Research on the Influence Mechanism of Different Depth Peak Shaving Transformation Methods on the Peak Operation Characteristics of Cogeneration Units and the Decoupling Transformation of Heat and Power in Northern Regions

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Abstract. This study aims at the problem of insufficient peak shaving capacity of gas-fired cogeneration units under the background of the construction of the new power system in China, and systematically analyzes the influence mechanism of thermoelectric decoupling transformation technology and the peak operation characteristics at the top of the units. By constructing thermodynamic coupling models and dynamic response models, the improvement effects of technologies such as low-pressure cylinder resection and hot water storage tanks on peak shaving performance were quantitatively evaluated. The results show that the heat storage technology can significantly reduce the minimum load rate to 30% and increase the climbing rate by 4.5%/min. Combined with the actual operation characteristics in the northern region, a phased transformation strategy was proposed. It was recommended to adopt the combined mode of "mild transformation (operation optimization) + deep transformation (hot water storage tank)", and a two-part electricity price scheme (40 yuan /kW· month +0.55 yuan /kWh) was designed. It was verified that it could effectively stimulate the regulation potential of the unit while ensuring an investment return rate of 6%-8%.

Keywords: Peak shaving capacity; Gas combined heat and power; Thermoelectric decoupling.

1. Introduction

1.1 Research Background and Significance

China's push toward a renewable-centric power system under its "dual carbon" strategy has elevated gas-fired generation as a critical flexibility provider, owing to its clean attributes and rapid operational response[1,2]. This importance is magnified in northern regions where gas cogeneration dominates, yet faces inherent heat-power coupling constraints that impair both peak-shaving performance and renewable energy accommodation[3]. Current heat-led or power-led operational modes exacerbate inefficiencies, driving up fuel costs while regulatory rigidities in gas-electricity pricing further complicate economic sustainability[4,5,6].

The imperative now lies in developing targeted heat-power decoupling strategies that combine technical retrofits with market-based solutions. Drawing on international cogeneration modernization experience, this research systematically evaluates thermodynamic modifications and policy instruments—with particular emphasis on adaptive pricing frameworks—to unlock operational flexibility[7]. By aligning technological interventions with northern China's specific grid and heating demands, the study provides actionable pathways to reconcile gas power's transitional role with accelerating renewable integration, offering policymakers both technical and economic implementation blueprints[8,9,10].

1.2 Literature Review

Globally, gas power plays a vital role in clean energy transitions, with the US leveraging shale gas, the EU utilizing pipeline networks, and Japan depending on LNG imports. However, China's gas power sector faces developmental challenges including low capacity share, regional imbalance, and immature policies[11,12].

While China has progressed in thermal unit flexibility retrofits—especially coal units achieving 30% peak-shaving—gas cogeneration decoupling remains underdeveloped. Limited pilot programs using two-part pricing show promise but require further refinement to address systemic operational challenges[13,14].

1.3 Research Content and Technical Approach

This study investigates gas-fired cogeneration units, analyzing how various deep peak-shaving retrofits affect their peak-load operation. Key focuses include:

Construct an evaluation index system and mathematical model to analyze how retrofits impact peak-shaving performance;

Design tailored thermoelectric decoupling modes (mild/deep) for northern gas units;

Develop two-part tariff models to assess economic effects.

By combining theoretical analysis, simulation and case studies, the response mechanisms of different deep modulation methods to the peak operation characteristics of gas units are systematically revealed, providing a scientific basis for the flexibility improvement and policy-making of gas units in northern regions and similar areas.

2. Analysis of the Influence Mechanism of Different Peak Shaving Transformation Methods on Peak Shaving Operation Characteristics

2.1 Evaluation Index System for Peak Shaving Capacity

To quantify the peak shaving operation characteristics of gas-fired cogeneration units under different peak shaving transformation methods, an index system including climbing rate, duration of continuous peak shaving, and load tracking accuracy was established:

Climbing rate (R_{up}) : The maximum increase in the load of the unit within a unit of time, reflecting the rapid response capability of the unit, with units of %/min or MW/min.

Continuous peak duration (T_{peak}) : The longest period during which a unit can maintain high-load operation, reflecting the sustainability of the unit's peak capacity.

Load tracking accuracy (E_{track}) : The deviation between the actual load of the unit and the dispatching command load, reflecting the precision of the unit's peak shaving.

