

Flexibility Analysis of Coal-fired Power Plants for Enhancing New Energy Consumption

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Abstract—The rapid development of new energy has increasingly highlighted the need for more flexibility in thermal power industry, making them suitable for new energy consumption. This paper proposes applying two heat-power decoupling technologies: low-pressure turbine zero output scheme and absorption heat pump combined heating technology to captive power plants to deeply tap the peak shaving potential of captive power plants and solve the current and future difficulties of new energy consumption. The former achieves heat-power decoupling by cutting off the steam inlet of the low-pressure turbine. At the same time, the latter recovers the heat of the condenser cooling water to achieve a higher heating load. A comparative evaluation of the two technologies was carried out. When #5 steam extraction was modified, the results show that in terms of maximum heat load increase, scheme one increased by 171 MW, scheme two increased by 164.50 MW, and scheme one showed the most significant increase in heating supply. Regarding the minimum electric load rate, scheme one is 50.86%, and scheme two is 78.00%, with scheme one showing the most significant improvement in the plant's peak shaving capacity.

Keywords—new energy consumption, thermal power flexibility, power output evaluation, heat-power decoupling, minimum electric load rate

I. INTRODUCTION

As the energy demand intensifies, the issues of energy shortage, ecological destruction, and climate deterioration caused by the overexploitation of traditional fossil fuels are becoming increasingly acute [1]. The only solution is to advocate for a "clean substitution" of traditional energy and an "electricity substitution" of energy consumption to achieve a dominant position for new energy and optimize the global energy configuration, thereby satisfying the global electricity demand in a clean and green manner [2]. Consequently, new

energy sources such as wind and solar power, which have large reserves, wide distribution, and high utilization rates, are developing rapidly. Their proportion in power generation is climbing yearly, gradually becoming an essential choice for sustainable energy development for humanity [3].

However, as the installed capacity of wind and solar power continues to increase, the average utilization hours show a counter-growth trend. Therefore, on the path of advocating for the active development of new energy, if we ignore the worsening phenomenon of wind and light abandonment, causing the number of utilization hours to decrease, adding more installed capacity will be in vain [4, 5]. In the long run, it will affect the role of new energy in the modern energy market. It will seriously affect and restrict the future power system's clean, low-carbon, and green development direction [6].

Wind and light abandonment is the most direct factor restricting the number of utilization hours of new energy [7]. The reasons can be analyzed from the following three perspectives: First of all, from the perspective of energy distribution, 80% of China's photovoltaics and onshore wind power are in the three northern regions [8], which have been developed on a large scale. The mainstream form of power generation in this region is still thermal power. In winter, cogeneration units operate on the principle of "heat determines electricity" [9], reducing the peak shaving capacity to cope with the counter-peak of wind and light and restricting the absorption level of a high proportion of new energy [10, 11]. Secondly, from the perspective of transmission channels, the existing cross-province and cross-region transmission channels in the northwest, northeast, and north China regions are specifically for the transmission of traditional coal power. Their channel characteristics adapt to stable electric energy. At the same time, wind and light power have stronger counter-peaking and

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fluctuation, requiring more robust transmission and interconnected channels to achieve peak-shaving mutual aid [12]. Thirdly, from the perspective of load distribution, China's load shows a reverse distribution characteristic, with 80% of the electricity load concentrated in the southeast region, far from the high wind and light emission area. The peak-valley difference of the load exacerbates the peak shaving pressure, and the absorption of wind and light power is restricted once again [13].

It is necessary to create a fair, competitive environment in the energy market, strengthen the peak shaving capacity of the power system, and construct an intelligent energy system that is complementary and coordinated in supply and demand to address the phenomenon of wind and light abandonment. How to tap the potential for peak shaving deeply, solve the current and future difficulties of new energy consumption, and reduce wind and light abandonment is an urgent problem that needs to be solved. When captive power plants participate in grid peak shaving clean energy consumption and other auxiliary services, they have a wide distribution range and have advantages such as small size and strong flexibility [14]. Captive power plants have left a clear and heavy historical imprint in their development process. From the late 1980s to the early 1990s, China's economy has been in a state of rapid development, and most areas have frequently experienced power rationing, affecting the regular operation of enterprises. In 1985, the State Council issued a directive encouraging the construction of power facilities through fundraising and implementing various electricity price policies. Local industrial enterprises have successively set up captive power plants to solve the problem of power supply shortage and low reliability of the public power grid [15]. From the perspective of primary energy types, captive power plants can be divided into coal-fired units, resource-comprehensive utilization units, and a small number of gas-fired units. Among them, coal-fired power generation units can be divided into traditional thermal and cogeneration units according to their power generation characteristics. The former mainly supplies power for enterprise production, and its self-use electricity accounts for a more significant proportion; the latter can also undertake regional heating tasks based on meeting enterprise self-use electricity and has achieved heating for residents in the way of "heat determines electricity" [16]. However, the heat and electricity ratio of captive power plants is fixed, and their ability to participate in peak shaving is limited. Using thermal and electrical decoupling technology to make flexible modifications to captive power plants will contribute to the peak shaving capacity of captive power plants and create conditions for new energy consumption [17]. In summary, to solve the problem of new energy consumption, it is urgent to include captive power plants in the scope of grid peak shaving. To enhance the peak shaving capacity of captive power plants, it is inevitable that thermal and electrical decoupling technology will be applied to them.

