Synergistic Optimization Model of Energy Storage and BF Gas Power Generation for Steel Enterprises Considering Power Spot Price and Maximum Demand

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Abstract. Aiming at the cost fluctuation and demand-side management pressure faced by iron and steel enterprises under the background of power market reform, this paper puts forward a collaborative optimization model of energy storage and blast furnace surplus gas power generation, which integrates the power spot price signal and the maximum demand (MD) constraint. This model employs a multi-timescale mixed-integer nonlinear programming (MINLP) framework, integrating rolling optimization strategies and robust optimization methods. It prioritizes minimizing the enterprise's total electricity costs while simultaneously accounting for grid power purchase costs, MD penalty costs, coal-gas power generation operational costs, and energy storage operational costs. Through case analysis, it is verified that the model has obvious advantages in balancing the penalty of power purchase cost and demand and realizing global optimization. The results show that, compared with the traditional operation mode and the scenario of only considering the time-of-use price optimization, the collaborative optimization model can effectively reduce the total power consumption cost of enterprises and improve the economy and power grid security. In addition, the robustness test of the model further proves its effectiveness in dealing with the fluctuation of electricity price. This study provides a feasible solution for iron and steel enterprises in the process of energy structure transformation and energy efficiency improvement.

Keywords: Cooperative Optimization; Energy Storage; Blast Furnace Surplus Gas; Power Generation; Steel Enterprises; Spot Prices; Maximum Demand.

1. Introduction

As one of the main sources of global industrial energy consumption and carbon emissions, the steel industry's energy structure transformation and energy efficiency improvement have become the key path to achieve the goal of "double carbon" [1]. Under this background, iron and steel enterprises are faced with double challenges: on the one hand, they need to reduce their dependence on fossil energy through technological upgrading, on the other hand, they need to cope with the cost fluctuation and demand-side management pressure brought about by power market reform.

As a by-product of ironmaking process, blast furnace gas accounts for more than 40% of the total waste gas in iron and steel enterprises, and its calorific value is lower than that of natural gas, but the total amount is huge [2]. Traditional utilization not only wastes resources, but also aggravates air pollution [3]. In recent years, blast furnace gas power generation technology has significantly improved the energy conversion efficiency through energy cascade utilization, but its power generation is affected by factors such as gas output fluctuation and equipment start-stop restrictions, and it is difficult to accurately match the rigid power demand of iron and steel enterprises [4]. At the same time, the comprehensive promotion of the spot market of electricity makes the electricity price show the characteristics of time-sharing fluctuation. Iron and steel enterprises need to use energy storage system (ESS) to stabilize the power generation fluctuation and optimize the electricity purchase strategy, so as to reduce the electricity consumption cost and avoid the maximum demand (MD) penalty [5]. However, the existing research mostly focuses on single objective optimization, or only considers the electricity price signal and ignores the process safety constraints, which leads to the limited feasibility of the model in practical application.

To address the aforementioned issues, this study proposes a synergistic optimization model for energy storage and blast furnace surplus gas power generation in steel enterprises, integrating electricity spot price signals with MD constraints. The research innovatively constructs a multi-timescale mixed-integer nonlinear programming (MINLP) model. Through a rolling optimization strategy, it responds in real time to fluctuations in gas production and electricity prices. Additionally, robust optimization methods are introduced to quantify the impact of uncertainty parameters on the optimal solution.

2. Objective Function

The core goal of this model is to reduce the total electricity consumption cost of iron and steel enterprises, and optimize the operation of blast furnace surplus gas power generation (BFG power generation) and ESS through collaboration, taking into account the time-sharing fluctuation of electricity spot price and MD penalty mechanism [6-7]. The model adopts MINLP framework, combined with rolling optimization strategy to respond to the uncertainty of gas production and electricity price in real time, and introduces robust optimization method to enhance the robustness of the model. The optimization period is typically 24 hours and the time resolution is 15 minutes or 1 hour.

The objective function aims to minimize the total cost, including power grid purchase cost, MD penalty cost, gas power generation operation cost and energy storage operation cost [8-9]. The formula is as follows:

$$\min\sum_{t=1}^{T}\left[C_{grid}(t)P_{grid}(t)\Delta t\right]+C_{md}\max_{t\in T}P_{grid}(t)+\sum_{t=1}^{T}\left[C_{gen}P_{gen}(t)\Delta t\right]+\sum_{t=1}^{T}\left[C_{ess}\left|P_{ess}(t)\right|\Delta t\right] \tag{1}$$

In the above formula, T——Total number of optimization periods.

t——Time index.

$C_{grid}(t)$——Spot electricity price (yuan /kWh) in t period is given by market forecast.

$P_{grid}(t)$——The power (kW) purchased from the power grid during t period is the decision variable.

Δt——Length of time interval (hours).

