Article

Multi-Angle Economic Analysis of Coal-Fired Units with Plasma Ignition and Oil Injection during Deep Peak Shaving in China

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Abstract: What China committed in the Paris Agreement encourages the penetration of renewable energy in power grid. To consume more renewable energy, coal-fired units undertake the most part of peak shaving task and are usually operated at a low-load level during off-peak hours. However, deep peak shaving has harmed the benefits of thermal power plants and also brought about environmental problems. To improve the peak-shaving capacity and operation efficiency of coal-fired units, the government encourages the flexibility retrofits for coal-fired units. In this paper, peak-shaving related cost functions are proposed for the multi-angle economic analysis of coal-fired unit with plasma ignition (UPI) and oil injection (UOI), respectively. First, the operation characteristic is analyzed for three stages of peak shaving, and then the peak-shaving costs related to these three stages are proposed in terms of the coal consumption cost, wear-and-tear cost, combustion-supporting cost, and environmental cost. Afterwards, a peak-shaving cost-based economic dispatch model is presented with consideration of the curtailed wind penalty, and an environmental efficiency index is defined to evaluate the environmental benefits. Finally, in the case study, quantitative economy analysis is performed from the aspects of thermal power plants, wind power plants, and the environment separately, and the simulation results indicate that UPI has better peak-shaving economy and environmental efficiency than UOI.

Keywords: deep peak shaving; coal-fired units; plasma ignition; peak-shaving cost; environmental efficiency; economic dispatch

1. Introduction

Due to wind power’s inherent properties of intermittent and volatility etc., [1], a high level of wind power penetration increases load peak-valley variations and further aggravates the existent peak shaving pressure [2]. It has been the main cause of wind curtailments, hindering further development of wind power in China [3]. In 2015, the average hour of wind power generation is 1728 h with a year-on-year decrement of 172 h, resulting in a significantly reduced wind utilization rate according to the statistics data of The National Energy Administration of PRC. In the case of increasing wind curtailment, the deep peak shaving demand of thermal power units mainly coal-fired units has grown in power engineering [4,5].

What is worth noting is that deep peak shaving of coal-fired units is actually a process of energy transformation like energy storage, which transfers the reduced output of coal-fired units to renewable energy generation; on the other hand, energy storage can be effectively used to consume wind power and plays a key role in deep peak shaving. Lots of research has been done on the ability...
of energy storage to peak shaving and benefit power systems [6–8]. However, energy storage has not been widely used due to its high capital investment costs, and there are only some small-scale demonstrated examples combining coal-fired units with storage devices for peak shaving [9]. In China, especially in regions with abundant wind resources such as the Northeast, the North, and the Northwest areas, since there are an excessive proportion of coal-fired units, irrational power supply structure, and insufficient flexible peak shaving resources, the aggravated peak shaving burden caused by large-scale wind power integration is mainly undertaken by the coal-fired units [10]. In regular peak shaving (RPS), these units normally are unable to turn down at the level to completely accommodate the integrated wind power, and thus a large amount of wind curtailment occurs due to its anti-peak characteristics. Currently, some coal-fired units are operated at the deep peak shaving states (usually 45% to 50% of rated power) to consume much more wind power. When the power output of a coal-fired unit is further reduced to 30% to 45% of its rated value, oil injection is usually adopted to ensure steady combustion of the boiler, but this strategy increases oil cost and results in high pollutant emissions. Simultaneously, since coal-fired units operated at the deep peak shaving states are very likely at low efficiency due to the expensive oil cost and the wear-and-tear cost etc., the enthusiasm of thermal power plants to participate in deep peak shaving is commonly low. On the other hand, though wind power saves fossil fuels and is environmentally friendly, deep peak shaving will markedly increase energy consumption and pollutant emissions of coal-fired units. In order to fulfill the low carbon commitments in the Paris Agreement and to improve the operating cost efficiency of coal-fired units in peak shaving, China’s government encourages coal-fired units to carry out the flexibility retrofits strategy under the low-load operation conditions such as the plasma ignition technology and tiny-oil ignition technology.

At present, there are few studies on the deep peak-shaving costs of coal-fired units with flexibility retrofit strategy. The authors of [11] studied the losses of coal-fired power plants induced by wind power intermittency while mainly focusing on the increased start/stop cost. In [12–14], the peak-shaving costs were only indicated by the coal consumption characteristic at the RPS period, and the oil saving benefits of deep peak shaving without combustion supporting (DPSW) was quantitative analyzed, but the unit wear-and-tear cost was not taken into account. In [15], the unit commitment problem was studied for the coal-fired units in deep peak shaving without flexibility retrofits. From an environmental point of view, the peak-shaving costs are not only related to units’ coal-fired cost, oil, and wear-and-tear cost, but also related to some additional costs such as the environmental cost [4,16–18].

When related to the economic dispatch with large-scale wind power integration, the reported results usually evaluated the economy of the coal-fired units from the standpoint of power grids and power plants during deep peak shaving. In [19], an economic dispatch model was proposed for coal-fired units, photovoltaic system, and wind energy generation system, and the economic effect was investigated from the perspectives of thermal power, wind power, and solar power plants. In [20], a wind power generation cost index was introduced to form the dynamic economic dispatch model from the view of wind power plants and thermal power plants. Prof. Plathottam of [21] presented an economic dispatch model for a renewable generation penetrated power system with energy storages, and optimized the heat and water consumption to raise the system operational economics. Based on the following observations; (1) though the use of retrofitted coal-fired units in deep peak shaving has become the mainstream, there is still a paucity of economic analysis of those units during deep peak shaving; and (2) most references such as those reviewed above all neglect to consider environmental pollution in deep peak shaving when conducting economy analysis; it is very necessary to investigate the economy of retrofitted coal-fired units with the consideration of environmental benefits in deep peak shaving.

The retrofits of coal-fired units include adding the external facilities and improved combustion technology. (1) For the external facilities, it is mainly to install electric boilers and large hot water tanks, which can convert excessive electric energy into heat energy and release it when necessary. This measure is usually with a large front-end investment and well applicable for heating units; (2)
the improved combustion technology mainly includes the plasma ignition, tiny-oil ignition, and oxygen-enriched combustion strategy, etc. Since the plasma ignition technology is the most promising technology applied in coal-fired units, in this paper, we will take the coal-fired unit with plasma ignition (UPI) as a representative to analyze its economy in deep peak shaving and compare it with coal-fired units with oil injection (UOI).