II. SCHEME DESCRIPTION

This paper proposes applying LPT (Low-Pressure Turbine) zero output scheme and AHP (Absorption Heat Pump) combined heating technology to captive power plants to deeply tap into the peak shaving potential of captive power plants and solve the current and future difficulties of new energy consumption. As shown in Figure 1, the factor limiting the minimum electrical

load of thermal power units is that the steam flow into the LPT cannot be too small. When using scheme one, the steam inlet of the LPT is wholly cut off, and a small amount of steam enters the LPT through the newly added bypass for cooling the fan heat generated by the rotation of the low-pressure rotor. All other steam is used to achieve a higher heating load, meeting the user's heat load demand, similar to a back-pressure turbine unit. The cooling steam is condensed in the condenser, and during non-heating periods, the LPT resumes average steam intake and standard power generation. The calculation constraints of this scheme are: the essential standard condition is 100% THA condition; the efficiency of the pipeline, boiler, and motor remains unchanged; after the LPT zero output modification, there will be no restriction on the minimum condensation flow of the LPT, at this time the LPT only flows through a small amount of steam for cooling, about 10 t/h.

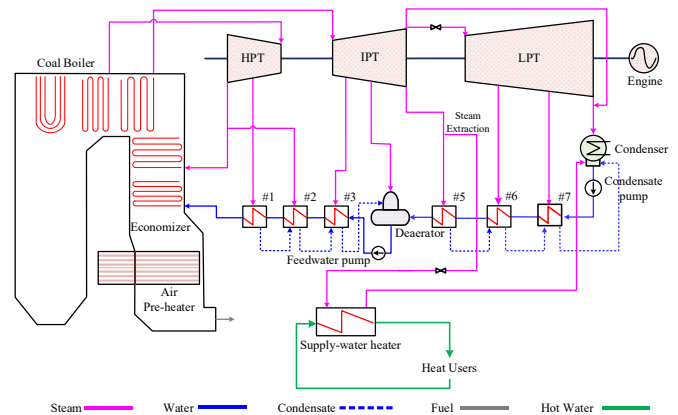


Fig. 1. Schematic diagram of LPT zero output scheme

As shown in Figure 2, scheme two uses an AHP to recover the heat of the condenser cooling water to achieve a higher heating load. In the case of #5 steam extraction, the steam extraction volume of the turbine is unchanged. The steam extraction of the turbine is used as the high-temperature driving heat source to recover the part of the heat of the condenser circulating cooling water to the maximum extent and produce a high-temperature heat source to supply the user's heat demand. The benchmark condition selected in this scheme is: the inlet temperature of the condenser circulating cooling water is 20 °C, and the outlet temperature of the condenser circulating cooling water is 44.4 °C. The AHP uses lithium bromide solution as the circulating solvent; the water in the circulating solvent is evaporated in the generator by the steam extraction of the turbine and then sent to the condenser to be cooled by the hot network circulating water. In contrast, the hot network circulating water is heated to the required temperature. The cooled steam is sent to the evaporator to be evaporated by the condenser circulating cooling water and sent to the absorber. The steam in the absorber is absorbed and heated by the concentrated lithium bromide solution, and the hot network circulating water is preliminarily preheated. The actual performance coefficient COP of the heat pump can reach about 1.5.

