW coal-fired units all participate in peak shaving at rated full load.

The above three peaking conditions are considered to invest 70%, 80%, 90% and 100% pumped storage capacity to participate in power grid peak shaving.

### *4.2. Calculation results and analysis*

When investing 70%, 80%, 90% and 100% pumped storage capacity respectively, compared with the low load peak shaving method, the 'TSTP-PS peak-shaving' method for reducing coal consumption is shown in table 2,table 3, table 4 and table 5 respectively. From Table 2 to Table 5, we know that:

(1) When the capacity of the pumped storage unit with peak load is constant, with the increase of peak load period, compared with the low load peak shift method, the coal consumption of 'TSTP-PS peak-shaving' mode shows an upward trend, corresponding $CO_2$ , $SO_2$ and $NO_x$ emissions are reduced.

(2) With the increase of the capacity of the pumped storage units that are put into peak shaving, the amount of coal saved by the 'TSTP-PS peak-shaving' mode shows a downward trend during the same peaking period, because with the pumped storage capacity, the increase has reduced the number of coal-fired unit involved in peaking start and stop, and correspondingly increased the load rate of thermal power units.

(3) Under the same situation of the capacity and peaking period of the pumped storage unit with peak shaving, the 'TSTP-PS peak-shaving' method can save coal consumption compared with the low-load peak-shaving method, and the 'TSTP-PS peak-shaving' mode scheme 1st option which is more economical than the 2nd option. This is because the 300MW unit of the North China Power Grid has the highest proportion. On the other hand, the 300MW unit itself consumes more energy than the 600MW (WC) units and 600MW (AC) units.

Based on the data of Tables 2, 3, 4, and 5, Table 6 is obtained, which can be seen from Table 6:

(1) With the increase of the proportion of pumped storage unit input, the low load peak regulation mode and the peak load coal consumption of the 'TSTP-PS peak-shaving' mode are reduced, and the low load peak regulation mode is reduced faster, which is due to pumping. The increase of energy storage capacity not only reduces the number of coal-fired units participating in start-stop, but also increases the load rate of thermal power units, so that the low-load peak-shaving mode and the 'TSTP-PS peak-shaving' mode coal consumption are both reduced, and also indicates that the load is low. Under the peak-shaving mode, the pumped-storage unit participates in the degree of peak-shaving, and its influence on peak-regulating coal consumption is more obvious.

(2) In the process of pumping storage capacity 70%～100%, during the peaking period of 1h～8h, the 'TSTP-PS peak-shaving' mode is lower than the peak load coal consumption of the low load peaking mode.

(3) When the capacity of the 100% pumped storage unit is used, and the scheme of 'TSTP-PS peak-shaving' is adopted, the peak coal consumption is the lowest. Compared with the low load peaking method, the peak is adjusted with the peaking period. Coal consumption decreased by 36.054g～132.859g.

The above calculation and analysis show that in the North China Power Grid, the two-shift combined peak shaving of the pumped storage power station and the 300 MW and 600 MW coal-fired units is economically feasible. Converting the low-load operation mode of 300 MW and 600 MW coal-fired units of a certain scale into two-shift operation will better alleviate the peaking pressure of the North China Power Grid, and effectively solve the problem of large difference between daily and weekly peak-valley of the North China Power Grid, and improve system peaking economy.

Tab.2 Coal saving emission reduction of ‘TSTP-PS peak-shaving’ (70%pumped storage capacity)

| item (units) | scheme | downtime/h 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|---|
| saving coal quantity (ton) | 1 | 7,948.50 | 21,226.16 | 34,503.82 | 47,781.48 | 61,059.14 | 74,336.80 | 87,614.46 | 100,892.11 |
| | 2 | 3,686.21 | 13,789.14 | 23,892.06 | 33,994.99 | 44,097.91 | 54,200.84 | 64,303.77 | 74,406.69 |
| $CO_2$ reduction (ton) | 1 | 17,635.35 | 47,094.49 | 76,553.63 | 106,012.77 | 135,471.91 | 16,493.05 | 194,390.19 | 223,849.33 |
| | 2 | 81,78.60 | 30,593.96 | 53,009.32 | 75,424.68 | 97,840.04 | 120,255.40 | 142,670.76 | 165,086.12 |
| NOx reduction (ton) | 1 | 6.26 | 16.71 | 27.17 | 37.62 | 48.07 | 58.53 | 68.98 | 79.43 |
| | 2 | 2.90 | 10.86 | 18.81 | 26.76 | 34.72 | 42.67 | 50.63 | 58.58 |
| $SO_2$ reduction (ton) | 1 | 1.91 | 5.11 | 8.31 | 11.51 | 14.70 | 17.90 | 21.10 | 24.30 |
| | 2 | 0.89 | 3.32 | 5.75 | 8.19 | 10.62 | 13.05 | 15.48 | 17.92 |
| profit (￥10K) | 1 | 556.40 | 1,485.83 | 2,415.27 | 3,344.70 | 4,274.14 | 5,203.58 | 6,133.01 | 7,062.45 |
| | 2 | 258.04 | 965.24 | 1,672.44 | 2,379.65 | 3,086.85 | 3,794.60 | 4,501.26 | 5,208.47 |