The main contributions of this paper are twofold as follows:

(1) A peak-shaving costs function representing the operation characteristics of UPI and UOI in three peak-shaving stages is proposed, and an economic dispatch model is presented to reflect the peak-shaving costs.

(2) An environmental efficiency index is defined to evaluate the environmental benefits; the multi-angle economic analysis of UPI and UOI in deep peak shaving is investigated from perspectives of thermal power plants, wind power plants, and the environment.

The paper is organized as follows: In Section 2, based on different load levels and power consumption characteristics of coal-fired units, the peak shaving process is divided into three phases: RPS, DPSW, and deep peak shaving with combustion supporting (DPSC), and the main factors influencing the deep peak shaving procedure are also analyzed. In Section 3, taking the coal consumption cost, wear-and-tear cost, combustion-supporting cost, and environmental cost into account, the peak-shaving costs function is proposed for UPI and UOI coal-fired units, and afterwards an economic dispatch model with an environmental efficiency index is presented to evaluate the environmental benefits. Then, economic analysis of UPI and UOI in deep peak shaving is investigated in Section 4 from perspectives of thermal power plants, wind power plants, and the environment. Finally, the conclusions are given in Section 5.

2. Three Periods of Peak Shaving

The early produced 200 MW and 300 MW low-capacity units were mainly designed for the baseload condition, and the minimum power output at steady combustion in DPSW is only 60% to 70% of the rated power ($P_n$). Therefore, the peak shaving capacity is very limited and not suitable for frequent start/stop operations [22]. The later-developed 600 MW and 1000 MW high-capacity units come with a slightly better peak-shaving capability, and the minimum output power for steady combustion in DPSW could be reduced to 40% to 50% of $P_n$. In accordance with the “Implementation Rules for the Management of Auxiliary Services for Grid-Connected Power Plants in North China”, the basic peak-shaving standard for units directly managed by grid operators is 50% of $P_n$, which means that the existing 600 MW and 1000 MW coal-fired units also have reached the practical operation limit during DPSW. However, if the combustion-supporting systems are installed, the minimum output power for steady combustion could be further brought down to 30% to 35% of $P_n$.

Based on the power generation characteristics for different load levels, the peak shaving procedure could be divided into three periods: RPS, DPSW, and DPSC as shown in figure 1, where $P_{\text{max}}$ is the maximum or rated output power; $P_a$ is the minimum power output in RPS period; $P_b$ and $P_c$ are, respectively, the minimum power output for steady combustion in DPSW and DPSC.

For the most part, the coal-fired units normally run in the RPS period with a comfortable operation condition, and the wear-and-tear loss is negligible. While in the DPSW and DPSC periods, the coal-fired unit is operated at a low-load condition with various operational risks and losses resulting, and its deep peak shaving capacity depends on several factors such as the combustion stability of boiler, safety of hydrodynamic work conditions (SHWC), boiler auxiliary machine parameters, and operators’ technical level, etc. [23,24].
Figure 1. Schematic diagram of peak shaving stages of coal-fired units.

(1) Combustion stability of boiler as the most key factor is closely relevant to the metal fatigue pressure, coal quality, fineness and concentration of coal powder, hot wind speed, and temperature, etc. Generally, when output is lower than $P_a$, the combustion conditions become worse, which is prone to cause accidents to coal-fired units because of flame failures;

(2) SHWC cannot be ignored when the boiler is running at a low load level. When loads change rapidly, the growing thermal deviation of the circulating pipeline on the water-cooled wall will reduce the circulation flow speed, and further results in boiler circulation stagnation or reversion. The test shows that when the flow speed falls below the critical value at 30% $P_n$, the SHWC cannot be guaranteed;

(3) Boiler auxiliary machines, such as the coal pulverizing system, water pumps, and fans, are the auxiliary facilities for combustion. On account of boilers’ large inertia, the coal pulverizing system is apt to blocking coals or suspending pulverizations while the boiler is running at low load level. Since the plasma ignition system must operate simultaneously with the coal pulverizing system and the ignition in DPSC is with a high furnace temperature, if there is too much coal powder in the furnace to be ignited timely, the accumulation of coal powder inside the furnace may cause deflagration. The expansion of flue gas from deflagration raises the furnace pressure suddenly and may further lead to the boiler explosion. Since the compressed air supply for the plasma burner contains water and oil, it may induce arcing failure or fire in the barrel of plasma igniter. Meanwhile, the probability of the pump and the fan failure is greatly raised;

(4) During the low-load level operation, the monitoring, protection, and control systems may frequently alert warnings because the boiler with its auxiliary machines is operating near a critical stable point. Operators should timely and agilely deal with alarm signals and ensure the stable combustion of boilers for preventing grievous boiler explosion, which may cause economic losses and casualties.

3. Peak-Shaving Costs and Economic Dispatch Model

3.1. Modeling Peak-Shaving Costs

The peak-shaving costs mainly include four sub-items: The coal consumption cost, wear-and-tear cost, combustion-supporting cost, and environmental cost. Detailed descriptions of these four parts are given below.

3.1.1. Coal Consumption Cost

The coal consumption cost of unit $i$ during period $t$ is characterized by a quadratic function given as follows [25].

$$f_i(P_{ct}) = \left(aP_{ct}^2 + bP_{ct} + c\right)$$  \hspace{1cm} (1)

where $a$, $b$, and $c$ are the coefficients determined experimentally by the generator producers.