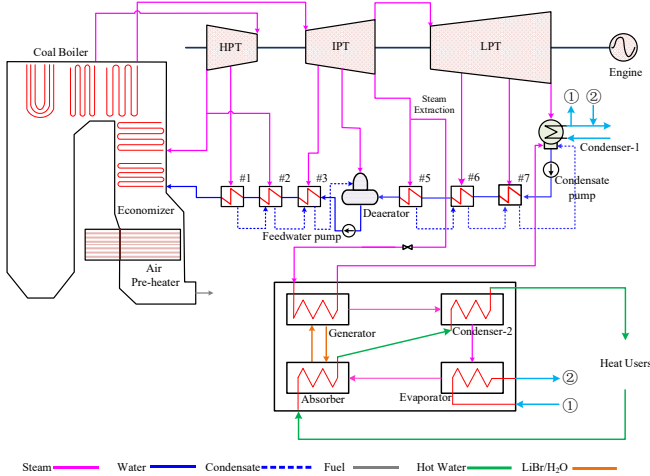


Fig. 2. Schematic diagram of AHP combined heat supply scheme

III. SYSTEM SIMULATION

A. Thermal System Modeling

This paper uses the EBSILON Professional software developed by STEAG Company in Germany for thermal power modeling. Ebsilon Professional is a simulation platform that can be used to design, check, and optimize different types of power stations, calculate mass balance and thermal balance, study the impact of environmental changes on the system, operate new equipment in the cycle, and also dynamically monitor and control power stations. When designing a power station, it can evaluate the substitutability of schemes or equipment; when operating a power station, it can evaluate its losses, optimize and transform it, and draw the feasibility of the scheme. The software is relatively mature, and many power station-related types of research at home and abroad have been realized through Ebsilon Professional, and it has decades of successful experience. The software can calculate closed-loop and open-loop systems, making it flexible and convenient to use.

B. System Parameters

This paper selects a captive power plant in the northwest region of China as the case unit. The turbine is a 350MW, supercritical, single reheat, double-cylinder double-exhaust steam, indirect air cooling, extraction condensing steam turbine, model CJK350-24.2/566/566. As shown in Figure 3, the reheating system consists of three high-pressure heaters, one deaerator, and three low-pressure heaters. The generator efficiency is 98.9%, and the rated power factor is 0.85. Steam extraction port is set at #5. Table 1 lists some of the thermal parameters of this plant.

C. Model Validation

The principle thermal diagram (balance diagram) of the THA condition of the case unit is taken as the benchmark, and the model is accurately verified. The calculation results of the model are shown in Table 2. The final power generation is 349.935MW, the power generation efficiency is 44.86%, and the heat consumption rate is 8025.8kJ/kWh. The error analysis of the model parameters is listed in Table 3. It can be seen from Table 3 that when the initial parameters of the plant balance diagram (pressure, temperature, flow, extraction, and pipeline

pressure loss) and the reheat steam parameters and exhaust steam parameters are used as the input parameters of the model, the THA condition is verified. The parameters obtained by the model calculation are not much different from the design values, and the errors of each section's extraction pressure and extraction flow are within a controllable range. Finally, the unit's power generation error is 0.02%, and the heat consumption rate error is 0.13%, which is very small. Therefore, the calculation results of the reference plant model are reliable and can be used for subsequent research.

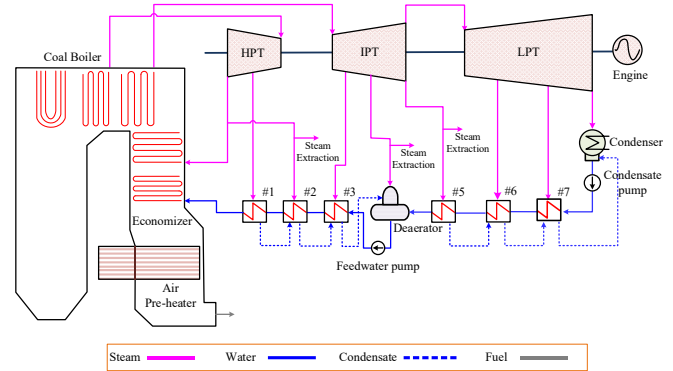


Fig. 3. Schematic diagram of the reference captive power plant

TABLE I. THERMAL PARAMETERS OF THE REFERENCE PLANT

Parameters		Unit	Value
Main steam	Temperature	°C	566
	Pressure	MPa	24.20
	Mass flow	t/h	1069.2
Reheat steam	Temperature	°C	566
	Pressure	MPa	4.205
	Mass flow	t/h	866.32
#5 Steam extraction	Temperature	°C	268.4
	Pressure	MPa	0.497
Back pressure		kPa	12
Feedwater Temperature		°C	281.8
Power output		MW	350
Heat consumption rate		kJ/kWh	8036

