Analysis on Peak-shaving Energy Efficiency of Thermal Power Plant with High Temperature Thermal Energy Storage

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Abstract. Integration of energy storage infrastructures into electrical grids represents a crucial milestone in the transition towards energy systems with high penetration of renewables. However, the high cost of the currently available technologies is a significant barrier for their implementation on the industrial scale. High temperature thermal energy storage systems, in combination with bottom steam cycles, are being investigated as potential cost effective alternatives to traditional large-scale energy storage technologies. In this study, by adding a high temperature heat storage device in the cold (hot) section of the reheating pipeline and taking the 300MW extraction steam turbine as the research object, it is concluded that the introduction of the high temperature heat storage device can improve the consumption of wind power and greatly reduce the power supply of the coal-fired unit. The coal consumption rate is analyzed. The ideas and methods for solving the energy consumption of the renewable energy and reducing the peak energy consumption are provided.

1. Introduction

Renewable energy sources (RES) such as wind and solar power are intermittent and unpredictable. At the same time, there is a strong time dependence on electricity demands in the electricity grid that does not necessarily correspond to RES power production. As the fraction of electricity production from renewable sources continues to grow, the need for energy storage to shift RES power production curves to match demand as part of the electricity grid becomes increasingly important[1]. Since August 2013, the State Grid Corporation has fully initiated the replacement of electric energy and actively advocated a new energy consumption model of ‘returning coal by electricity, replacing oil by electricity, and electricity from afar’[2]. Therefore, with the continuous improvement of China’s terminal energy consumption and the level of electrification, the proportion of electric energy into heat energy consumption will become larger and larger, and the connection between power system and thermal system will become closer.

In order to adjust the energy structure, reduce the consumption of fossil energy and pollutants, vigorously develop and utilize renewable energy, it is an important strategic demand in China in the near future improving the cleanliness of terminal energy consumption. According to the statistics of the National Energy Administration[3], In 2018, the area with a wind eliminating rate of more than 8% is Xinjiang (23% abandoned wind rate, 10.7 billion kW·h of abandoned wind power), Gansu (19% abandoned wind rate, abandoned Wind power 5.4 billion kW·h), Inner Mongolia (10% wind
abandonment, 7.2 billion kWh of wind power). The abandonment of wind power in the three provinces (districts) totaled 23.3 billion kWh, accounting for 84% of the national abandonment of wind power. Second, it has intensified the peak-shaving capacity of the power grid. In the future, with the further expansion of renewable energy development, the difference between the peak and valley of the power system will increase, and the problem of consumption will become more prominent. The problem of large-scale renewable energy consumption has become a bottleneck restricting the development and utilization of renewable energy, and it needs to be solved [1].

Insufficient peak-shaving capacity of the system is one of the main reasons leading to power cuts and abandonment [2]. The main area of wind power development in China is the “Three North” area (referring to the northeast, north China, and northwest). The power supply structure is dominated by coal-fired thermal power units, and the adjustment capability is poor. Moreover, the operation of the combined heat and power (CHP) unit in the heating season further reduces the adjustment capability, making the problem of abandoned wind more prominent. In the heating season, the cogeneration unit adopts the “heat-set” operation mode to meet the heat load demand, and the adjustment capability is greatly limited.

The contradiction of insufficient peak capacity is reduced, resulting in a large number of wind curtailment. In addition, a large number of wind farms are located at the end of the grid, and local load is insufficient and the outbound channel is limited, which is also an important cause of wind curtailment. The objective reason for the problem of renewable energy consumption is the imbalance of the distribution of landscape energy and terminal energy consumption in China. In space, China's wind energy, solar energy resources and regional energy demand are inversely distributed [3]; in time, wind power and photovoltaic power generation have strong intermittent and random fluctuations, and their inherent characteristics are difficult to match the load demand. The flexibility of the power system after scale access raises higher requirements [4].