3.1.2. Wear-and-Tear Cost
In DPSW and DPSC periods, substantially low-level power output result in the very large axial thermal stress on turbines, which will cause low-cycle fatigue life loss and creep loss due to the long-term exposure of metal parts in a high temperature [26]. We consider the turbine wear-and-tear cost in terms of the low-cycle fatigue life loss and creep loss. For low-cycle fatigue life loss, the temperature field and stress field of turbines are simulated to obtain the axial thermal stress $\sigma_{eq}$ [27], and the total strain range of turbines $\Delta \varepsilon$ is obtained by

$$\Delta \varepsilon = \frac{(1 + \mu)\sigma_{eq}}{1.5M}$$  \hspace{1cm} (2)

where $\mu$ is a Poisson’s ratio, $\mu = 0.3; M$ is the elastic modulus, and $M = 172.8 \times 10^3$ MPa. Then, the Manson–Coffin Equation (3) is used to implicitly derive the number of cycles to failure $N(P_{it})$.

$$\Delta \varepsilon = A\left[2N\left(P_{it}^d\right)\right] + B\left[2N\left(P_{it}^e\right)\right]$$  \hspace{1cm} (3)

where $d$ is the fatigue strength index; $e$ is the fatigue ductility index. As suggested in [28], the constant parameters are settled as $A = 0.00332, d = -0.06974, B = 0.6264,$ and $e = -0.7553$. Afterward, the low-cycle fatigue life loss is calculated as

$$q_1 = \frac{1}{2N(P_{it})^\tau}$$  \hspace{1cm} (4)

where in the later section, $\tau_1$ is used for DPSW period, $\tau_2$ for DPSC period, and $\tau_2 > \tau_1$.

For creep loss, Larson–Miller Equation (5) is used to calculate creep time $t_{ul}$

$$L(\sigma_{eq}) = 10^{-3} G \left[C + \lg(t_{ul})\right]$$  \hspace{1cm} (5)

where $L(\sigma_{eq})$ is a Larson–Miller parameter [29]; $G$ is the operating temperature (°C); $C$ is a material constant value; and $C = 20$. With regard to $t_{ul}$ in Equation (5), the creep loss rate $q_2$ is obtained as Equation (6).

$$q_2 = \frac{1}{t_{ul}}$$  \hspace{1cm} (6)

Finally, the linear cumulative damage theory is used to calculate the total wear-and-tear cost as

$$W_{cost}\left(P_{it}\right) = (q_1 + q_2)S_{unit}$$  \hspace{1cm} (7)

where $S_{unit}$ is the purchase price of coal-fired units.

3.1.3. Combustion Supporting Cost

During the DPSC period, the combustion stability and SHWC are rapidly decreased, and combustion supporting is required to ensure safe operation of the boiler. The combustion supporting cost of UOI (oil cost) is
while the combustion supporting cost of UPI (plasma ignition cost) consists of electricity fee of a burner and the anode-cathode cost.

\[ W_{i,j}^{pla} = P_{i,j}^b S_e + W_{i,j}^{a-c} \]  

where \( P_{i,j}^b \) includes the power consumption of igniter and air compressor.

### 3.1.4. Environmental Cost

Environmental pollution is also serious in the DPSC period. On the one hand, the desulfurization efficiency is decreased while the sulfur content of pollutants increased; on the other hand, the emission of NOx will be raised during low load level. Thermal power plants may be fined for excessive emissions of pollutants, and the corresponding environmental cost of UPI could be described as

\[ W_{i,j}^{env-p} = 1.6 \times 10^6 f_i(P_{i,j}) \delta_i \Delta \eta_i W_s \left[ 1.63 \times 10^6 \delta_N \Delta \eta_N + 1530 \right] f_i(P_{i,j}) W_N. \]  

For UOI, oil injection will bring oil pollutant and the UOI environmental cost is

\[ W_{i,j}^{env-o} = 1.6 \times 10^6 f_i(P_{i,j}) \delta_i \Delta \eta_i + 2 \times 10^6 \alpha_i \right] W_s + \left[ 1.63 \times 10^6 \delta_N \Delta \eta_N + 1530 \right] W_N \left[ f_i(P_{i,j}) + \alpha_i \right]. \]  

Based on the four parts of costs analyzed above, the total peak-shaving costs of coal-fired units with UPI can be piece-wisely represented as Equation (12). In RPS, the coal consumption cost accounts for the main part; in DPSW period, the peak-shaving costs are composed of the coal consumption cost and the wear-and-tear cost; while in DPSC period, the combustion supporting cost and the environmental cost should be extra considered in the peak-shaving costs.

\[
F_i(P_{i,j}) = \begin{cases} 
  f_i(P_{i,j}) & P_a < P_{i,j} \leq P_{max} \\
  f_i(P_{i,j}) + W_{cost}(P_{i,j}) & P_a < P_{i,j} \leq P_a \\
  f_i(P_{i,j}) + W_{cost}(P_{i,j}) + W_{i,j}^{pla} & P_a < P_{i,j} \leq P_b \\
  f_i(P_{i,j}) + W_{cost}(P_{i,j}) + W_{i,j}^{env-p} & P_a < P_{i,j} \leq P_b \\
  f_i(P_{i,j}) + W_{cost}(P_{i,j}) + W_{i,j}^{env-o} & P_a < P_{i,j} \leq P_b \\
\end{cases}
\]  

The peak-shaving costs model of coal-fired units with UOI can be similarly summarized for the RPS, DPSW, and DPSC periods, respectively, as Equation (13).

\[
F_i(P_{i,j}) = \begin{cases} 
  f_i(P_{i,j}) & P_a < P_{i,j} \leq P_{max} \\
  f_i(P_{i,j}) + W_{cost}(P_{i,j}) & P_a < P_{i,j} \leq P_a \\
  f_i(P_{i,j}) + W_{cost}(P_{i,j}) + W_{i,j}^{oil} & P_a < P_{i,j} \leq P_b \\
  f_i(P_{i,j}) + W_{cost}(P_{i,j}) + W_{i,j}^{env-o} & P_a < P_{i,j} \leq P_b \\
\end{cases}
\]  

According to formulas (12) and (13), the peak-shaving costs of coal-fired units with UOI and UPI could be visually shown in figure 2.
Although the start/stop cost is not considered in the peak-shaving, it is used to calculate the marginal price $V_m$ of coal-fired units for evaluating its operation economy.

$$V_m = \frac{\sum_{i=1}^{T} \sum_{j=1}^{N} F_i(P_{i,j}) + \sum_{i=1}^{T} \sum_{j=1}^{N} \left[ U_{i,j} \left(1 - U_{i,j-1}\right) S_{up} + U_{i,j-1} \left(1 - U_{i,j}\right) S_{down}\right]}{E_c}$$ \hspace{1cm} (14)

where $U_{i,j} = 0$ for the OFF state and $U_{i,j} = 1$ for the ON state.

