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Selection of Technical Routes for Flexible Retrofit of Thermal Power Units Under the New-Type Power System

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Abstract: Against the background of new-type power system construction, large-scale grid-connection of wind and solar power creates prominent peak-shaving gaps in the power system. Constrained by the "power-determined-by-heat" principle, conventional combined heat and power (CHP) units have limited accommodation space for new energy. This paper sorts out six mainstream heat-power decoupling retrofit schemes, and elaborates the retrofit principles and equipment composition of each technology combined with system schematic diagrams and retrofit flow charts. Taking a 300 MW heating extraction-condensation unit as an engineering case, four typical retrofit technologies are selected, and comparative analysis on energy-saving and economic benefits is carried out through quantitative indicators. The results show that the composite coupling scheme of low-pressure cylinder zero-output plus hot-water heat storage delivers the best comprehensive benefits, and multi-technology collaborative retrofit represents the mainstream direction for unit flexibility upgrading. The research conclusions can provide data support and decision-making reference for technical-renovation demonstration and scheme argumentation of thermal power plants.

Keywords: New-type power system; Thermal power unit; Flexible retrofit; Heat-power decoupling; Deep peak shaving; Technology selection

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1. Introduction

Under the dual-carbon strategy, the installed capacity of wind and solar new energy in China keeps expanding. The randomness and volatility of new-energy output significantly increase the intraday peak-shaving pressure of power grids. As the basic support and back-up peak-shaving power sources of power grids, traditional coal-fired CHP units feature operating flexibility that directly determines the new-energy accommodation capacity of the system [1]. Conventional extraction-condensation CHP units are subject to rigid operating constraints of "power-determined-by-heat". During heating seasons, to guarantee heating stability for end heat users, units have to maintain the minimum through-flow power-generation load,

and cannot reduce output deeply for peak shaving when new-energy output drops, which constitutes one of the core causes for frequent wind and solar curtailment in regional power grids [2].

To resolve the contradiction between source-load mismatch and revitalize the regulating resources of existing coal-fired power units, the National Energy Administration keeps promoting special retrofits for flexibility improvement and heat-power decoupling of coal-fired power units. It clearly requires existing CHP units to break rigid heat-power coupling and enhance wide-load regulation capacity [3]. At present, six mature retrofit systems have been formed in China, including steam turbine body optimization, steam bypass heating, electric heating for peak shaving, heat storage, waste-heat recovery, and multi-technology collaborative coupling. Different technologies show remarkable differences in retrofit investment, peak-shaving depth, heating expansion capacity and operating energy consumption [4].

Existing studies mostly focus on the operating mechanism and performance tests of a single retrofit technology, or merely conduct one-dimensional economic analysis. There is a lack of horizontal quantitative comparison covering multi-technology routes under identical unit working conditions from both energy-saving and economic-benefit dimensions. Moreover, research on differentiated selection criteria for units under different scenarios is insufficient [5]. For this reason, this paper systematically sorts out the principles and construction procedures of various flexible retrofit technologies. Based on an engineering case of a typical 300 MW heating extraction-condensation unit, it quantitatively compares the energy-saving and economic benefits of four mainstream retrofit schemes, clarifies the applicable boundary of each technology, and summarizes the development trend of multi-technology coupling retrofit. It can provide references for scheme design and engineering implementation of flexibility technical renovation for similar thermal power units [6].

2. Operating mechanism and classification of various flexible retrofit technologies

Combined with retrofit engineering practices of mainstream 300 MW and 600 MW extraction-condensation units in China, existing heat-power decoupling and flexibility-improvement technologies can be classified into six categories. Each scheme has essential differences in equipment configuration, retrofit logic and regulation characteristics. Supporting system schematic diagrams and retrofit flow charts can intuitively reflect equipment layout and medium operation processes [7].

2.1. Steam turbine body optimization retrofit technology

Steam turbine body retrofit belongs to internal-potential-tapping renovation. Large-scale addition of external equipment is not required. It breaks heat-power coupling constraints by optimizing low-pressure cylinder operation modes or rotor structures, and mainly includes three processes: low-pressure cylinder zero-output isolation, low-pressure cylinder solid-shaft replacement, and high-back-pressure dual-rotor switching [8].

The low-pressure cylinder zero-output retrofit installs hydraulic fast-closing isolation valves on the intermediate-low-pressure connecting pipe. Under deep peak-shaving conditions, main steam inflow to the low-pressure cylinder is cut off. Only trace cooling steam is fed to carry away windage friction heat of the rotor and avoid excessive blade temperature and excessive vibration. Exhaust steam from the intermediate-pressure cylinder is fully used for external heating. Without reducing boiler evaporation capacity, the heating extraction steam volume is greatly increased and unit power-generation output is lowered, realizing deep load-reduction peak shaving of the unit [9].