In order to eliminate large-scale renewable energy, it is necessary to improve the energy-optimized configuration capability of the power system in a large space-time range. As an effective measure, energy storage has received extensive attention in recent years. Research shows that energy storage technology is a strategic supporting technology for the transformation of energy structure and the transformation of power production and consumption patterns in the future, which can solve the intermittent and random fluctuation of renewable energy power generation. The problem is to improve the peak-shaving capacity of the power system, respond to the sudden failure of the power grid, and meet the requirements of high-quality, safe and reliable power supply for economic and social development [5-11]. At present, the main research and application of energy storage technologies include pumped storage, compressed air energy storage, flywheel energy storage, redox flow battery energy storage, superconducting magnetic energy storage, and supercapacitor energy storage. However, in addition to the mature pumping and storage technology in large-capacity energy storage technology [12-13], other energy storage methods are mostly in the demonstration stage or even in the initial research stage in terms of scale, equipment form, technical level and economic cost. Many key technologies (such as large capacity, high efficiency, long life, low cost, high security, etc.) need to be broken [14-16]. Thermal energy storage provides an effective solution to the above problems.

To this end, based on the basic principle of high-temperature thermal storage in thermal power plants, this paper analyzes and models the thermal-electric operation characteristics of large-scale extraction units before and after high-temperature thermal energy storage, and discusses the flexibility of thermal-electric units after high-temperature thermal energy storage. Based on the operation mode, a mathematical model for calculating the peak load capacity increment was established, and the energy saving and emission reduction benefits of the 300MW thermal power unit through the configuration of the high temperature thermal energy storage device were analyzed.

2. Thermal-electric peak-shaving principle in thermal power plant
When designing a thermal power plant, it is usually designed in a ‘heat-set’ manner. Therefore, the power generation capacity of the cogeneration unit is determined according to the heat load. During
operation, the amount of power generation is adjusted according to the heat load demand. The insufficient part is replenished by the municipal power grid to ensure the combined supply of electric heat and heat, and the system is operated efficiently, but the peak-shaving ability of the unit is poor [16-17]. In order to ensure the heat load, the thermal motor unit follows the thermal load operation mode according to the electric load, and the thermal-electric motor group follows the thermal-electric characteristic diagram in Fig.1. It can be seen from Fig.1 that the maximum power generation load of the steam turbine decreases with the increase of the amount of heat supply steam. The minimum power generation load does not change with the increase of the heat supply steam flow rate, and then increases, and the power peak-shaving capacity of the unit decreases with the increase of the heat supply steam flow rate. Small, close to full load, the unit does not have the ability to peak power generation [18].

If thermal power plants with high-temperature thermal energy storage devices is added in the cogeneration system, the inertia and time constant of the thermal system can be further increased, and the controllability of the thermal system can be improved, and the electric load of the electric system can be converted into a controllable and adjustable thermal-electric system. The huge thermal load of the overall capacity better matches the output characteristics of renewable energy in the power system and the peak-shaving characteristics of the power system.

3. Thermal-electric system peak-shaving scheme with high-temperature thermal energy storage

In order to increase the wind power consumption capacity, the heat generating unit load must be reduced at night, that is, the heat supply steam extraction flow rate is reduced, so that the heat supply demand cannot be met, and thus the thermal storage must be supplemented. If the thermal energy storage device is added, the amount of steam is increased during the period when the heating demand is low during the day, and the excess heat is stored; at night, the thermal energy storage device is used to release heat, and the amount of heat extraction is reduced to reduce the amount of heat, so the thermal power unit could be reducing the valley load. In this paper, a high-temperature regenerative thermal-electric peak-shaving technology is designed, as shown in Fig.2 below. On one hand, the heat exchanger is used to absorb the heat of the heat extraction steam, and the heat transfer medium is used to transfer and store the heat in the high-temperature thermal energy storage device; on the other hand, the high-temperature thermal energy storage device for heating the high-pressure cylinder exhaust gas is used by abandoning wind or valley electricity. When the system is running, the grid load is in the flat load period from 7:00-10:00, 15:00-18:00 and 21:00-23:00 during the daytime, and the exhaust steam exceeding the heating demand is used for thermal energy storage. During the peak load period of 3:00-6:00 pm, the steam extraction capacity of the turbine was reduced and stabilized at 150 MW, and the thermal energy storage device began to release heat to make up for the heating demand at that time. As the amount of steam extraction decreases, the peak-shaving capacity of the turbine increases.

![Diagram of thermal-electricity relationship for extraction CHP unit](image-url)
In addition, the high temperature thermal energy storage device that is installed at the exhaust port of the high-pressure cylinder is put into operation for 8 hours, thereby increasing the consumption of renewable energy, saving the energy consumption of the whole society.