3.2. Prioritized Dispatch Model of Integrated Wind Power

Considering the peak-shaving costs function above, the economic dispatch model with consideration of wind power integration is established to minimize the summation of the peak-shaving costs, the start/stop cost, and the penalty of curtailed wind power generation as Equation (15).

$$\min \sum_{i=1}^{T} \sum_{j=1}^{N} \left[ F_i(P_{i,j}) + U_{i,j} \left(1 - U_{i,j-1}\right) S_{up} + U_{i,j-1} \left(1 - U_{i,j}\right) S_{down}\right] + \theta \sum_{i=1}^{T} \left( P_{w,i}^{max} - P_{w,i} \right)$$ \hspace{1cm} (15)

The full set of constraints includes the power balance constraint, the unit power constraint, minimum ON-OFF time constraint, wind power output limits, and spinning reserve requirements, detailed as follows.
As the presented economic dispatch is a mixed-integer non-linear programming problem, it is solved by the self-modified branch-and-bound algorithm embedded with DICOPT solver of GAMS software[30].

### 3.3. Environmental Efficiency Index

Advocating energy conservation and emission reduction, China promised at the G20 summit that by 2030, the non-fossil resource will account for almost 20% of primary energy supply. As one of the main contributors to carbon emissions, power systems undertake the major energy conservation and emission reduction tasks. Therefore, we define an environmental efficiency index to evaluate the economy of coal-fired units participating in peak shaving from an environmental perspective. The energy consumption here includes the following two parts: (1) The amount of coal consumption \( Q_{\text{coal}} \) and oil consumption \( Q_{\text{oil}} \) for units operation, which can be converted into standard coal according to the method given in [31]; (2) the total amount of pollutants during power generation, which could also be quantified by converting the sewage charges \( Q_{\text{ev}} \) into the amount of standard coal. The economic benefits are expressed as the sum of electricity generated by wind power \( E_w \) and thermal power \( E_c \) during 24 h, and minus the penalty charges of curtailed wind. Based on the energy consumption and economic benefits, the environmental efficiency index is defined as the economic benefits over the energy consumption given by Equation (17).

\[
B_E = \frac{E_w + E_c - \theta \sum_{t=1}^{T} (P_{w,t}^D - P_{w,t})}{Q_{\text{coal}} + \alpha Q_{\text{oil}} + \beta Q_{\text{ev}}} \\
Q_{\text{ev}} = \frac{\sum_{t=1}^{T} \sum_{j=1}^{N} W_{ij}^\text{ev}}{S_{\text{coal}}}
\]

where \( W_{ij}^\text{ev} \) is counted by Equations (10) and (11). \( \alpha \) is the oil-coal conversion coefficient; \( \beta \) is the pollutant-coal conversion coefficient in terms of sewage charges. The typical value \( \alpha = 1.4571 \) and \( \beta = 0.011 \text{ kg/}$ are used in this paper.

The rate of wind utilization is:
\begin{equation}
R_{\text{wind}} = \left(1 - \frac{\sum_{i=1}^{T}(P_{\text{wt},i} - P_{\text{w,i}})}{\sum_{i=1}^{T}P_{\text{wt},i}}\right) \times 100\%.
\end{equation}

4. Case Study and Economic Analysis

4.1. Parameters Setting of Case Study

The simulation is conducted on a 24-hour day-ahead dispatch with 10 coal-fired units and wind power plants. The capacity of the thermal and wind power plant is, respectively, 1600 MW and 900 MW; namely, the wind power penetration rate is 36%. In China, thermal generator outputs are mainly determined by the day-ahead dispatch schedule with an hourly resolution, therefore the proposed peak-shave economic analysis of thermal units is also conducted accordingly on an hourly temporal interval. The coal-fired units data are given in Table A1 and A2 of Appendix [32], while the daily load level and wind power output are displayed in figure 3. Two cases are studied: In case 1, all coal-fired units are assumed UPI units, while in case 2, all are assumed UOI units. According to the typical oil and coal price, \( S_{\text{oil}} \) is 0.96 $/kg and \( S_{\text{coal}} \) is 0.1 $/kg in the following cases; \( \tau_1 \) is 1.2 and \( \tau_2 \) is 1.5[33]; \( P_{\text{ij}}^0 \) and \( W_{\text{ij}}^{x-e} \) are, respectively, 105 kW and 22 kW [34]; \( S_e \) is 0.03 $(/kWh); the type of coal in cases is coking coal with \( \delta_t \) and \( \delta_N \) are 0.53% and 0.58%, respectively; \( \alpha \) is 1.4571 and \( \beta \) is 0.011 kg/$, and \( W_t \) and \( W_N \) are, respectively, 100 $(/mg/m^3) and 125 $(/mg/m^3). Referring to the peak-shaving requirements in China, \( P_a, P_b, \) and \( P_c \) are, respectively, set to 50%, 45%, and 30% of rated power \( P_n \) for defining RPS, DPSW, and DPSC in figure 1.

![Figure 3. Daily load level and wind power prediction.](image)

4.2. Results of Economic Dispatch

The State Grid of China adheres to the principle of unified dispatch and hierarchical management, and the peak-shaving standards are not unique in different regions. Figure 4 is the wind power utilization of UPI and UOI at different peak-shaving levels. The result shows that UPI and UOI have the comparable peak shaving capability, because different combustion-supporting technology of UPI and UOI does not greatly influent the peak-shaving ability.
Figure 4. Wind power utilization of UPI and UOI.

Figure 5 and 6 show the power output of a 455 MW unit and an 80 MW unit of cases 1 and 2 at three representative peak-shaving levels as 45%, 55%, and 65%.

Figure 5. Power output of the 455 MW unit.

Figure 6. Power output of the 80 MW unit.
The operation states of the 455 MW unit and the 80 MW unit are quite different from each other when participating in peak shaving. In figure 5 the 455 MW unit in both cases keeps in ON state for 24 h, while in figure 6 the 80 MW unit only operates during peak-demand hours and in RPS and DPSW periods. This is because the start/stop cost of the 80 MW unit is much lower than that of the 455 MW unit; and for the 80 MW unit, it is more economical to be shut down than being operated in DPSW and DPSC mode during the off-peak hours. With increased levels of peak-shaving, both UPI and UOI are more frequently to engage in deep peak shaving. To fully exploit renewable resources, thermal power plants should be encouraged to actively engage in deep peak shaving. However, deep peak shaving will increase environmental pollution and influence the marginal price of coal-fired units. Therefore, the economy of deep peak shaving should be comprehensively evaluated from different perspectives, and comparative economic analysis of UPI and UOI should be investigated.