Tab.3 Coal saving emission reduction of ‘TSTP-PS peak-shaving’(80%pumped storage capacity)

| item (units) | scheme | downtime/h 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|---|
| saving coal quantity (ton) | 1 | 7,943.18 | 21,132.78 | 34,322.39 | 47,511.99 | 60,701.59 | 73,891.19 | 87,080.79 | 100,270.39 |
| | 2 | 3,606.68 | 13,621.55 | 23,636.42 | 33,651.29 | 43,666.16 | 53,681.03 | 63,695.89 | 73,710.76 |
| $CO_2$ reduction (ton) | 1 | 17,623.54 | 46,887.31 | 76,151.08 | 105,414.84 | 134,678.61 | 163,942.38 | 193,206.15 | 222,469.92 |
| | 2 | 8,002.147 | 30,222.14 | 52,442.13 | 74,662.11 | 96,882.10 | 119,102.09 | 141,322.08 | 163,542.07 |
| NOx reduction (ton) | 1 | 6.25 | 16.64 | 27.02 | 37.41 | 47.79 | 58.17 | 68.56 | 78.94 |
| | 2 | 2.84 | 10.72 | 18.61 | 26.49 | 34.38 | 42.26 | 50.15 | 58.03 |
| $SO_2$ reduction (ton) | 1 | 1.91 | 5.09 | 8.27 | 11.44 | 14.62 | 17.79 | 20.97 | 24.15 |
| | 2 | 0.87 | 3.28 | 5.69 | 8.10 | 10.52 | 12.93 | 15.34 | 17.75 |
| profit (￥10K) | 1 | 556.02 | 1,479.30 | 2,402.57 | 3,325.84 | 4,249.11 | 5,172.38 | 6,095.66 | 7,018.93 |
| | 2 | 252.47 | 953.51 | 1,654.55 | 2,355.59 | 3,056.63 | 3,757.67 | 4,458.71 | 5,159.75 |

Tab.4 Coal saving emission reduction of ‘TSTP-PS peak-shaving’(90%pumped storage capacity)

| item (units) | scheme | downtime/h 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|---|
| saving coal quantity (ton) | 1 | 7,937.86 | 21,039.40 | 34,140.95 | 427,242.490 | 60,344.04 | 73,445.58 | 86,547.13 | 99,648.67 |
| | 2 | 3,527.15 | 13,453.96 | 23,380.78 | 33,307.59 | 43,234.40 | 53,161.21 | 63,088.02 | 73,014.84 |
| $CO_2$ reduction (ton) | 1 | 17,611.72 | 46,680.12 | 75,748.52 | 104,816.91 | 133,885.31 | 162,953.71 | 192,022.11 | 221,090.50 |
| | 2 | 7,825.69 | 29,850.31 | 51,874.93 | 73,899.55 | 95,924.16 | 117,948.78 | 139,973.40 | 161,998.02 |
| NOx reduction (ton) | 1 | 6.25 | 16.56 | 26.88 | 37.19 | 47.51 | 57.82 | 68.14 | 78.45 |
| | 2 | 2.78 | 10.59 | 18.41 | 26.22 | 34.04 | 41.85 | 49.67 | 57.48 |
| $SO_2$ reduction (ton) | 1 | 1.91 | 5.07 | 8.22 | 11.38 | 14.53 | 17.69 | 20.84 | 24.00 |
| | 2 | 0.85 | 3.24 | 5.63 | 8.02 | 10.41 | 12.80 | 15.19 | 17.58 |
| profit (￥10K) | 1 | 555.65 | 1,472.76 | 2,389.87 | 3,306.97 | 4,224.08 | 5,141.19 | 6,058.30 | 6,975.41 |
| | 2 | 246.90 | 941.78 | 1,636.65 | 2,331.53 | 3,026.41 | 3,721.29 | 4,416.16 | 5,111.04 |