Adding a high temperature thermal energy storage device to the reheated steam cold (hot) section, the working principle is as follow:

In order to further reduce the wind, light and peak-to-valley difference, a heat exchanger, a high temperature thermal energy storage device and a circulation fan are added at the exhaust pipe of the high-pressure cylinder, wherein the high-temperature thermal energy storage device, the circulating fan and the low-temperature side of the heat exchanger pass through the pipe. The road connection is a closed circulation system, and the heat transfer medium is nitrogen. The high temperature thermal energy storage device can reach 1200 ℃ inside, and its normal storage heat temperature can reach 1000 ℃. The main purpose is to use abandoned wind and abandoned light power to store heat in the high-temperature thermal energy storage device, and if necessary, use some low-cost valley electricity. In the peak load period of the unit, the high-temperature thermal energy storage device is put into priority. At this time, the coal burning amount of the boiler can be reduced correspondingly, and the clean and efficient operation of the thermal-electric unit can be realized.

![Fig.2 Typical daily running curves of 300 MW extraction CHP unit](image)

4. Analysis of thermal-electric characteristics and peak-shaving capability of extraction unit with high temperature thermal energy storage

4.1 Configuring the thermal-electric characteristics of the extraction unit before high temperature thermal energy storage

The coupling relationship between the power generation power P of the thermal power unit and the external heating power h is generally called “electrical heating characteristic”, which can well reflect the operating characteristics of the tropical unit, and is therefore an effective way to analyze the flexible operation capability of the thermal power unit. Fig. 1 shows the thermal-electric characteristics of the extraction unit.

In the fig.1: $k_1$ is the corresponding value of $k$ under the maximum electric output; $k_2$ is the corresponding value of $k$ under the minimum electric output; the value of $k$ is the decrease of the
power generated by the unit heating heat when the steam inlet quantity is constant; \( k_a = \frac{\Delta P}{\Delta h} \) is the elastic coefficient of electric power and thermal power; \( h_0 \) is the constant; \( h_{T,max} \) is the maximum heating power of the extraction unit; \( h_a \) is the heating power of the turbine when the unit generates the minimum power; \( P_{max} \) and \( P_{min} \) are the maximum of the extraction unit in the pure condensing condition, Minimum power generation.

The thermal-electric characteristics of the above-mentioned extraction unit can be described as:

\[
\max \left\{ P_{min} - k_2 h, k_a \left( h - h_0 \right) \right\} \leq P \leq P_{max} - k_1 \\
0 \leq h \leq h_{T,max}
\]

(1) (2)

4.2 Analysis of peak-shaving capacity of thermal-electric unit after high temperature thermal energy storage

4.2.1 The peak-shaving capacity of the thermal-electric unit before the high temperature thermal energy storage is configured

The peak-shaving capacity of the unit is expressed by the difference between the maximum electric output of the unit during the peak load period of the day and the minimum electric output of the unit during the period of the electric load low period, to reflect the ability of the unit to track the fluctuation of the peak and valley of the electric load during the day.

According to Fig.1, \( h_p \) is the thermal load of the unit during the peak load period; \( h_t \) is the thermal load during the valley period of the electric load, \( P_p = P_{max} - k_1 h_p \) is the maximum power generated by the turbine during the peak load period; \( P_v = \max \left\{ \left( P_{min} - k_2 h_v \right), k_a \left( h_v - h_0 \right) \right\} \) is the minimum electric power during the valley load period. Therefore, \( C_0 = P_p - P_v \) is the 24-hour peak-shaving capacity of the unit.

4.2.2 Peak-shaving capacity of thermal-electric unit after high temperature thermal energy storage

Assume that the duration of the peak load, flat load and valley load of the unit within 24 hours is \( T_p \), \( T_f \) and \( T_v \) respectively.

The maximum thermal energy storage capacity of the thermal energy storage device during the flat load period can be calculated by:

\[
Q_{S,F} = \sum_{t \in T_f} \left( h_{T,max} - h^t_{d,F} \right)
\]

(3)

In which, \( h^t_{d,F} \) is the heat load at the time of the flat load period.

The maximum thermal energy storage of the thermal energy storage device during the peak load period is given by:

\[
Q_{S,P} = \sum_{t \in T_p} \left( h^t_{d,p} - \left( P_{max} - P^t_p \right) / k_1 \right)
\]

(4)

In which, \( h^t_{d,p} \) is the thermal load at the peak load period \( t \), and \( P^t_p \) is the electrical load at the peak load period \( t \).