4.3. Multi-Angle Economic Analysis

4.3.1. Economy of Thermal Power Plants in Peak Shaving

Referring to the costs defined in Section 3, figure 7 and figure 8 separately illustrate the coal consumption cost, wear-and-tear cost, combustion supporting cost (oil cost and plasma ignition cost), and environmental cost of UPI and UOI per MWh at different peak shaving level and TABLE A3 and A4 give the sub-item cost ($). As peak-shaving level increases, the wear-and-tear cost, combustion supporting cost, environmental cost, and coal consumption cost of both UPI and UOI are raised. For combustion supporting cost, since UPI substitute the oil combustion by coal combustion in DPSC stages and the extra coal consumption cost is only one-third of the oil cost, the UPI has a much lower plasma ignition cost than the oil cost of UOI. Because the boiler combustion efficiency reduced with the load rate decreased, the coal consumption cost per MWh increased. For the coal consumption cost of UPI during DPSC, it is a little bit higher than that of UOI because of the extra coal consumption of UPI. Further, during the ignition, the electrostatic precipitation and desulfurization device can be put into use for UPI to greatly reduce the pollutant emission, and therefore the environmental cost of UPI is much lower than that of UOI.

![Figure 7. Sub-item costs of UPI.](image-url)
The marginal prices of coal-fired units in case 1 and case 2, as shown in Figure 9, increase significantly during DPSW and DPSC period. But the marginal price of case 1 is 3% or 5% lower than that of case 2 at the peak-shaving level at 55% or 65%, which indicates that the UPI in case 1 presents better economic benefits than UOI in case 2 during DPSW and DPSC period.

We further investigated the marginal price with consideration of peak shaving compensations. As specified by the “Implementation Rules for the Management of Auxiliary Services for Grid-Connected Power Plants in North China”, the reduced amount of electricity for the deep peak-shaving units will be compensated by the government (only for peak-shaving level deeper than 50%). The peak shaving compensation can be calculated as follows

\[ C_{\text{comp}} = (E_R - E_D) S_{\text{comp}} \] (19)

where \( E_R \) is the power generation under the condition all units do not engage in deep peak shaving; \( E_D \) is the power generation during DPSW and DPSC stages; \( S_{\text{comp}} \) is the compensation price and settled as \( S_{\text{comp}} = 37.2 \text{ $/(MWh)} \) according to [35]. Then, the marginal price with compensation could be refined as

\[ V'_a = V_a - \frac{C_{\text{comp}}}{E_c} \] (20)

When counting the compensation in, the refined marginal prices of UPI and UOI both drops about 3% and 4% during DPSW and DPSC. But for UPI in case 1, its marginal price at peak-shaving level of 55% and 65% is, respectively, 2% and 6% higher than that at the level of 45%. For UOI in case 2, its marginal price at the level of 55% and 65% is, respectively, 2% and 9% higher than that at the level of 45%, which means the monetary compensation for UPI and UOI cannot cover the increased generation cost of participating in deep peak shaving.
In recent years, in order to encourage coal-fired units to actively take part in deep peak shaving, China has continuously lifted the compensation price for the reduced power generation during the peak shaving process. Taking North China as an example, the Regional Regulatory Authority of The National Energy Administration first raised the compensation price from 7.44 $/(MWh) to 37.2 $/(MWh) in January 2017. Later, in December 2018, it released “Notice on Printing and Distributing the Operating Rules of North China Peak-shaving Service Market (Trial Version)”. In this notice, the price for peak-shaving service is offered by the service provider, and the service fee is shared by the party who benefits from peak-shaving services (wind power plants and PV power stations, for example). The notice stipulates that for a peak-shaving level of 30%–60%, the service price thermal power plants could offer ranges from 0 to 44.64 $/(MWh) during normal operation conditions, while for peak-shaving level deeper than 60%, the upper limit of service price is increased to 59.52 $/(MWh). For the case in this paper, the service revenue at the peak-shaving level of 65% will reduce the marginal price by 3% if the compensation price is counted by 59.52 $/(MWh), but it still cannot cover the increased peak-shaving costs of UPI and UOI. It is clear that the operation economy of both UPI and UPI is reduced in deep peak shaving, even if the compensation for peak shaving is taken into account. Hence, thermal power plants will not involve in deep peak shaving on their own initiative in this case. In the future, only if the peak-shaving costs of retrofitted coal-fired units are further reduced, thermal power plants may participate in deep peak shaving actively.

Then, we take UPI as an example to study how the marginal price of coal-fired units would change at different wind power penetration levels. The wind power penetration rate is 36% in case 1 and we add two cases, respectively, with 533 MW and 1067 MW wind capacity, which correspond to 25% and 45% wind penetration, respectively; the marginal price of units at 25%, 36%, and 45% wind power penetration is shown in figure 10, where the dotted and solid lines respectively represent the marginal price with and without peak-shaving compensation (if compensated, the revenue price is 37.2 $/(MWh). Figure 10 indicates that the marginal price will be reduced as the wind power penetration decreases. At 25% wind penetration, the marginal price of 65% peak-shaving level increases only by 6% compared to that of 45% peak-shaving level and if the compensation is considered, the marginal price of DPSW and DPSC period is basically the same as that of RPS period. At low wind penetration level, the peak-shaving demand is relatively small, and the peak-shaving costs of UPI is correspondingly reduced.
4.3.2. Benefit of Wind Power Plants in Peak Shaving

The cost of wind power in China has been continuously reduced in the last few years. Onshore wind power feed-in tariffs are trimmed to 0.067 $/(kWh) in 2018 and the generation cost is 0.061 $/(kWh), so the net revenue of wind power plants is 0.006 $/(kWh). The purchase price of wind power is consistent with the thermal power feed-in tariff in China, and the difference is subsidized by the state government. Based on the cases and operating strategy in Section 0 for all UPI and UOI participating in deep peak shaving, figure 11 indicates the relationship of wind power utilization and wind power revenue with regard to the peak-shaving level under condition of 36% wind power penetration. It is clear that the revenue is positively related to peak-shaving levels, so wind power plants are the direct gainers in deep peak shaving programs. If the peak-shaving service market is established, wind power plants would be required to pay peak-shaving service fees, which will undoubtedly reduce their revenue. To ensure the benefits, it is necessary for wind power plants to further cut down the power generation cost, or on the other hand, they may take initiative to curtail wind power.