Tab.5 Coal saving emission reduction of ‘TSTP-PS peak-shaving’(100%pumped storage capacity)

| item (units) | scheme | downtime/h 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|---|
| saving coal quantity (ton) | 1 | 7932.53 | 20946.02 | 33959.51 | 46973.00 | 59986.48 | 72999.97 | 86013.46 | 99026.95 |
| | 2 | 3447.62 | 13286.38 | 23125.13 | 32963.89 | 42802.64 | 52641.40 | 62480.15 | 72318.91 |
| $CO_2$ reduction (ton) | 1 | 17599.91 | 46472.93 | 75345.96 | 104218.98 | 133092.01 | 161965.04 | 190838.06 | 219711.09 |
| | 2 | 7649.24 | 29478.48 | 51307.73 | 73136.98 | 94966.22 | 116795.47 | 138624.72 | 160453.96 |
| NOx reduction (ton) | 1 | 6.25 | 16.49 | 26.74 | 36.98 | 47.23 | 57.47 | 67.20 | 77.96 |
| | 2 | 2.71 | 10.46 | 18.21 | 25.95 | 33.70 | 41.44 | 49.19 | 56.94 |
| $SO_2$ reduction (ton) | 1 | 1.91 | 5.04 | 8.18 | 11.31 | 14.45 | 17.58 | 20.71 | 23.85 |
| | 2 | 0.83 | 3.20 | 5.570 | 7.94 | 10.31 | 12.68 | 15.05 | 17.41 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| profit | 1 | 555.28 | 1466.22 | 2377.16 | 3288.11 | 4199.05 | 5110.00 | 6020.94 | 6931.89 |
| （￥10K） | 2 | 241.33 | 930.05 | 1618.76 | 2307.47 | 2996.19 | 3684.90 | 4373.61 | 5062.32 |

Tab.6 Different peak shaving package unit load coal consumption/g·kW$^{-1}$

| percentage | scheme | downtime/h | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| 70% | Low load peak-shaving | 365.92 | 540.51 | 643.33 | 711.10 | 759.12 | 794.93 | 822.66 | 844.77 |
| | 1 | 329.09 | 467.61 | 549.21 | 607.00 | 641.12 | 669.55 | 691.57 | 709.12 |
| | 2 | 348.42 | 492.23 | 576.86 | 632.60 | 672.09 | 701.53 | 724.33 | 742.50 |
| 80% | Low load peak-shaving | 365.04 | 539.25 | 641.95 | 709.67 | 757.68 | 793.49 | 821.23 | 843.35 |
| 70% | 1 | 328.31 | 466.79 | 548.45 | 602.30 | 640.49 | 668.97 | 691.04 | 708.64 |
| 70% | 2 | 347.95 | 491.63 | 576.26 | 632.05 | 671.58 | 701.06 | 723.89 | 742.10 |
| 90% | Low load peak-shaving | 364.16 | 537.99 | 640.57 | 708.24 | 756.25 | 792.06 | 819.81 | 841.94 |
| 70% | 1 | 327.54 | 465.98 | 547.69 | 601.61 | 639.86 | 668.40 | 690.52 | 708.15 |
| 70% | 2 | 347.48 | 491.03 | 575.67 | 631.49 | 671.07 | 700.59 | 723.46 | 741.69 |
| 100% | Low load peak-shaving | 363.28 | 536.74 | 639.19 | 706.82 | 754.81 | 790.63 | 818.39 | 840.53 |
| | 1 | 326.78 | 465.17 | 546.94 | 600.92 | 639.23 | 667.83 | 689.99 | 707.67 |
| | 2 | 347.01 | 490.44 | 575.08 | 630.94 | 670.55 | 700.12 | 723.02 | 741.29 |

## 5. Conclusion and proposal

Through the analysis and calculation of practical examples, the following conclusions are obtained:

(1) Compared with the low-load peak-shaving mode, the ‘TSTP-PS peak-shaving’ method is economically feasible, and the coal consumption is the lowest when using the scheme 1st peak-shaving mode.

(2) Adopting the ‘TSTP-PS peak-shaving’ method, compared with the low-load peak-shaving method, considering the peaking period of 8 hours, according to the pumping storage capacity involved in peak-shaving, an annual 9.90-10.09 million ton of standard coal was saved , corresponding to an emission reduction of 22.19-22.38 million ton $CO_2$, 77.96-79.43 ton $NO_x$, and 23.85-24.30 ton $SO_2$. In this way, the researched area could harbor an effective reduction of the total amount of pollutant emission and also an annual revenue of ￥69.32-70.62 million (if the coal price was ￥700/t and the annual operation time was 5000h). If the capacity and social benefits brought about by the ‘TSTP-PS peak-shaving’ method are considered at the same time, the advantages of the peak-shaving method are more obvious.

(3) In this paper, a combined peaking model of pumped storage and thermal power two-shift system is established, which is in line with the development goals of energy-saving dispatching and national energy policy, and can be used as the decision-making basis for determining the peaking mode of coal-fired units.

(4) Through data analysis of four kinds of capacity inputs for pumped storage units, it can be obtained that it is the most economical way to put the 100% pumped storage units into peak load regulation. However, when determining the exact percentage of capacity, it is supposed to consider such factors comprehensively as the potential spinning reserve capacity and emergency capacity for pumped storage units.

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