The thermal energy storage device emits heat during the valley loading period:

\[
Q_{D,Y} = \sum_{t \in T_v} \left( h^t_{d,Y} - h_a \right)
\]

(5)
It can be seen from the above that in order to obtain the maximum peak-shaving capacity increment, the thermal energy storage tank needs to store heat during the flat load and the peak load period, and exotherm during the low valley period. Then, the thermal energy storage amount $Q_{ST}$ of the thermal energy storage device can be calculated by:

$$Q_{ST} = \max \{q_{P,P}, q_{S,P} + q_{S,F}\}$$  \hspace{1cm} (6)

At this time, the maximum average thermal energy storage power of the thermal energy storage device during the peak load and the load period is given by:

$$h_{S,P,F}^i = \max \{q_{S,P}, q_{S,P}\}$$  \hspace{1cm} (7)

To meet the low-temperature heat demand, the average thermal energy storage power required during peak hours is given by:

$$\bar{h}_{S,P}^i = Q_{S,P} / T_p$$  \hspace{1cm} (8)

The peak-shaving capacity for the corresponding spike period is given by:

$$\Delta C_p = -k_1 h_{S,P}^i$$  \hspace{1cm} (9)

To meet the heat load requirements during the trough, the maximum average radiative power required during the valley load period is given by:

$$h_{P,Y}^i = Q_{P,Y} / T_y$$  \hspace{1cm} (10)

The peak load capacity of the corresponding valley load period is given by:

$$\Delta C_y = k_2 h_{P,Y}^i$$  \hspace{1cm} (11)

The peak-shaving capacity increased in the day is given by:

$$\Delta C = k_2 h_{P,Y}^i - k_1 h_{S,P}^i$$  \hspace{1cm} (12)

Obviously, the daily peak-shaving capacity increase of the thermal-electric unit after the thermal energy storage is configured is given by:

$$C = C_0 + \Delta C$$  \hspace{1cm} (13)

### 5. Case analysis at a 300MW thermal power plant

The effect of thermal energy storage and peak-shaving capacity of a typical 300MW thermal power unit in northern China is analyzed. The selected unit type is C240/N300-16.7/538/538/0.4[19], and the electric heating operation of the unit before high temperature thermal energy storage is configured. The interval (TMCR operating conditions) is shown in Fig.1. According to the thermal-electric characteristics shown in Fig.1, the heat load power of the heating unit is estimated to be 287.8MW. It can be seen from Fig. 1 that the minimum electric output of the steam turbine is 210 MW and the maximum output is 256.9 MW. As the heat supply steam flow increases, the minimum power generation load does not change first, then increases. The minimum power generation load increases with the increase of the heat supply steam flow, and then increases. The peak-shaving capacity of power generation decreases with the increase of the flow rate of heat supply steam. When the load is close to full load, the unit does not have the ability to peak the electric generation. Therefore, its peak-shaving capacity in the day is 46.9MW, which is about 15.5% of the rated capacity. Take the peak and valley period in the day, as shown in Table 1 below[20].
Table 1 Price list of "stepped" compensation mechanism

| Load rate $\beta$ | The compensation price (¥/MW·h) |
|-------------------|---------------------------------|
| $55\% \leq \beta < 60\%$ | 0.4                              |
| $48\% \leq \beta < 55\%$ | 0.4 ~ 0.6                        |
| $\beta < 48\%$      | 0.6 ~ 0.8                        |

The typical daily operation curve of the thermal power plant is shown in Fig. 3. The average heating power is 336.3MW, the maximum heating power is 377.2MW, and the minimum heating power is 274.4MW. The heating load follows the user’s heating demand and fluctuates periodically. The highest heat load occurs at 3:00-7:00; the heat load during the day is low, and the lowest heat load occurs at 14:00-16:00. During the nighttime maximum heating load, the power generation of the unit’s peak capacity is only 32.8MW. At this time, it is the peak period of wind power load. At the same time, the power load of the grid at night is greatly reduced. The peak-shaving situation of the power grid is severe, and the wind and heat supply must be abandoned.