![Figure 11. Wind power utilization and revenue of wind power plants.](chart)

Then, we consider the wind power utilization for coal-fired units with three different operating strategies as follows: (a) All UPI have to participate in deep peak shaving; (b) units with capacity larger than 100 MW participate in deep peak shaving, while capacity less than 100 MW can only participate in peak shaving of RPS stage; (c) units with capacity larger than 400 MW take part in deep...
peak shaving, while less than 400 MW can only participate in RPS stage. The results of these three operating strategies are shown in figure 12.

**Figure 12.** Wind power utilization in different operating strategies.

Figure 12 indicates that the units with smaller capacity have a greater impact on wind power utilization at the peak-shaving level of 55% and 60%, especially at the level of 55%. The wind power utilization at the peak-shaving level of 65% does not change much among three operating strategies; this means that the units with capacity more than 400 MW mainly undertake the peak-shaving task under that level. Hence, the peak-shaving effect of units with relatively larger capacity is more obvious at the high peak-shaving level. Figure 12 also shows a tendency where the more units engage in deep peak shaving, the higher the wind power utilization and the more revenue wind power plants will gain.

### 4.3.3. Environmental Efficiency in Peak Shaving

Figure 13 indicates the environmental efficiency of UPI and UOI at different peak-shaving levels. It shows that both the environmental efficiencies of UPI and UOI grow monotonically with increased peak shaving levels during RPS and DPSW. For UOI, the environmental efficiency reaches the optimal point around at the peak-shaving level of 55%, and then in DPSC period, it drops significantly. That is because the oil injection of UOI has a negative effect on environmental efficiency and increases oil consumption cost. For UPI, the environmental efficiency is notably improved in DPSC period and reaches the optimal point at the peak-shaving level of 65%. Since UPI at that peak shaving level could effectively reduce wind curtailment with relatively low coal consumption, UPI is much more environmentally friendly in DPSC period. Comparing UPI with UOI at the peak-shaving level of 65%, the environmental efficiency of UPI improves by 3% and shows better environmental benefits than UOI. That means from an environmental perspective, UPI is more apt to operate at deeper peak-shaving levels than UOI.
5. Conclusions

In this paper, a peak-shaving cost function is first proposed for UPI and UOI during RPS, DPSW, and DPSC periods. Afterwards, the peak-shaving cost-based economic dispatch model with consideration of curtailed wind penalty is proposed for the multi-angle economic analysis of UPI and UOI in deep peak shaving. Simulation results of a 10-unit system demonstrate that (1) UPI has better peak-shaving economics and environmental efficiency than UOI, and is also more apt to operate at deeper peak-shaving levels than UOI; (2) the economics of both UPI and UOI are reduced during deep peak shaving in our cases, though the price compensation is taken into account; (3) the wind energy utilization rate could be influenced by the operating strategy of thermal power plants; (4) in DPSW period, the peak-shaving ability of coal-fired units with relatively small capacity has greater impact on wind power utilization, while in DPSC, it relies more on the peak-shaving ability of units with relatively larger capacity.

Considering China is continuously adjusting the subsidy standards for coal-fired units engaging in deep peak shaving and the peak-shaving performance of UPI and UOI with flexibility retrofits may be further enhanced, the benefits of thermal power plants, wind power plants, and the social environmental efficiency would change and needs to be updated under new conditions in the future. As wind variability and prediction error could affect the economy of thermal power plants and wind power plants, establishing a probabilistic optimization model to consider the wind variability for the peak shaving economic analysis is also worthy of further study.

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Nomenclature

A. Acronyms

UPI  Coal-fired Unit with Plasma Ignition
UOI  Coal-fired Unit with Oil Injection
RPS  Regular Peak Shaving
DPSW Deep Peak Shaving Without combustion supporting
DPSC Deep Peak Shaving with Combustion supporting
SHWC Safety of Hydrodynamic Work Conditions

B. Indices and Sets

$i, N$ Index and total number of coal-fired units
$j$ Index for power-flow interface
$t, T$ Index and total number of time interval
$k, \Omega_j$ Index and Set of tie line in power-flow interface $j$

C. Parameters

$a, b$ and $c$ Coefficient of coal consumption cost
$\tau$ Coefficient of low-cycle fatigue life
$P_{b_{i,j}}$ Operating power of the burner
$W_{a-c_{i,t}}$ Anode- cathode cost of unit $i$ during period $t$
$\delta_{i} , \delta_{N}$ Sulfur content and nitrogen content of the coal
$W_{s}, W_{N}$ Charge for SO2 and NOX emissions
$\alpha, \beta$ Oil-coal conversion coefficient and pollutant-coal conversion coefficient
$\theta$ Penalty coefficient of wind power curtailment
$S_{oil}, S_{coal}$ Oil price and coal price
$S_e$ Electricity price of power plants;
$S_{iup}, S_{idown}$ Shut-up and shut-down cost of unit $i$
$P_{pr_{w,t}}$ Predicted wind power output at time period $t$
$P_{i_{min}}, P_{i_{max}}$ Minimum and maximum output of unit $i$
$P_{S_{max}, j}$ Maximum active power transmitted by interface $j$
$T_{i_{on}}, T_{i_{off}}$ Minimum continuous ON/ OFF state of unit $i$
$\alpha_{i_{up}}, \alpha_{i_{down}}$ Ramping up and down limits of unit $i$
$\alpha_{i_{start}}, \alpha_{i_{shut}}$ Start-up and shut-down power limits of unit $i$
\( P_{it}^U , P_{it}^D \) Maximum and minimum output of unit \( i \) at time period \( t \)

\( R_{sw,t}, R_{sh,t} \) Upper and lower reserve requirements

D. Variables

\( P_{it} \) Power output of unit \( i \) during period \( t \)

\( N(P_{it}) \) Number of cycles of failure

\( o_{it} \) Oil consumption of unit \( i \) during period \( t \)

\( \Delta \eta_{i} , \Delta \eta_{N} \) Desulfurization and denitrification efficiency

\( E_{c} \) Sum of electricity generated by coal-fired units during \( T \) time intervals;

\( U_{it} \) ON-OFF state variable of unit \( i \) during period \( t \)

\( P_{it} \) Dispatched wind power output at time period \( t \)

\( P_{kij} \) Active power transmitted by tie line \( k \) in interface \( j \)

\( T_{on}^{it-i-1}, T_{off}^{it-i} \) The continuously On and OFF hours of unit \( i \) on time period \( t \).