TABLE II. THE CALCULATION RESULTS OF THE SIMULATION MODEL

Parameters		Unit	Value
Main steam	Temperature	°C	566
	Pressure	MPa	24.20
	Mass flow	kg/s	297
Reheat steam	Temperature	°C	566
	Pressure	MPa	4.205
	Mass flow	kg/s	240.61
Exhaust steam	Temperature	°C	49.42

	Pressure	kPa	12
	Mass flow	kg/s	248.06
Power output		MW	349.935
Gross power efficiency		%	44.86
Heat consumption rate		kJ/kWh	8025.8
Fuel consumption rate		g/kWh	298.12

TABLE III. MODEL VALIDATION OF THE REFERENCE CAPTIVE POWER PLANT BASED ON DESIGN VALUES

Item		Design	Simulation	Difference (%)
Main steam temperature (°C)		566	566	0.00
Main steam Pressure (MPa)		24.20	24.20	0.00
Main steam mass flow (t/h)		1069.20	1069.20	0.00
Reheat steam mass flow (t/h)		866.32	866.20	-0.01
#1 steam extraction	Pressure (MPa)	6.63	6.63	0.00
	Mass flow (t/h)	62.80	59.97	-4.51
#2 steam extraction	Pressure (MPa)	4.67	4.76	1.93
	Mass flow (t/h)	103.9	106.87	2.86
#3 steam extraction	Pressure (MPa)	1.96	1.96	0.00
	Mass flow (t/h)	36.12	36.38	0.72
#4 steam extraction	Pressure (MPa)	1.07	1.07	0.00
	Mass flow (t/h)	40.77	40.23	-1.32
#5 steam extraction	Pressure (MPa)	0.49	0.50	2.04
	Mass flow (t/h)	33.67	34.70	3.06
#6 steam extraction	Pressure (MPa)	0.25	0.25	0.00
	Mass flow (t/h)	30.70	30.70	0.00
#7 steam extraction	Pressure (MPa)	0.12	0.12	0.00
	Mass flow (t/h)	63.95	64.57	0.97
Exhaust steam pressure (MPa)		0.012	0.012	0.00
Power output (MW)		350.00	349.94	-0.02
Heat consumption rate (kJ/kWh)		8036	8025.8	-0.13

IV. RESULTS AND DISCUSSION

A. Reference Plant Extraction Performance

The case unit was subjected to electrical and thermal characteristic calculations only when steam extraction was at level #5, the results of which are shown in Figure 4. Due to the extraction of steam at level #5, the heat absorption of the boiler is affected, and the power generation efficiency at the minimum/maximum electrical load decreases as the heat load increases; the coal consumption after allocation gradually decreases as the heat load increases. The minimum power generation of the unit is 185.95MW, which is higher than the minimum production load. AB is the line with the maximum main steam flow, and BC is the line with the minimum steam inlet flow of the LPT; the safe operating range of the unit is the

area enclosed by ABC, and the point with the maximum heating supply is at B, its power generation and heating supply are 326.06MW and 302MW respectively.

As shown in Figure 5, the larger the heat load, the larger the maximum heat-electricity ratio of the unit, which increases from 0.1075 to 1.021; at the same time, the unit's minimum electric load rate also increases from 53.13% with the increase of heat load to 93.16%. The unit's minimum power generation increases at high heat loads, indicating that the larger the heat load, the less power generation can be reduced, and the weaker the unit's peak shaving capacity is. The minimum electric load rate is still higher than 50% at low heat loads, limiting the unit's peak shaving capacity. It is necessary to use some techniques to supply ample space for electrical and thermal decoupling, which can meet the high/low heat load and achieve as low an electrical load as possible.

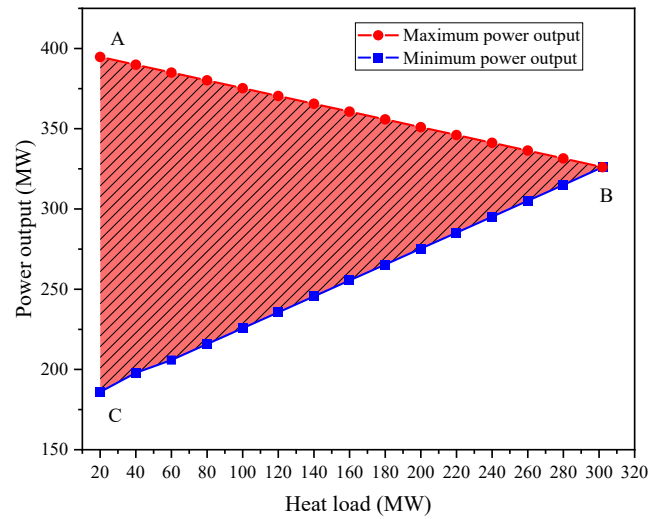


Fig. 4. Electrical and thermal characteristics of the plant with #5 steam extraction