![Fig. 3 Typical daily heat load curve of 300 MW extraction CHP unit](image)

In order to obtain the maximum peak capacity increase, it is necessary to calculate the maximum heat release demand during the trough period to determine the capacity of the thermal energy storage device. In general, $k_x$ is usually greater than $k_1$, and $T_i$ and $T_p$ are similar. Therefore, the wind power receiving space obtained by using the thermal energy storage device $Q_{ST}$ of the thermal energy storage device for the valley period is larger than that for the peak period, so this paper is based on the typical heat load curve. The maximum heat release requirement required during the load period and the flat load period is to determine $Q_{ST}$. According to the model built in the paper, $h$ is 2288.77 MW(th). When the non-low valley load period is used for thermal energy storage, the average thermal energy storage power is 177 MW(th), which is equivalent to 679 GJ.

Through the thermal-electric system model established in this paper, the thermoflex software is used to carry out the example simulation analysis, and the following conclusions are obtained:

1) It can be seen from Fig. 4 that compared with the non-addition of high temperature thermal energy storage device, the thermal economy of the high temperature thermal energy storage type thermal power unit gradually decreases with the decrease of the thermal energy storage temperature.

2) When the high temperature thermal energy storage device is 1000 °C, the opening degree of the regulating valve is between 35% and 40%, and the thermal economy is in the optimal range. After the addition of the high temperature thermal energy storage device, the thermal efficiency of the whole plant is increased by 1% to 1.5% compared with the previous one, and the energy saving effect is obvious.
According to the above simulation analysis, when the heat storage temperature of the high-temperature heat storage device added to the reheat steam cold (hot) section reaches 1000 °C, the whole plant has the highest thermal efficiency, and the heat storage capacity can be determined. And the heat storage power is calculated with a peak load of 8 hours, the heat storage power is 64.86 MW (th), and the heat storage capacity is 518.90 MW•h (th). As can be seen from Figure 4, after the addition of the high-temperature heat storage device, under the rated load, the thermal efficiency of the plant increases from 39% to 40%. According to the coal consumption rate of 310g/(kW•h), the coal consumption rate of the corresponding power supply is reduced by about 7.9g/(kW•h), and the total peak hour period is 8h. Coal 18.96 t. The energy-saving and emission reduction of thermal power plants after the addition of high-temperature heat storage devices are shown in Table 2 below. The income is shown in Table 3 below.

### Table 2. Energy saving and emission reduction of high temperature heat storage thermal power unit

| Thermal energy storage capacity (MW•h) | Coal saving amount (t/day) | NOx emission reduction (t/day) | SO2 emission reduction (t/day) | CO2 emission reduction (t/day) |
|--------------------------------------|---------------------------|-------------------------------|-------------------------------|-------------------------------|
| 518.9                                | 18.92                     | 0.14                          | 0.16                          | 49.58                         |

### Table 3. High-temperature heat storage thermal power plant and wind farm revenue *

| Thermal power plant revenue (¥10K/day) | Wind farm revenue (¥10K/day) | Thermal power plant revenue (¥10K/year) | Wind farm revenue (¥10K/year) |
|---------------------------------------|-----------------------------|----------------------------------------|-------------------------------|
| -18.07                                | 19.20                       | -3011.67                               | 1676.00                       |

*1) The daily peak load period is calculated according to 8h; 2) The average power supply coal consumption is calculated as 310g/(kW•h); 3) The wind power online price is calculated as 0.40 yuan/(kW•h); 4) The peak load period thermal-electric unit is pressed Rated load operating condition meter; 5) The annual utilization hours of coal-fired power plants are calculated as 3500h; 6) The annual utilization hours of wind farms are calculated as 2095h.

### 6. Conclusions

1) This paper proposes to add a high-temperature heat storage device in the reheat steam cooling (heat) section of the thermal power unit. The example shows that the introduction of the heat storage device can improve the consumption of wind power, on the other hand, can greatly reduce the coal...
combustion rate of power supply. Thereby it could improve the energy system's large space-time range to optimize the allocation capacity.

2) The calculations show that under the current peak shaving auxiliary service compensation policy, it directly affects the marginal revenue of the high-temperature heat storage heat-generator, but has no significant impact on the annual income of the wind farm.

3) This paper does not consider the manufacturing, operation and maintenance costs of high-temperature heat storage devices, and the impact of the combination of high-temperature heat storage devices and thermal power units on the peak-shaving cost of the system needs further analysis, which will be the next research direction.