C_{md}——MD penalty unit price (yuan /kW), based on the contract demand setting.

$\max_{t\in T}P_{grid}(t)$——Optimize the maximum power (kW) purchased in the cycle, that is, the actual demand, and avoid excess through the penalty term.

C_{gen}——Unit operating cost of gas power generation (yuan /kWh), including fuel and maintenance costs.

$P_{gen}(t)$——The generating power (kW) of BFG in t period is the decision variable.

C_{ess}——The unit operating cost of ESS (yuan /kWh) mainly corresponds to the loss.

$P_{ess}(t)$——The charging and discharging power (kW) of energy storage in t period is the decision variable; A positive value indicates discharge and a negative value indicates charging. The absolute value term indicates the cost of both charging and discharging.

3. Key Constraint Conditions

1. Power balance constraint

Ensure that power generation and power purchase match the load demand:

$$P_{load}(t)=P_{grid}(t)+P_{gen}(t)+P_{ess}(t) \tag{2}$$

$P_{load}(t)$ is the total load power (kW) of iron and steel enterprises in t period, which is regarded as known or predictable.

2. Gas power generation constraint

BFG power generation is limited by gas production and equipment operation, and the upper and lower limits of power generation are:

$$P_{gen}^{\min} \le P_{gen}(t) \le P_{gen}^{\max} \tag{3}$$

$P_{gen}^{\min}, P_{gen}^{\max}$ is the minimum and maximum technical output (kW) of BFG generator.

Climbing rate constraint (to ensure equipment safety):

$$\left| P_{gen}(t) - P_{gen}(t-1) \right| \le \Delta P_{gen}^{\max} \tag{4}$$

$\Delta P_{gen}^{\max}$ is the maximum allowable power change rate (kW/ period).

3. ESS constraint

ESS model considers energy dynamics and operation limitations, and the equation of state of energy storage (SOC):

$$SOC(t) = SOC(t-1) + \left[\eta_{ch} \max(0, -P_{ess}(t)) - \frac{\max(0, P_{ess}(t))}{\eta_{dis}} \right] \Delta t / E_{rated} \tag{5}$$

$SOC(t)$ is the energy storage state (percentage) of the period t, and the initial state $SOC(0)$is given. η_{ch}, η_{dis} is the charging and discharging efficiency (between 0 and 1). E_{rated} is the rated energy storage capacity (kWh).

SOC boundary constraint:

$$SOC^{\min} \le SOC(t) \le SOC^{\max} \tag{6}$$

Charge and discharge power limit:

$$-P_{ess}^{ch,\max} \le P_{ess}(t) \le P_{ess}^{dis,\max} \tag{7}$$

$P_{ess}^{ch,\max}, P_{ess}^{dis,\max}$ is the maximum charge-discharge power (kW).

4. MD soft constraint

Through the indirect constraint of the penalty term in the objective function, no solution can be caused by setting hard constraints. When the actual demand exceeds the contract value, C_{md} will significantly increase the cost.

4. Optimization Method

The optimization is divided into two layers: day-ahead planning and day-to-day rolling. Solve the MINLP model based on the forecast data (electricity price and gas output) in the previous stage to generate the all-day plan; The intra-day phase is updated every 15-30 minutes, and the plan is adjusted by using the latest measured data to cope with fluctuations.

Aiming at the randomness of gas output and electricity price, interval robust optimization method is adopted. For example, the uncertainty parameter is set to the bounded interval $\left[\underline{Q}_{gas}(t), \overline{Q}_{gas}(t)\right]$, and the objective function is changed to minimize the worst-case cost:

$$\min \max_{Q_{gas}(t) \in [\underline{Q}, \overline{Q}]} total\ cost \tag{8}$$

The problem is transformed into deterministic optimization by dual transformation or scene reduction, and the feasibility of the scheme is improved.

The model is solved by a commercial solver, and the nonlinear term is linearized.In practical application, the steel plant energy management system (EMS) is integrated to collect data in real time and perform rolling optimization. The model can be extended to additional targets such as carbon transaction cost to meet the policy requirements.

5. Case Demonstration and Result Analysis

5.1 Case Basic Data Setting

Select a large iron and steel enterprise as the analysis object. The optimization period is 24 hours and the time resolution is set to 1 hour ($T = 24$). The spot market price of electricity on a typical day in a certain area is adopted, as shown in Figure 1. The electricity price is higher in peak hours (10:00-15:00, 18:00-21:00) and lower in valley hours (00:00-07:00). The typical daily rigid power load curve of an enterprise is shown in Figure 1, and the maximum load is about 80MW.