D. Functions

\( F_i(P_{it}) \) Peak shaving cost function of unit \( i \)

Appendix

Table A1. Generation cost parameters of coal-fired units.

| Unit Number | \( a \) ($/\text{MWh}^2$) | \( b \) ($/\text{MWh}$) | \( c \) ($) | \( P_{n} \) (MW) | \( S_{\text{up}} \) ($) | \( S_{\text{down}} \) ($) | \( P_{Fe} \) (MW) | \( P_{fL} \) (MW) | \( P_{c} \) (MW) |
|-------------|-----------------|-----------------|------|--------------|---------------|-----------------|-------------|-------------|-------------|
| U 1         | 0.00048         | 16.19           | 1000 | 455          | 4500          | 4500            | 227.5       | 204.75      | 136.5       |
| U 2         | 0.00031         | 17.26           | 970  | 455          | 5000          | 5000            | 227.5       | 204.75      | 136.5       |
| U 3         | 0.002           | 16.6            | 700  | 130          | 550           | 550             | 65          | 58.5        | 39          |
| U 4         | 0.00211         | 16.5            | 680  | 130          | 560           | 560             | 65          | 58.5        | 39          |
| U 5         | 0.00398         | 19.7            | 450  | 162          | 900           | 900             | 81          | 72.9        | 48.6        |
| U 6         | 0.00712         | 22.26           | 370  | 80           | 170           | 170             | 40          | 36          | 24          |
| U 7         | 0.00079         | 27.74           | 480  | 85           | 260           | 260             | 42.5        | 38.25       | 25.5        |
| U 8         | 0.00413         | 25.92           | 660  | 55           | 30            | 30              | 27.5        | 24.75       | 16.5        |
| U 9         | 0.00222         | 27.27           | 665  | 55           | 30            | 30              | 27.5        | 24.75       | 16.5        |
| U 10        | 0.00173         | 27.79           | 670  | 55           | 30            | 30              | 27.5        | 24.75       | 16.5        |
Table A2. Hourly oil consumption of UOI during deep peak shaving with combustion supporting (DPSC).

| Unit number | U 1 | U 2 | U 3 | U 4 | U 5 | U 6 | U 7 | U 8 | U 9 | U 10 |
|-------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|------|
| Oil consumption (kg/h) | 3800 | 3800 | 2300 | 2300 | 2500 | 1200 | 1500 | 800 | 800 | 800 |

Table A3. Costs of UPI.

| Level of peak shaving | 45% | 50% | 55% | 60% | 65% |
|-----------------------|-----|-----|-----|-----|-----|
| Electricity by UOI (MWh) | 15,148.1 | 15,084.9 | 14,980.3 | 14,912.3 | 14,841.05 |
| Coal consumption cost ($) | 414,834.29 | 412,561.35 | 410,463.23 | 411,528.41 | 411,943.71 |
| Wear-and-tear cost ($) | 0 | 0 | 22,531.16 | 28,463.56 | 36,338.79 |
| Plasma ignition cost ($) | 0 | 0 | 0 | 2429.20 | 3572.76 |
| Environmental cost ($) | 0 | 0 | 0 | 3777.22 | 4043.96 |

Table A4. Costs of UOI.

| Level of peak shaving | 45% | 50% | 55% | 60% | 65% |
|-----------------------|-----|-----|-----|-----|-----|
| Electricity by UOI (MWh) | 15,148.1 | 15,057.4 | 14,980.3 | 14,912.3 | 14,841.05 |
| Coal consumption cost ($) | 414,927.87 | 412,558.27 | 410,463.34 | 409,351.93 | 408,229.01 |
| Wear-and-tear cost ($) | 0 | 0 | 22,513.16 | 27,842.38 | 34,180.82 |
| Oil cost ($) | 0 | 0 | 0 | 13,110 | 13,110 |
| Environmental cost ($) | 0 | 0 | 0 | 8713.33 | 9148.67 |

