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Optimal scheduling of a byproduct gas system in a steel plant considering time-of-use electricity pricing

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HIGHLIGHTS

- A scheduling model of byproduct gas system under time–of–use tariff was proposed.
- The boiler efficiency change with operation load was considered in the model.
- Pareto optimality was used to balance the gasholder stability and electricity cost.
- The overall boiler efficiency was improved by 3.3% after optimisation.
- Electricity purchasing cost was reduced by 29.7% through peak–valley shifting.

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ABSTRACT

Most integrated iron and steel corporations have built on–site power plants (OSPPs) to reduce their purchased electricity and thus to decrease the overall electricity cost. Due to their large quantities and easy access, the byproduct gases generated in the steel production process are the main fuels used for the OSPPs. The introduction of time–of–use (TOU) electricity pricing in the steel industry has made it possible to decrease electricity costs through an optimal collaboration between the energy storage equipment (gasholders) and OSPPs. In this paper, a byproduct gas scheduling model based on mixed–integer linear programing (MILP) considering the TOU electricity pricing is proposed. In this model, Pareto optimality and fuzzy sets were used to find the best compromise solution for two conflicting objectives: achieving the gasholder stability and reducing the electricity purchasing cost. In addition, the influence of the operation load on the boiler efficiency was considered to improve the model accuracy. The results show that the optimisation can achieve better peak–valley shifting of the electricity generation and decrease the electricity purchasing cost by 29.7% with improved gasholder stability. Optimisation increased the overall boiler efficiency by 3.3%, indicating that the byproduct gases are effectively and efficiently used. The sensitivity analysis results indicate that the peak–valley shifting of the electricity generation improves with increasing peak–valley price rate (PVR) at the expense of decreasing the overall gasholder stability.

1. Introduction

As a fundamental industry, the steel industry accounts for approximately 15% of the gross electricity consumption in China [1]. Recently, as a result of fierce market competition, increasing attention has been paid to reducing the electricity cost in steel enterprises [2–5].

To reduce electricity purchases, most integrated iron and steel corporations have built on–site power plants (OSPPs) to cover 50–80% of the power demand, and the remaining demand is supplied by the main grid [6–9]. The fuels consumed by the OSPPs include coal and the byproduct gases generated in the steel–making process, such as coke oven gas (COG), blast furnace gas (BFG) and Linz–Donawitz process gas (LDG). With the recent improvements in byproduct gas management and stricter environmental protection requirements, byproduct gases have become the only fuel used for OSPPs in China [10]. However, both the production and consumption of those gases are not stable, which leads to fluctuations in the byproduct gas system. Therefore, it is necessary to install gasholders to compensate for these fluctuations. However, if the capacity of the gasholders is limited, the imbalance will not be

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Nomenclature

Sets

- B — $\{i|\text{boilers}\}$
- G — $\{j|\text{byproduct gases}\}$
- P — $\{t|\text{periods}\}$
- TB — $\{m|\text{turbines}\}$

Parameters

- C_t^{elec} — unit price for electricity, CNY/kW h
- C^{flar} — unit price for byproduct gas flaring, CNY/m^3
- $E_{t,dem}$ — electricity demand in the iron and steel making process in time period t, kW h
- $f_{i,j}^{max}$ — maximum consumption rate of the jth byproduct gas of boiler i, m^3/h
- $f_{i,j}^{min}$ — minimum consumption rate of the jth byproduct gas of boiler i, m^3/h
- $GH_{j,HH}$ — maximum level of gasholder j, m^3
- $GH_{j,LL}$ — minimum level of gasholder j, m^3
- H_j — lower heating value of byproduct gas j, kJ/m^3
- H^{stm} — enthalpy of steam, kJ/t
- q_i^{max} — maximum operation load of boiler i, GJ/h
- q_i^{min} — minimum operation load of boiler i, GJ/h
- Δt — time period, h
- $V_{j,mid}$ — middle level of gasholder j, m^3
- $\Delta V^{max}{}_j$ — maximum changing volume of gasholder j during period t, m^3
- η_i^b — efficiency of boiler i
- η_m^{tb} — steam–electricity conversion efficiency of turbine m