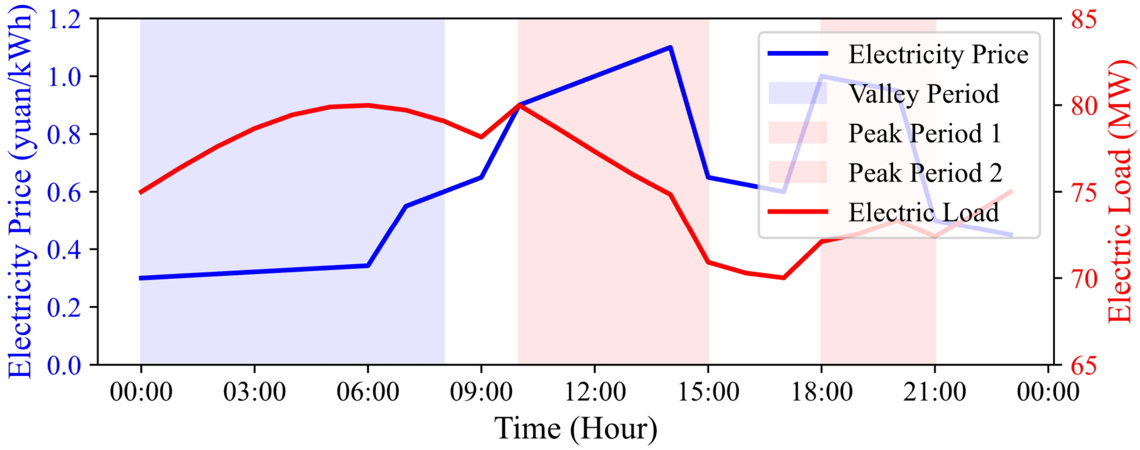

Figure 1. Rigid power load curve of enterprise on typical day

Maximum technical output $P_{gen}^{\max} = 30MW$, minimum technical output $P_{gen}^{\min} = 10MW$ and unit power generation cost $C_{gen} = 0.25 yuan / kWh$ of BFG generator set. The lithium-ion battery equipped with rated capacity $E_{rated} = 60MWh$ has the maximum charge/discharge power $P_{ess}^{ch,\max} = P_{ess}^{dis,\max} = 15MW$, charge/discharge efficiency of 92%, initial SOC=50%, and operating cost $C_{ess} = 0.05 yuan / kWh$. The contract demand is set at 70 MW, and the unit price of excess penalty is C_{md}=40 yuan /kW/ month (converted to daily cost of about 1333 yuan /MW/ day).

5.2 Contrast Scene Design

Set the following three contrast scenarios:

1) Scenario 1 (basic scenario): The BFG generator set operates at a fixed power (average power of 20MW), and ESS does not input. This scenario represents the traditional and non-optimized operation mode.

2) Scenario 2 (time-of-use electricity price optimization): consider spot electricity price, optimize BFG power generation and energy storage operation, but ignore MD punishment.

3) Scenario 3 (collaborative optimization): the complete model proposed in this study is adopted, and the spot electricity price and MD penalty are considered for collaborative optimization.

5.3 Results Analysis and Discussion

Table 1 below shows the breakdown of the daily total electricity cost in three scenarios.

The total cost of scenario 3 (collaborative optimization) is the lowest, which is 624 820 yuan, which is about 14.1% lower than scenario 1 (basic scenario) and about 6.3% lower than scenario 2 (time-of-use price optimization). This proves the comprehensive advantages of the collaborative optimization model.

Although scenario 2 reduces the cost of electricity purchase by using time-of-use electricity price, its MD penalty is still high. Scenario 3 successfully controls the actual MD within the contract value

(70MW) by actively managing the peak power of power grid purchase, and completely avoids the penalty cost. This is the main reason why the total cost is lower than that in scenario 2.

Table 1. Comparison of daily operating costs in different optimization scenarios

Cost item	Scenario 1 (basic scenario)	Scenario 2 (time-of-use pricing optimization)	Scenario 3 (collaborative optimization)
Cost of electricity purchase (yuan)	554,160	496,280	501,940
Cost of gas power generation (yuan)	120,000	122,850	121,500
Energy storage operation cost (yuan)	0	1,450	1,380
MD Punishment (Yuan)	**53,320**	**46,620**	**0**
Total cost (yuan)	**727,480**	**667,200**	**624,820**

The electricity purchase cost in scenario 3 is slightly higher than that in scenario 2, because the model may choose to increase energy storage discharge or BFG power generation during the peak load period when the electricity price is not the lowest, which leads to a slight increase in electricity purchase cost. However, the increase of this part of the cost is far lower than the avoided demand penalty, which reflects the global economy of the model.

Figure 2 below compares the typical daily curves of grid purchase power, BFG generation power and energy storage SOC in Scenario 3 and Scenario 1. In the basic scenario, the power purchase curve closely follows the load curve, and there are two peaks around 11:00 and 19:00, both of which exceed 80MW. In the collaborative optimization scenario, the model significantly "leveled" the two peaks by scheduling energy storage and BFG power generation, especially at the peak load period of 11:00, and the power purchased was strictly limited below 70MW.