References

1. Lin, L.; Cai, X.; Xu, B.; Xia, S. Wind Farm-LA Coordinated Operation Mode and Dispatch Model in Wind Power Accommodation Promotion. Energies 2018, 11, 1227.
2. Anastasiadis, A.G.; Vokas, G.A.; Konstantinopoulos, S.A.; Kondylis, G.P.; Khalil, T.; Polyzakis, A.; Tsatsakis, K. Wind Generation and Electric Vehicles coordination in Microgrids for Peak Shaving purposes. Energy Procedia 2017, 119, 407–416.
3. Huang, Y.; Liu, B.Z.; Wang, K.Y.; Ai, X. Joint Planning of Energy Storage and Transmission Network Considering Wind Power Accommodation Capability. Power Syst. Technol. 2018, 42, 1480–1489.
4. Yin, S.; Zhang, S.; Andrews-Speed, P.; Li, W. Economic and environmental effects of peak regulation using coal-fired power for the priority dispatch of wind power in China. J. Clean. Prod. 2017, 162, 361–370.
5. Bertsch, J.; Growitsch, C.; Lorenzczik, S.; Nagl, S. Flexibility in Europe’s power sector — An additional requirement or an automatic complement? Energy Econ. 2016, 53, 118–131.
6. Prasatsap, U.; Kiravittaya, S.; Polprasert, J. Determination of Optimal Energy Storage System for Peak Shaving to Reduce Electricity Cost in a University. Energy Procedia 2017, 138, 967–972.
7. Kang, B.O.; Lee, M.; Kim, Y.; Jung, J. Economic analysis of a customer-installed energy storage system for both self-saving operation and demand response program participation in South Korea. Renew. Sustain. Energy Rev. 2018, 94, 69–83.
8. Pimm, A.J.; Cockerill, T.T.; Taylor, P.G. The potential for peak shaving on low voltage distribution networks using electricity storage. *J. Energy Storage* 2018, *16*, 231–242.
9. NEA. *The National Energy Administration of PRC Releases 2018 National Power Industry Statistics; NEA: Beijing, China, 2019.*
10. Xue, Y.; Ge, Z.; Yang, L.; Du, X. Peak shaving performance of coal-fired power generating unit integrated with multi-effect distillation seawater desalination. *Appl. Energy* 2019, *250*, 175–184.
11. Simla, T.; Stanek, W.; Czarnowska, L. Thermo-Ecological Cost of Electricity Generated in Wind Turbine Systems. *J. Energy Resour. Technol.* 2018, *141*, 031201.
12. Hetzer, J.; Yu, D.C.; Bhattacharai, K. An Economic Dispatch Model Incorporating Wind Power. *IEEE Trans. Energy Convers.* 2008, *23*, 603–611.
13. Andervazh, M.; Javadi, S. Emission-economic dispatch of thermal power generation units in the presence of hybrid electric vehicles and correlated wind power plants. *IET Gener. Transm. Distrib.* 2017, *11*, 2232–2243.
14. Wulandhari, L.A.; Komsiyah, S.; Wicaksono, W. Bat Algorithm Implementation on Economic Dispatch Optimization Problem. *Procedia Comput. Sci.* 2018, *135*, 275–282.
15. Yang, Y.; Qin, C.; Zeng, Y.; Wang, C. Interval Optimization-Based Unit Commitment for Deep Peak Regulation of Thermal Units. *Energies* 2019, *12*, 922.
16. Wang, J.; Wang, R.; Zhu, Y.; Li, J. Life cycle assessment and environmental cost accounting of coal-fired power generation in China. *Energy Policy* 2018, *115*, 374–384.
17. Turconi, R.; O’Dwyer, C.; Flynn, D.; Astrup, T. Emissions from cycling of thermal power plants in electricity systems with high penetration of wind power: Life cycle assessment for Ireland. *Appl. Energy* 2014, *131*, 1–8.
18. Oates, D.L.; Jaramillo, P. Production cost and air emissions impacts of coal cycling in power systems with large-scale wind penetration. *Environ. Res. Lett.* 2013, *8*, 024022.
19. Arriagada, E.; Lopez, E.; Lopez, M.; Blasco-Gimenez, R.; Roa, C.; Poloujadoff, M. A probabilistic economic dispatch model and methodology considering renewable energy, demand and generator uncertainties. *Electr. Power Syst. Res.* 2015, *121*, 325–332.
20. Weng, Z.; Shi, L.; Xu, Z. Power System Dynamic Economic Dispatch Incorporating Wind Power Cost. *Proc. CSEE* 2014, *34*, 514–523.
21. Plathottam, S.J.; Salehfar, H. Unbiased economic dispatch in control areas with conventional and renewable generation sources. *Electr. Power Syst. Res.* 2015, *119*, 313–321.
22. Niu, Y.; Du, M.; Ge, W.; Luo, H.; Zhou, G. A dynamic nonlinear model for a once-through boiler-turbine unit in low load. *Appl. Therm. Eng.* 2019, *161*, 113880.
23. Pawlak-Kruczek, H.; Niedziwiecki, L.; Ostrycharczyk, M.; Czerep, M.; Plutecki, Z. Potential and methods for increasing the flexibility and efficiency of the lignite fired power unit, using integrated lignite drying. *Energy* 2019, *181*, 1142–1151.
24. Prause, J.H.; Hübels, M.; Holtz, D.; Nocke, J.; Hassel, E. Local steam temperature imbalances of coal-fired boilers at very low load. *Energy Procedia* 2017, *120*, 439–446.
25. Gherbi, Y.A.; Bouzoubaa, H.; Gherbi, F.Z. The combined economic environmental dispatch using new hybrid metaheuristic. *Energy* 2016, *115*, 468–477.
26. Shibli, A.; Ford, J. Damage to Coal Power Plants due to Cyclic Operation. In *Coal Power Plant Materials and Life Assessment*; Shibli, A., ed.; Woodhead Publishing, Cambridge, UK: 2014; pp. 333–357.
27. Bian, S.; Li, W. Calculation of Thermal Stress and Fatigue Life of 1000 MW Steam Turbine Rotor. *Energy Power Eng.* 2013, *5*, 1484.
28. Zhang, W.; Hu, Y.-F. Study on Low Cycle Fatigue Loss of Turbine Rotor based on Finite Element Analysis. *J. Eng. Therm. Energy Power* 2018, *33*, 31–38.
29. Tamura, M.; Abe, F.; Shiba, K.; Sakasegawa, H.; Tanigawa, H. Larson-Miller Constant of Heat-Resistant Steel. *Mettall. Mater. Trans. A* 2013, *44*, 2645–2661.
30. Hemmecke, R.; Köppe, M.; Lee, J.; Weismantel, R. Nonlinear Integer Programming. In *50 Years of Integer Programming 1958–2008: From the Early Years to the State-of-the-Art*; Jünger, M., Liebling, T.M., Naddef, D., Nemhauser, G.L., Pulleyblank, W.R., Reินelt, G., Rinaldi, G., Wolsey, L.A., Eds.; Springer: Berlin/Heidelberg, Germany, 2010; pp. 561–618.
31. General principles for calculation of the comprehensive energy consumption. Beijing, China: National Development and Reform Commission. 2008.
32. Kazarlis, S.A.; Bakirtzis, A.G.; Petridis, V. A genetic algorithm solution to the unit commitment problem. *IEEE Trans. Power Syst.* **1996**, *11*, 83–92.

33. Lin, L.; Zou, L.; Zhou, P.; Tian, X. Multi-angle Economic Analysis on Deep Peak Regulation of Thermal Power Units with Large-scale Wind Power Integration. *Autom. Electr. Power Syst.* **2017**, *41*, 21–27.

34. Xia, S.; Jianhua, W.; Dingzhong, H. Benefit evaluation for boiler with application of plasma ignition. *J. Shanghai Electr. Power* **2003**, *3*, 270–271.

35. National Energy Administration. *Notice of the North China Energy Regulatory Bureau on Printing and Distributing the “Two Rules” for the Grid-Connected Power Plants in North China (Revised 2019)*; Beijing, China, 2019.

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