2.2 Influence Mechanism and Construction of Mathematical Model

The top peak capacity of gas-fired cogeneration units is affected by multiple factors such as the thermoelectric coupling relationship of the units, retroactive technologies, and heat storage facilities. Based on thermodynamic and dynamic response characteristics, the following key models are constructed:

2.2.1 Thermodynamic Coupling Model

There is a coupling relationship between the power generation load P_e of the unit and the heating load Q_h:

$$P_e = P_{GT} + P_{ST} = P_{GT} + \eta_{ST} \cdot \left(m_s \cdot \left(h_{in} - h_{out}\right)\right) \tag{1}$$

Where:

P_{GT} : The power generation capacity of the gas turbine

P_{ST} : Steam turbine power generation capacity

η_{ST} : Steam turbine efficiency

m_s : Steam Flow rate of Steam Turbine

h_{in} , h_{out} : enthalpy values of the steam inlet and outlet.

The heating load is mainly determined by the steam extraction volume and the temperature of the heat network, and the steam extraction volume is affected by the renovation method. After the transformation, the relationship between the steam extraction volume m_{heat} and the steam generation flow rate m_s is adjusted as follows:

$$m_s = m_{total} - m_{heat}$$

Among them, m_{total} represents the total steam flow rate.

2.2.2 Dynamic Response Model

The load change of the gas turbine follows the first-order inertial process. The load change rate is limited by the combustion system, the guide vane Angle and the control system, which is simplified as:

$$\frac{dP_{GT}}{dt} = \frac{1}{\tau}\left(P_{GT,ref} - P_{GT}\right) \tag{2}$$

Where:

τ : Response time constant of the gas turbine,

$P_{GT,ref}$: reference power set by the control system.

The response of the steam turbine is limited by the steam flow rate and the action of the regulating valve. The dynamic response can be described by a model similar to the first order.

2.2.3 Heat Storage System Regulation Model

The capacity C_{stor} and the heat release power P_{stor} of the hot water storage tank have a significant impact on the top peak capacity. The heat storage energy balance equation is:

$$\frac{dE_{stor}}{dt} = P_{charge} - P_{discharge} \tag{3}$$

Where:

E_{stor} : Heat energy stored in the heat storage tank,

P_{charge} : charging power (heat storage),

$P_{discharge}$: Heat release power (heat release).

The existence of the heat storage system enables the unit to reduce the extraction of heating steam during high-load periods and release more steam for power generation, thereby enhancing the peak capacity.

2.3 Sensitivity Analysis of Renovation Technical Parameters

Based on the above model, using the parameters of typical 9FB gas turbine units and combining different transformation technical parameters for simulation, the main calculation results are as follows:

Table 1. Main Calculation Results

Reconstruction	Minimum power generation load rate	Maximum climbing rate (%/min)	Duration of the peak (h)	Load tracking error (%)
Original unit (without modification)	50%	2.5	1.5	5
Low-pressure cylinder resection	35%	3.8	2.5	3
High back pressure heating	40%	3.2	2.0	4

Heating along the road	45%	3.0	1.8	4
Configuration of hot water storage tank	30%	4.5	4.0	2
Electric boiler auxiliary	25%	5.0	5.0	2

The minimum power generation load rate reflects the peak shaving depth of the unit. The removal of the low-pressure cylinder and the transformation of the hot water storage tank significantly reduce the minimum load rate and expand the peak shaving range.

The increase in the climbing rate indicates that the response speed of the unit is accelerated, and the auxiliary effect of the hot water storage tank and the electric boiler is the best.

The prolonged duration of the peak at the top indicates that the unit can maintain high-load operation for a longer time, and the role of the heat storage facilities is prominent.

The reduction of load tracking error reflects the improvement of peak shaving accuracy of the units after the transformation, which is beneficial to power grid dispatching.

2.4 Model Verification and Simulation Analysis

Taking a certain 9FB unit as an example, the load regulation simulation was carried out using the above model. The results show that:

After the low-pressure cylinder was disassembled and retrofit, the minimum load of the unit decreased from 50% to approximately 35%, the climbing rate increased by approximately 52%, and the peak duration was prolonged by approximately 67%.

The configuration of the hot water storage tank enables the unit to respond rapidly to load fluctuations under high load conditions, reducing the load tracking error to 2%.

The auxiliary transformation of the electric boiler has further enhanced the peak shaving depth and flexibility, but it is accompanied by a significant increase in operating costs.

The simulation results are basically consistent with the actual operation data, verifying the validity of the model and the positive role of the transformation technology in improving the performance of the top peak.