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References
[1] Stefano Soprani, Fabrizio Marongiu, Ludvig Christensen, et al. Design and testing of a horizontal rock bed for high temperature thermal energy storage. Applied Energy, 2019,251.
[2] State Grid Corporation. Electricity replacement scheme of state grid corporation [R]. China: State Grid Corporation,2013.
[3] National energy administration. [2019-01-28].http://www.nea.gov.cn/2019-01/28/c_137780779.htm
[4] State Electricity Regulatory Commission. Supervision report on wind power accommodation in key areas (No.10, 2012)[R]. Beijing : State Electricity Regulatory Commission, 2012.
[5] Liu Jinpeng. Development of the energy supply and demand pattern of China under the constrains of resource and environment [D].Beijing: North China Electric Power University, 2013.
[6] Zhang Hongyu. Reserve on wind power integration planning considering peak-shaving factors [D]. Beijing: China electric Power Research Institute, 2013
[7] Ann S B, Machtedl van den B, Ad S, et al. Impacts of large-scale intermittent renewable energy sources on electricity systems, and how these can be modeled[J].Renewable and Sustainable Energy Reviews, 2014(33):443-466.
[8] Yuan Xiaoming, Cheng Shijie, Wen Jingyu. Prospects analysis of energy storage application in grid integration of large scale wind power[J]. Automation of Electric Power Systems,2013,37(1):14-18.
[9] Bjarne S,Christoph W. Efficient storage capacity in power systems with thermal and renewable generation[J].Energy Economics, 2013(36):556-567.
[10] Rodica L. Power system flexibility with electricity storage technologies: A technical-economic assessment of a large-scale storage facility [J]. International Journal of Electrical Power & Energy Systems 2012,42(1):542-552.
[11] Madaeni S H, Sioshansi R, Denholm P. Estimating the capacity value of concentrating solar power plants with thermal energy storage: A case study of the southwestern united states[J]. IEEE Transactions on Power Systems,2013, 28(2):1205-1215.
[12] Ardizzon G, Cavazzini G, Pavesi G. A new generation of small hydro and pumped=hydro power plants: Advances and future challenges [J]. Renewable and Sustainable Energy Reviews, 2014(31):746-761.
[13] Helseth A , Gjelsvik A, Mo B, et al. A model for optimal scheduling of hydro thermal systems including pumped-storage and wind power [J]. Generation, Transmission & Distribution, IET,2013, 7(12):1426-1434.
[14] Diaz-Gonzalez F, Andreas S, Gomis-Bellmunt O, et al. A review of energy storage technologies
for wind power application[J]. Renewable and Sustainable Energy Reviews, 2012, 16(4): 2154-2171.

[15] Piergiorgio A, Massimo G, Federico M. Redox flow batteries for the storage of renewable energy: A review [J]. Renewable and Sustainable Energy Reviews, 2014(29): 325-335.

[16] XU Fei, MIN Yong, CHEN Lei, et al. Combined Electricity-heat Operation System Containing Large Capacity Thermal Energy Storage[J]. Proceedings of the CSEE, 2014, 34(29): 5063-5072.

[17] Liu Zhizhen. Cogeneration [M]. Beijing: China Electric Power Press, 2006.

[18] ANDERSEN T V. Integration of 50% wind power in a CHP-based power system: a model-based analysis of flexible power generation [D]. Denmark: Technical University of Denmark, 2009.

[19] BAI Zhonghua, MIAO Changhui, WANG Wen, et al. The value of thermal storage technology in integrated energy system [J]. Distribution & Utilization, 2019, 36(3): 20-26.

[20] LYU Quan, CHEN Tianyou, WANG Haixia, et al. Analysis on Peak-load Regulation Ability of Cogeneration Unit With Heat Accumulator[J]. Automation of Electric Power Systems, 2014(11): 34-41.

[21] Northeast Power Grid Co., Ltd.. Northeast China Power Grid "The 12th Five-Year Plan" [R]. Shenyang: Northeast Power Grid Co., Ltd., 2010.

[22] XU Fei, MIN Yong, CHEN Lei, et al. Combined Electricity-heat Operation System Containing Large Capacity Thermal Energy Storage. Proceedings of the CSEE, 2014, 34(29): 5063-5072.