The low-pressure cylinder solid-shaft retrofit is a permanent structural renovation. By removing the original bladed low-pressure rotor and replacing it with a non-working solid-shaft rotor, the power-generation capacity of the low-pressure cylinder is completely eliminated. Exhaust steam from the intermediate-pressure cylinder is maximally used for heating to fully release the heat-power decoupling potential of the unit, which is applicable to working conditions with high annual heating loads [10].

The high-back-pressure dual-rotor retrofit adopts seasonal switching operation modes. During heating seasons, the high-back-pressure rotor is installed to raise unit exhaust back-pressure, and waste low-temperature exhaust steam of the steam turbine is recovered for municipal heating. During non-heating seasons, it is switched back to the conventional rotor to restore the pure-condensation power-generation capacity of the unit, taking into account waste-heat efficiency improvement in winter and power-generation demands in summer [11].

2.2. Main-reheat-steam bypass heating retrofit

The steam bypass heating retrofit centers on expanding main-steam, cold-reheat-section bypass and temperature-reduction pressure-reduction systems, and belongs to a fast-decoupling emergency retrofit technology [12]. During grid-valley periods with abundant new-energy output, the boiler maintains stable combustion conditions. Part of high-temperature and high-pressure steam does not enter the steam turbine for work, and is directly fed into the heating main pipe after temperature and pressure reduction via bypasses. It rapidly increases the overall heating load and reduces the power-generation output of the steam turbine, delivering outstanding short-term limit peak-shaving capacity. Nevertheless, throttling loss of high-grade steam is relatively large, leading to poor economy for long-term operation [13].

2.3. High-voltage electrode electric boiler decoupling technology

High-voltage electrode electric boilers are load-transfer flexible retrofit equipment. They utilize surplus valley-period grid electricity and new-energy curtailed power to produce hot water or low-pressure steam to replace steam-turbine extraction-steam for heating [14]. This technology completely decouples heat-power relations. Its load-regulation response speed can reach the second level. It can simultaneously participate in deep grid peak shaving and fast frequency-regulation auxiliary services, and is suitable for units in regions rich in new energy with frequent negative-price electricity. However, multi-level energy conversion leads to high operating energy consumption under conventional electricity prices [15].

2.4. Heat-power decoupling technology based on thermal energy storage

Thermal-energy-storage technology realizes heat-load peak-valley matching through time-space shifting of heat, and is divided into atmospheric hot-water sensible-heat storage and high-temperature molten-salt heat storage [16]. Atmospheric hot-water storage adapts to municipal low-temperature heating loads. It stores heat in daytime and releases heat at night to smooth diurnal heat-load fluctuations and extend the duration of unit deep peak shaving. High-temperature molten-salt heat storage features high storage temperature and high energy density. It adapts to high-temperature industrial steam loads and is applicable to CHP units in industrial parks [17].

2.5. Absorption heat-pump waste-heat-recovery coupling technology

Absorption heat pumps take a small amount of steam-turbine extraction steam as driving heat source. They

recover low-temperature waste heat from condenser circulating water and boiler flue gas, upgrade waste-heat grade for external heating, and belong to energy-saving efficiency-improving auxiliary retrofit technology [18]. This technology can effectively enhance unit heating capacity, reduce mandatory extraction-steam volume, and indirectly lower the minimum power-generation output of units. It is usually coupled with body retrofits and heat-storage systems to further improve the comprehensive energy-saving benefits of units.

2.6. Multi-technology composite coupling retrofit schemes

Single retrofit technologies generally have working-condition adaptation deficiencies and can hardly take peak-shaving depth, duration and operating economy into account simultaneously. Multi-technology composite coupling retrofit can complement the strengths of various technologies and realize stable heat-power decoupling for units under all working conditions. At present, the three most widely-applied combinations in engineering practice include low-pressure cylinder zero-output plus atmospheric hot-water storage, steam bypass plus molten-salt storage, and electric boiler plus hot-water storage, which constitute mainstream schemes for flexibility upgrading of large-scale CHP units.