3. Thermoelectric Decoupling Transformation Mode and Economic Analysis of Gas Turbine Units in Northern Regions

3.1 Current Operating Status and Main Problems of Gas Turbine Units in Northern Regions

In recent years, the proportion of new energy installed capacity in the power grid of northern regions has continued to increase, and the peak-valley load difference has gradually expanded. Thermal power units mainly provide heating, and their peak shaving capacity in winter is limited, which brings considerable pressure to the power grid's peak shaving. The power load in this area shows a "dual peak" feature in winter and summer, with the peak-valley difference constantly increasing. Especially in winter, the heating demand is high, and the gas-fired cogeneration units undertake a large amount of heating tasks, which limits the flexibility of power generation of the units.

The installed capacity of gas turbine units accounts for a large proportion of the total installed capacity in the local area, and most of the units operate under high load during the winter heating period, with limited peak shaving capacity. In terms of gas supply, due to the guarantee of gas sources and the influence of extreme weather, there is a temporary tight supply of natural gas. During extremely cold weather, the gas shortage is obvious, which affects the stable operation of the units and the peak shaving capacity. In addition, gas-fired power generation enterprises are confronted with economic pressures such as high fuel costs and difficulties in passing on electricity prices. The heating cost is much higher than the bulk purchase price of the heating company, making it hard to effectively pass on the heating cost and resulting in significant operational pressure on the enterprises.

3.2 Thermoelectric decoupling transformation mode applicable to gas turbine units in northern regions

Combined with the operational characteristics of gas turbine units and peak shaving requirements, a two-step transformation strategy is proposed:

Light retrofit mode: Aiming at a relatively small investment, it maximizes the utilization of the existing unit's regulating capacity. The main technical routes include unit operation optimization, wide-load denitrification retrofit, and low-load stable combustion retrofit. This mode aims to enhance the stability and environmental performance of the unit during low-load operation, ensure the rapid disconnection of the low-pressure cylinder during the heating period, and improve the flexibility of peak shaving.

Deep transformation mode: The goal is to break the constraint of "determining electricity based on heat", achieve decoupling of heat and electricity, and it is recommended to adopt the technical route of hot water storage tanks. By configuring heat storage facilities, the "peak shifting and valley filling" of thermal energy can be achieved, significantly enhancing the peak shaving capacity and flexibility of the units. Deep transformation requires a large investment and needs to be accompanied by a complete market mechanism for peak shaving auxiliary services to ensure the return on investment.

3.3 Design of Two-Part Tariff Mechanism and Economic Calculation

In response to the high fuel costs and peak shaving demands of gas-fired units, a two-part electricity price mechanism is adopted, dividing the electricity price into capacity electricity price and electricity consumption electricity price, which respectively compensate for the fixed costs and variable costs of the units.

3.3.1 Design Concept

The core of the two-part tariff system lies in reasonably determining the capacity tariff and the electricity price, so that while ensuring a reasonable internal rate of return, the units can be encouraged to participate in peak shaving and thermoelectric decoupling renovations. Capacity electricity prices mainly cover capital expenditures and fixed operating costs, while electricity prices cover fuel and variable costs.

The net present value (NPV) model is used to calculate the reasonable range of electricity prices:

$$NPV=\sum_{n=0}^{N}\frac{CI_n-CO_n}{\left(1+IRR\right)^n}=0 \tag{4}$$

Among them, CI_{n} represents the cash inflow in the year n, including income from capacity charges and electricity charges; CO_{n} represents the cash outflow in year n, including investment, operation, finance and taxes. IRR stands for the internal rate of return on capital.

3.3.2 Typical unit Parameters and Calculation results

Taking a typical 9F gas generator set as an example, the parameters are as follows:

Table 2. The Parameters

Parameter	Numerical value
Unit capacity	12 MW
Annual power generation hours	2500-3000 h
Return on Capital (IRR)	6%-8%
Fuel price	2.2 yuan/Nm³
Fixed operating costs	87.5 yuan/kW

Variable operating costs	Including fuel costs

The results of calculating the changes in the internal rate of return of the unit under different combinations of capacity electricity price and electricity price show that:

When the capacity electricity price is 40 yuan /kW· month and the electricity price is within the range of 0.53 to 0.57 yuan /kWh, the unit can maintain a reasonable rate of return of 6% to 8%.

The higher the capacity electricity price, the lower the electricity price required, and vice versa.

The number of power generation hours has a significant impact on the rate of return. Reasonable control of the number of power generation hours is conducive to optimizing the income structure.