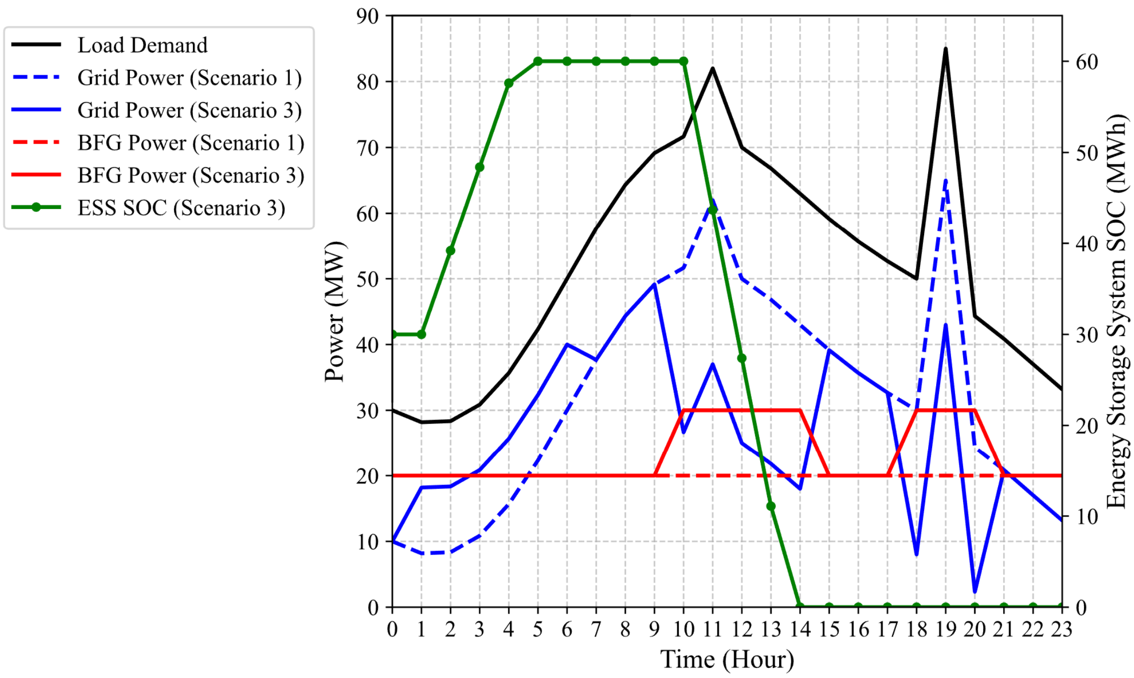

Figure 2. Comparison of operation strategies between collaborative optimization scenario (scenario 3) and basic scenario (scenario 1)

When the electricity price is low at night (00:00-07:00), the collaborative optimization model will appropriately reduce the generation power of BFG (but still above the technical lower limit), and use the cheap grid power to charge the energy storage (SOC rising) to prepare for the daytime peak. During the daytime peak hours (10:00-15:00), the electricity price is high and the load is heavy. The model commands BFG to generate electricity at full load (30MW), and at the same time, it stores energy and discharges with high power to support the load together, greatly reducing the power purchase of high-priced power grid, and successfully suppressing the peak power purchase. In the evening rush hour (18:00-21:00), the strategy is similar to that in the daytime, but because the stored energy has been partially consumed by daytime discharge, the discharge power is controlled to ensure sufficient charging space in the next valley hour.

In order to further test the robustness of the model and improve the fluctuation range of spot electricity price (the peak-valley price difference is expanded by 20%). The results show that the advantages of collaborative optimization model are more obvious in the environment of greater electricity price fluctuation. Because the bigger price difference provides more space for ESS's arbitrage of "low storage and high incidence" and the marginal benefit of avoiding demand penalty is also higher, the total cost saving rate of scenario 3 is increased from 6.3% to 8.1% compared with scenario 2.

6. Conclusion

1) The collaborative optimization model proposed in this study can effectively utilize the flexibility of ESS, cooperate with blast furnace gas to generate electricity, and realize accurate response to spot price signal and MD constraint.

2) The model has a remarkable effect in reducing the total electricity consumption cost, and its core advantage lies in its ability to balance the electricity purchase cost and demand penalty to achieve global optimization, while the single time-of-use electricity price optimization may fall into local optimization due to ignoring demand penalty.

3) The operation strategy of the model is in line with expectations, that is, storing energy when the electricity price is low and releasing it when the electricity price and load are high, while smoothing the power purchase curve of the power grid, ensuring the safety of the power grid and improving the economy of the enterprise.

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