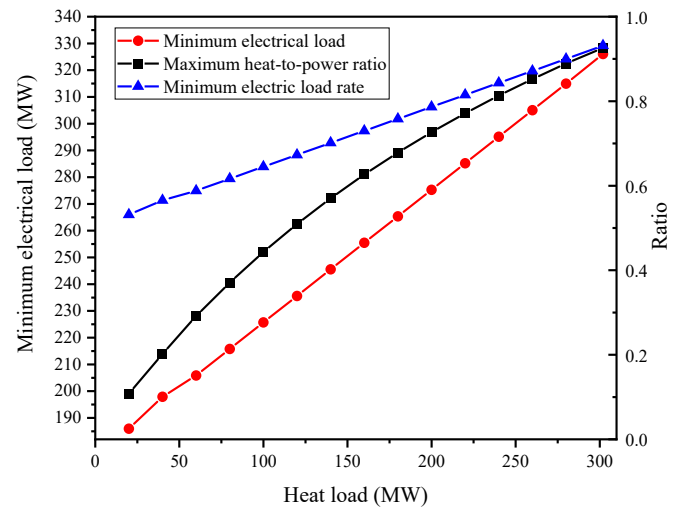


Fig. 5. Minimum electrical load, maximum heat-to-power ratio and minimum electric load rate of the reference plant with #5 steam extraction

B. Impact of Zero Output of Low-pressure Turbine Scheme

As shown in Figure 6, scheme one adopts the LPT zero output, reducing the power generation while allowing more extracted steam to heat the network water; the minimum power generation load is far less than the power generation load of the original unit. It can be seen from Figure 7 that the minimum electric load rate of the LPT zero output decoupling is far lower than that of the original unit. When the heating load is 20~200 MW, due to the minimum production load restriction, the unit's minimum power generation must not be less than 120MW. When the heating load exceeds 200 MW, the minimum power generation of the unit is already more significant than the minimum production load of 120 MW. Still, due to the restriction of the steam inlet flow of the LPT, it cannot continue to reduce to the minimum production load of 120 MW. After modification, the LPT zero output scheme only extracts steam from #5 for heating compared with the case where only #5 extracts steam as a heat source; under the original maximum heating load of 302 MW, the minimum electrical load can reach 178 MW, reducing 148.06 MW; the minimum electric load rate is 50.86%, reducing 42.30%. In addition, the maximum heat load that the LPT zero output scheme can reach is 473 MW, an increase of 171 MW.

C. Impact of AHP Combined Heating Scheme

Figures 8 and 9 compare the electrical and thermal characteristics and the minimum electric load rate between scheme two and the reference plant. It can be seen from the figure that scheme two adopts the AHP, reducing the power generation while recovering part of the heat of the condenser cooling water; the minimum power generation load is far less than the power generation load of the original unit. It can be seen from Figure 9 that the minimum electric load rate of the AHP decoupling is far lower than that of the original unit. After modification, the AHP completely decoupled the scheme from #5 extracting steam as a high-temperature driving heat source compared with the case where only #5 extracts steam for heating, under the original maximum heating load of 302MW, the minimum electrical load is 273MW, reducing 53.06MW; the minimum electric load rate is 78%, reducing 15.16%. In addition, the maximum heat load that scheme two can reach is 466.5MW, an increase of 164.5MW.