3.3.3 Policy Mechanism Suggestions

The two-part electricity price mechanism helps alleviate the contradiction between heat and electricity in gas-fired units and stimulates the flexible regulation potential of the units. Suggestion:

Gradually promote the two-part tariff system, clarify the reasonable range of capacity tariff and electricity price, and ensure the return on investment of generating units.

Capacity electricity prices can be set by the government and gradually marketized. Electricity prices can refer to the market price of coal-fired generating units and gradually achieve market linkage.

Based on the actual operation data of the units, the two-part tariff is dynamically adjusted to promote the participation of gas-fired units in the decoupling transformation of heat and power.

Establish a tripartite information sharing and coordination mechanism among gas, power and power grids to ensure the supply of gas sources and the safety of power grids, and improve the peak shaving efficiency of generating units.

4. Conclusions

Gas-fired cogeneration units face key challenges in thermoelectric decoupling, including immature retrofit technologies and inadequate incentive policies, limiting their peak-shaving capacity to 30%. While solutions like low-pressure cylinder modifications and steam bypass heating offer partial improvements, only hot water storage tanks enable full decoupling (despite space constraints), and electric boilers provide maximum flexibility at higher costs. A phased retrofit approach is recommended: initial mild upgrades (operation optimization, denitrification) to enhance existing capabilities, followed by deep retrofits (e.g., hot water storage) to achieve full decoupling. Implementing a two-part electricity pricing system (e.g., 40 yuan/kW-month + 0.55 yuan/kWh) can effectively address heat-power conflicts and incentivize flexible operation, supporting the transition toward China's dual-carbon goals.

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References

[1] Zhang Shan. The Current Situation of Natural Gas Power Generation Abroad and Its Implications for China [J]. Electric Power Science and Technology & Environmental Protection,2020,36(5):26-30.

[2] Wang Zhenxia Experience and Policies of Natural Gas Power Generation in Japan [J]. China Energy,2016,38(6):34-38.

[3] WANG Jianzhou, JIANG Haiyan, ZHOU Qingping, et al. China's natural gas production and consumption analysis based on the multicycle Hubbert model and rolling Grey model[J]. Renewable and Sustainable Energy Reviews, 2016, 53: 1149-1167.

[4] Yang Jianhong Analysis of the Sustainable Development of China's Natural Gas Market [J]. Natural Gas Industry,2018,38(4):145-152.

[5] Zhen Qian, Guo Xiaoqi, Yan Qiang. Decomposition of China's Natural Gas Consumption Factors from an Industry Perspective [J]. China Mining,2018,27(2):50-57.

[6] MORET S, BABONNEAU F, BIERLAIRE M, et al. Decision support for strategic energy planning: A robust optimization framework[J]. European Journal of Operational Research, 2020, 280(2): 539-554.

[7] MUNOZ F D, HOBBS B F, WATSON J P. New bounding and decomposition approaches for MILP investment problems: Multi-area transmission and generation planning under policy constraints[J]. European Journal of Operational Research, 2016, 248(3): 888-898.

[8] Zhou Shuhui, Wang Jun, Liang Yan. The Development of China's Natural Gas Industry during the 14th Five-Year Plan under the Background of Carbon Neutrality [J]. Natural Gas Industry,2021,41(2):171-182.

[9] Li Jian, She Yuanqi, Gao Yang, et al. The Development Situation and Prospect of China's Natural Gas Industry [J]. Natural Gas Industry,2020,40(4):133-142.

[10] Chen Rui, Zhu Boqi, Duan Tianyu. The Role and Development Suggestions of Natural Gas Power Generation in China's Energy Transition [J]. Natural Gas Industry,2020,40(7):120-128.

[11] Zhang Wenhua, Yan Qingyou, He Gang, et al. The Path and Strategy of Low-Carbon Transformation of China's Power System under the Constraint of Climate Change [J]. Progress in Climate Change Research,2021,17(1):18-26.

[12] Yin Jianping, Wang Zepeng Strategic Choices for the Development of Natural Gas Power Generation Industry in China: A Comparative Study of Natural Gas Cogeneration and Gas-Power Peak Shaving [J] Price Theory and Practice,2019(11):11-14.

[13] Liu Zhitan, Ye Chun, Wang Wenfei. The Development path of Natural Gas Power Generation Industry from the Perspective of Industrial Chain [J]. Natural Gas Industry,2020,40(7):129-137.

[14] National Development and Reform Commission Natural gas utilization policy [EB/OL]. (2007-09-04) [2021-04-09]. http://www.gov.cn/zwgk/2007-09/04/content 736629 HTM.