Variables

- $E_{t,gen}$ — electricity generated by the turbines in time period t, kW h
- $E_{t,pur}$ — electricity purchased from the main grid in time period t, kW h
- $F_{j,t,gen}$ — byproduct gas j generated in period t, m^3
- $F_{j,t,con}$ — byproduct gas j consumed in the iron and steel making system in period t, m^3
- $\Delta f_{i,j,t}$ — load change of byproduct gas j consumed in boiler i from period $t-1$ to t, m^3/h
- $f_{i,j,t}$ — flow rate of byproduct gas j consumed in boiler i during period t, m^3/h
- $F_{i,t}^{dem}$ — steam demand of the iron and steel making system in boiler i during period t, t
- $f_{i,t}^{steam}$ — flow rate of steam produced in boiler i during period t, t/h
- $F_{i,t}^{tb}$ — flow rate of steam into the turbine from boiler i during period t, t
- $V_{j,t-1}$ — jth gasholder level in period $t-1$, m^3
- $V_{j,t}$ — jth gasholder level in period t, m^3
- $V_{j,t,flar}$ — flaring volume of byproduct gas j during period t, m^3
- W_D — penalty factor for normal-level deviation, CNY/m^3
- W_H — penalty factor for high-level deviation, CNY/m^3
- W_L — penalty factor for low-level deviation, CNY/m^3
- $pw_{m,t,gen}$ — electricity generated by turbine m during period t, kW h
- $S_{D,t}^j$ — normal-level deviation volume of gasholder j during time period t, m^3
- $S_{H,t}^j$ — high-level deviation volume of gasholder j during time period t, m^3
- $S_{L,t}^j$ — low-level deviation volume of gasholder j during time period t, m^3
- $S_{flar,t}^j$ — flaring volume of byproduct gas j during time period t, m^3
- SDV_j — standard deviation volume of gasholder j, m^3
- x — common variable for the gasholder penalty factor

Abbreviations

- BFG — blast furnace gas
- CNY — Chinese yuan
- COG — coke oven gas
- EPC — electricity purchasing cost
- GPC — gasholder penalty cost
- HA — heuristic algorithm
- LDG — Linz–Donawitz process gas
- LHV — lower heating value
- MILP — mixed-integer linear programming
- MOO — multi–objective optimisation
- MPP — moderate price period
- NNs — neural networks
- OSPP — on–site power plant
- PPP — peak price period
- PVR — peak–valley price rate
- SA — simulated annealing
- SDV — standard deviation volume
- SOO — single–objective optimisation
- SSDV — sum of standard deviation volume
- SSM — supply side management
- TOU — time–of–use
- VPP — valley price period

Subscripts

- con — consumption
- elec — electricity
- flar — flaring
- dem — demand
- gen — generation
- pur — purchase
- stm — steam
- tb — turbine
- D — deviation
- H — high
- HH — higher
- L — low
- LL — lower

compensated well, which results in the need for byproduct gas flaring or decreased electricity generation of the OSPPs. Thus, maintaining the stability of the gasholders is very important and has been the focus of many previous studies [11–16].

The main method used to sustain the stability of the gasholders is to dynamically adjust the consumption of byproduct gases in an OSPP. Varying this consumption changes the internal electricity generation and fluctuates the power source structure (the proportion between the internal electricity generation and the electricity purchased from the main grid). Fluctuations of the power source structure have little effect on the overall electricity cost for iron and steel making because the fluctuation scale is limited. In other words, if the power source structure changes considerably, the overall electricity cost may change accordingly, which indicates a potential method for reducing the overall electricity cost. Currently, a new trend that several OSPPs in steel enterprises are taking advantage of is the time–of–use (TOU) electricity tariff, which can drastically adjust the power source structure by changing the gas consumption and fully utilising the storage ability of the gasholders. With this approach, more electricity is generated during the peak price period (PPP), and less electricity is generated during the valley price period (VPP). Thus, more byproduct gases are stored in