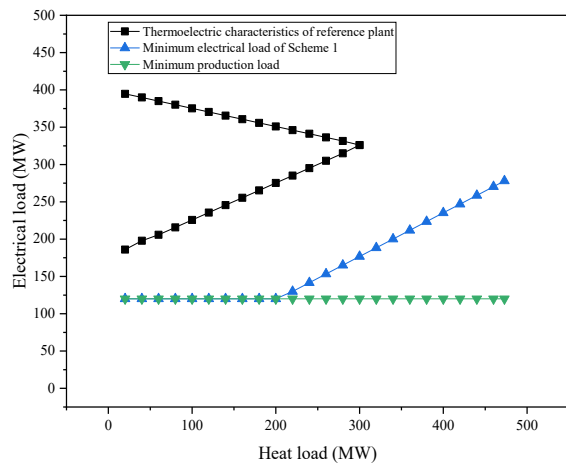


Fig. 6. Electrical and thermal characteristics of the plant in scheme one

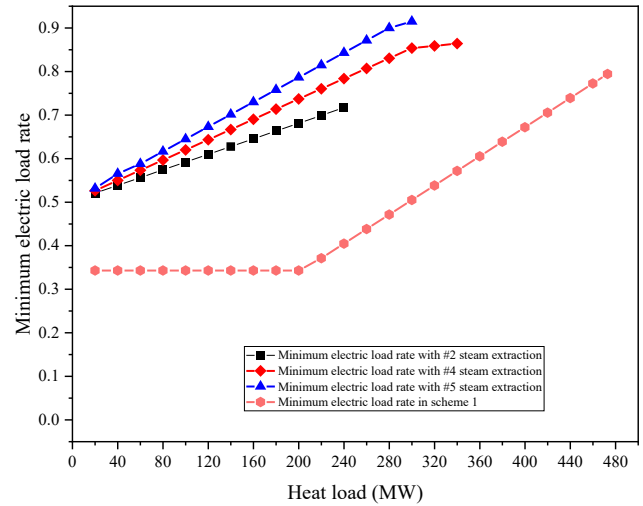


Fig. 7. Minimum electric load rate in scheme one

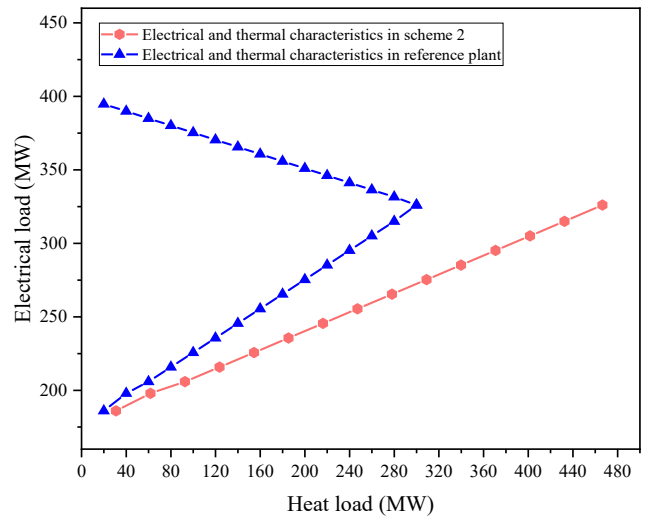


Fig. 8. Electrical and thermal characteristics of the plant in scheme two

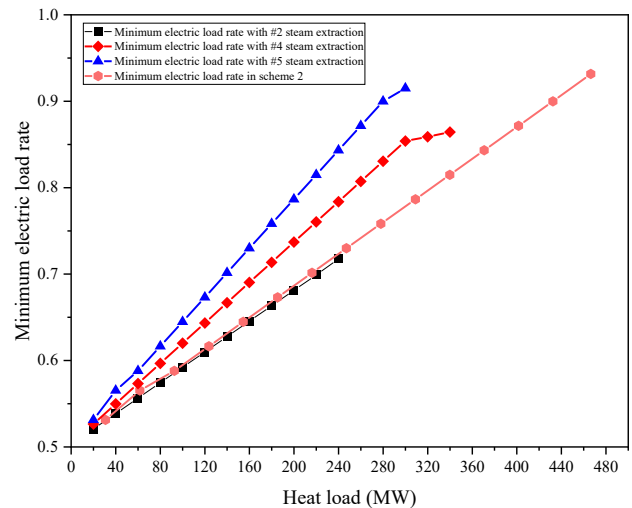


Fig. 9. Minimum electric load rate in scheme two

V. CONCLUSIONS

This study primarily focuses on the spatial prediction of the load of self-provided power plant units. A single-stage independent steam extraction analysis was conducted on the reference captive power plant. Subsequently, two thermal-electrolysis decoupling schemes were proposed and compared with the reference plant. The main conclusions are as follows:

(1) Considering the maximum thermal load increase after optimization, Scheme 1 increased by 171MW, and Scheme 2 increased by 164.50MW. From the perspective of the maximum thermal load, Scheme 1 has the most significant increase in heating supply.

(2) Looking at the electric load rate under the maximum heating supply of the original case without transformation, Scheme 1 is 50.86%, and Scheme 3 is 78.00%. The peak-shaving capability of the unit that has been most improved is also Scheme 1.

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