3. Benefit comparison of four retrofit technologies based on a 300 MW extraction-condensation unit case

3.1. Basic parameters of the case unit

This paper selects a 300 MW extraction-condensation CHP unit of a northern city as the research object. The rated heating extraction-steam flow of the unit is 420 t/h. The annual heating season lasts 120 days. The 8-hour nighttime period every day corresponds to valley peak-shaving hours with abundant new-energy output. The local standard coal unit price is 820 yuan/t, and the deep peak-shaving subsidy is 0.35 yuan/kW·h. The plant has idle space for heat-storage facilities. Four most widely-applied independent retrofit schemes are selected for horizontal comparison of energy-saving and economic benefits: Scheme 1: low-pressure cylinder zero-output; Scheme 2: steam bypass heating; Scheme 3: high-voltage electrode electric boiler; Scheme 4: atmospheric hot-water heat storage.

3.2. Quantitative comparison table of energy-saving and economic benefits

Thermal simulation and economic calculation are carried out. Core indicators of the four retrofit technologies are shown in **Table 1**.

Table 1. Comparison of energy-saving and economic-benefit indicators of four flexible retrofit technologies

Evaluation indicator	Scheme 1 low-pressure cylinder zero-output	Scheme 2 steam bypass heating	Scheme 3 high-voltage electrode electric boiler	Scheme 4 atmospheric hot-water heat storage
Total initial investment per unit / 10 000 yuan	1 650	920	4 300	6 800
Annual standard-coal-saving quantity / t	8 620	−4 750 (increased coal consumption)	−3 120	11 460
Annual change in fuel cost / 10 000 yuan	−706.8	+389.5	+255.8	−939.7
Annual income from deep peak-shaving subsidies / 10 000 yuan	542	716	985	623

Annual operation-and-maintenance cost / 10 000 yuan	36	22	115	48
Annual net income / 10 000 yuan	1 212.8	304.5	614.2	1 514.7
Static payback period / year	1.36	3.02	7.00	4.49
Energy-saving grade	Good	Poor	Fair	Optimal
Long-term operation stability	Good	Poor (not suitable for long-term operation)	Fairly good	Excellent

3.3. Analysis of comparison results

From the perspective of energy-saving benefits, the atmospheric hot-water heat-storage system realizes off-peak utilization of surplus daytime heat without extra fuel loss, delivering the largest annual coal-saving quantity and optimal energy-saving performance. The low-pressure cylinder zero-output retrofit only generates minor cooling-steam windage loss, ranking second in energy-saving performance. Steam bypass and electrode electric boilers produce multi-level energy loss, coal consumption rises instead of falling during long-term operation, and their energy-saving performance is weak.

From the perspective of economic benefits, the atmospheric hot-water heat-storage system achieves the highest annual net income, yet its initial civil-construction and equipment investment is high with a relatively long payback period. The low-pressure cylinder zero-output retrofit features moderate investment and the shortest payback period, which adapts to low-cost upgrading demands of existing units. The electrode electric boiler gains considerable peak-shaving-subsidy income, yet high auxiliary-power consumption restricts its overall economy. The steam-bypass scheme is only fit for short-term emergency peak shaving with extremely low long-term operating income. On the whole, single technologies cannot satisfy multiple requirements for energy saving, economy and stability simultaneously, and coupling retrofit serves as the optimal solution.

4. Multi-dimensional indicator comprehensive comparison and engineering selection criteria

4.1. Summary and comparison of multi-dimensional indicators for mainstream retrofit technologies

Comprehensive comparison and analysis of all technical routes are conducted from multiple dimensions including heating expansion capacity, peak-shaving performance, continuous operation duration, long-term economy and initial construction investment. Various technologies show obvious differences in applicable scenarios (see **Table 2**).

Table 2. Comparison of comprehensive performance indicators for various flexible retrofit technologies

Retrofit technical route	Heating expansion potential	Heat-Power decoupling peak-shaving capacity	Continuous stable peak-shaving duration	Long-term operation economy	Initial constr uction invest ment	Core applicable operating conditions
Low-pressure cylinder zero-output isolation	Medium (only for heating hot water)	Strong	8–12 h	Good	Medium	Seasonal municipal heating extraction condensation units; preferred for existing-unit retrofits
Permanent low-pressure cylinder solid-shaft retrofit	Medium (only for heating hot water)	Very strong	Full-year heating period	Good under high-load conditions; poor in summer	Relatively high	Park units with long annual heating hours and stable hot-water loads throughout the year
High-back-pressure dual-rotor switching retrofit	Medium (only for heating hot water)	Medium	Complete heating season	Optimal (waste-heat energy saving)	Medium high	Pure heating power plants in severely cold regions without industrial steam supply
Main-reheat-steam bypass direct heating	Very strong (heating + high-temperature industrial steam)	Very strong (short-term peak value)	2–4 h	Poor (large throttling loss)	Relatively low	Projects with newly-added temporary industrial heat load and short-term emergency limit peak shaving
High-voltage electrode electric boiler	Very strong (hot water / low-pressure steam)	Very strong (second-level fast regulation)	Unlimited duration	Feasible under high subsidies / negative-price electricity	Medium high	Units in new-energy-rich regions requiring participation in grid frequency regulation and peak shaving
Atmospheric hot-water heat-storage system	No expansion capacity, only heat load shifting	Strong (cross-day-and-night peak shaving)	10–24 h	Optimal for the full cycle	Relatively high	Municipal heating projects with large diurnal heat-load differences and sufficient plant idle land
High-temperature molten-salt heat-storage system	Very strong (heating + high-temperature industrial steam)	Very strong	12–24 h	Good under stable industrial-steam supply	Extremely high	Power plants in industrial parks with year-round high-temperature industrial-steam supply

Absorption waste-heat heat pump	Medium (low-temperature waste-heat supplementary heating)	Medium	Stable all-day operation	Optimal for energy saving (auxiliary supporting equipment)	Relatively high	Power plants with abundant circulating-water / flue-gas waste heat; used as supporting efficiency improving equipment
Low-pressure cylinder zero-output + hot-water heat-storage coupling	Medium, realizing both load shifting and heating potential tapping	Balanced peak-shaving performance for the whole period	Continuous all-day operation	Comprehensive optimum	Medium high	Main CHP heat-source units for large-scale cities

4.2. Implementation criteria for scenario-based engineering selection

(1) Municipal seasonal heating power plants: Priority shall be given to low-pressure cylinder zero-output isolation retrofit. If sufficient plant space is available, it shall be matched with an atmospheric hot-water heat-storage system to balance investment, energy consumption and peak-shaving capacity. It constitutes the standardized optimal scheme.

(2) Power plants in industrial parks with year-round industrial-steam supply: High-temperature molten-salt heat-storage is preferred for long-term retrofits. Steam-bypass systems can be equipped for short-term emergency peak shaving to satisfy both industrial steam supply and limit peak-shaving demands.

(3) Power plants in new-energy-rich regions: High-voltage electrode electric boilers are applicable to scenarios with negative-price electricity and strict peak-shaving assessment. Auxiliary-service income shall offset operating losses.

(4) Power plants with sufficient waste heat in severely-cold regions: Adopt high-back-pressure retrofit or absorption heat pumps for waste-heat recovery, combined with cylinder-cutoff retrofit to improve peak-shaving capacity.

(5) Emergency projects with tight construction periods: Steam-bypass retrofit can be adopted temporarily, and must not be taken as a regular-operation scheme.

5. Conclusion and prospect

Targeting new-energy accommodation and grid peak-shaving demands of the new-type power system, this paper systematically sorts out six categories of flexible retrofit technologies for thermal power units including steam-turbine body retrofit, steam bypass, electric heating, heat storage, waste-heat heat-pump and multi-technology coupling. It illustrates the operating mechanism of each technology combined with system principles and construction procedures. Based on a typical 300 MW unit, quantitative comparison is carried out from both energy-saving and economic-benefit dimensions, and the applicable working-condition boundaries, advantages and drawbacks of each technology are clarified.

The research shows that every single retrofit technology has inherent deficiencies. Steam-turbine body retrofits deliver good energy-saving and economic performance and adapt to conventional heating units. Heat-storage systems realize time-space shifting of heat and resolve the diurnal output-mismatch problem of new energy. Electric boilers and bypass technologies feature prominent short-term peak-shaving capacity

yet high long-term energy consumption. Waste-heat heat pumps are only suitable for auxiliary energy-saving and efficiency-improving purposes. Against the background of high-proportion new-energy grid-connection, multi-technology collaborative coupling retrofit represents the core trend for flexibility upgrading of coal-fired power units. The coupled scheme of low-pressure cylinder zero-output plus hot-water heat-storage delivers the best comprehensive performance. It can well satisfy deep peak shaving, energy-saving consumption reduction and operating-economy requirements, and adapts to most urban CHP units.

Follow-up flexible retrofits for thermal power units shall select schemes differentially in accordance with unit parameters, heat-load characteristics, site conditions and local policies. Optimize unit operation modes through multi-technology collaborative control, promote the transformation of traditional coal-fired power units from base-load power sources to peak-shaving support and comprehensive-energy-service subjects, and facilitate the low-carbon, safe and efficient operation of the new-type power system.

Disclosure statement

The author declares no conflict of interest.

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