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A MINLP Scheduling Model Based on the Coupling of the Byproduct Gases, Steam and Power in Iron and Steel Industry

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ABSTRACT

Byproduct gases, steam and electricity are important energy medium coupling tightly in the iron and steel plant. The implementing of time-of-use (TOU) power price in Chinese countries has made it possible to reduce operation cost and relieve the stress of the electricity on the grid with optimal distribution of byproduct gases between boilers and gasholders. In this paper, a scheduling model based on the coupling of the byproduct gases, steam and power considering the TOU power price is proposed. In this model, the quadratic fitting curves are used to describe the operating characteristic of boilers and turbines in the energy management system. The results show that the model can distribute the gases more reasonable considering the steady operation of equipment and the TOU power price, that have the higher average efficiency to generate more power and reduce the operation cost by 3.2%.

Keywords: TOU power price, coupling, gasholder, optimization, MINLP, efficiency

1. INTRODUCTION

The iron and steel plant are one of the energy-intensive and CO_2 intensive plants. The energy consumption from the iron and steel industry accounts for about 18% of the total energy consumption in the world [1]. Moreover, its CO_2 emission can account for approximately 6.7% of the global CO_2 emission [2]. At the past 2020, China government made a promise that the carbon dioxide emissions of China will meet the peak before 2030, and achieve carbon neutrality by 2060, what drives industries to seek technologies to reduce CO_2 emission.

Energy management system (EMS) is considered to be an effective means of saving energy and resources. Optimal scheduling of various energy mediums in the iron and steel plant with advanced mathematical programming model was a useful way to management energy. Kong et al. [3] introduced mixed-integer linear program (MILP) model to consider the steady demand of steam and power. Liu et al. [4] added the coupling of gas-steam-electricity to the mixed-integer nonlinear program (MINLP) model in a byproduct gas system. Zeng et al. [5] proposed a novel MILP model to optimal the distribution of byproduct gases, steam and power and introduced binary variables to determine electricity purchase or sale without considered the power price of time-of-use (TOU).

These papers implement in EMS in iron and steel plant with great efforts to optimal the coupling gas-steam-power by take the steady of gasholder and the annual cost into account. However, in previous studies, the efficiency of boilers and turbines were considered as a constant. Besides, these researches over pursued the stability of the gasholder that may not gain a maximum optimization schedule of the energy and therefore the economic advantage on the optimization. Thus, in this study, a MINLP model is established, which consider the dynamic efficiency change of the boiler and turbine and reduce some constraints of the gasholder. This MINLP optimization model is not only applied to make a more reasonable distribution of byproduct gas and generation of steam and power, but use gasholder to transmit the byproduct gas to reduce the cost in electricity.

Following this section, the optimization modelling is shown in Section 2. The mathematical model of evaluation equipment, and solving approach are shown in Section 3. Finally, the optimal results and conclusion are provided in Section 4 and Section 5, respectively.

2. OPTIMIZATION METHOD

The byproduct gases generated from iron and steel making system are considered as one of the system fuels, which are the virtual distribution medium in the network. Steam and power distribution network involve fuel boilers, steam turbines and combined heat and power (CHP) units in the iron and steel plant. Byproduct gases are fed through boilers to turn water into steam, and then the stream push turbine to rotate, that generating electricity power.0

2.1 Objective function

The objective function is defined to minimize the operation costs of the byproduct gases, steams, and power system under the TOU power price, which contains the byproduct gases usage cost (GUC), the steam usage cost (SUC), the electricity purchase cost (EPC), the byproduct gases flaring penalty cost (GPC) and the coal usage cost (CUC), as shown in Eq. (1)-(5). And the nomenclature of this paper is in Appendix A.

$$Y=min\left\{GUC+CUC+SUC+EPC+GPC\right\}$$
$$=min\sum_{t=1}^{T}\left\{\begin{array}{l}\sum_{G}(C_g\times\sum_{B}f_{b,g,t})+\sum_{S}\left[\left(C_s^{sp}\times\sum_{B}D_{b,s,t}^{sp}\right)+\left(C_s^{se}\times\sum_{ST}D_{st,s,t}^{se}\right)\right]\\+C_{p,t}\times\left(E_{de,t}-E_{ge,t}\right)+\sum_{gh}^{GH}(C_{gh,flare}\times f_{gh,flare,t})+C_c\times\sum_{B}f_{b,c,t}\end{array}\right\} \quad (1)$$

2.2 Operational model

2.2.1 Operational model for fuel boilers

Fuel boilers are used to generation steam to satisfy the need of plant for steam supply. The capacity of fuel boilers depended on the quantity of the steam with required pressure and temperature.

$$D_{b,s}^{min}\le D_{b,s,t}\le D_{b,s}^{max} \quad (2)$$

Eq. (3) shows the feed flow rate of the consumption of the byproduct gases of the boilers.

$$\mathrm{f}_{\mathrm{b,g}}^{\mathrm{min}}\le\mathrm{f}_{\mathrm{b,g,t}}\le\mathrm{f}_{\mathrm{b,g}}^{\mathrm{max}} \quad (3)$$

The heating value provided by the byproduct gas to a boiler *b* should limit in the minimum heating value and the maximum heating value.

$$H_b^{min}\le\frac{\sum_G\left(f_{b,g,t}\times H_g\right)}{\sum_G f_{b,g,t}}\le H_b^{max} \quad (4)$$

The energy balance of a boiler *b* during every time period *t* is expressed as Eq. (4). There has a assumption that the water feed into the boiler would transform into steam with no loss.

$$\eta_{b,t}\times\sum_S\left(D_{b,s,t}\times H_{b,s,t}\right)=\sum_G\left(f_{b,g,t}\times H_g\right)+Water_{b,t}\times H_{b,Water,t} \quad (5)$$

2.2.2 Operational model for steam turbines

A steam turbine is designed to transform the steam to the electricity power, and relieve medium or low-pressure steam to supply the demand of the steel plant, meanwhile.

Eq. (6) shows the energy balance constraints in each turbine. The inlet steam flow rate of a turbine during period t must between its lower ($D_{st,in}^{min}$) and upper ($D_{st,in}^{max}$) limits, showed in Eq. (7). Eq. (8) and (9) shows the limit of the outlet steam flow rate and the power generation rate.

$$P_{st,t}\times HC^P=\eta_{st,t}\left[D_{st,t}^{in}\times H_{st,t}^{in}-\sum_S\left(D_{st,s,t}^{out}\times H_{st,s,t}^{out}\right)-D_{st,t}^{exh}\times H_{st,t}^{exh}\right] \quad (6)$$

$$D_{st,in}^{min}\le D_{st,t}^{in}\le D_{st,in}^{max} \quad (7)$$

$$D_{st,out}^{min}\le D_{st,t}^{out}\le D_{st,out}^{max} \quad (8)$$

$$P_{st}^{min}\le P_{st,t}\le P_{st}^{max} \quad (9)$$

2.2.3 Operational model for gasholders

The gasholder operation model contains the buffer capacity constraint and limit constraint, which ensure the security of the gasholder. The maximum capacity of the gasholder is assumed via Eq. (9). And Eq. (10) shows the buffer capacity constraint of the gasholder.

$$GV_{gh,min}\le V_{gh,t}\le GV_{gh,max} \quad (10)$$

$$-\Delta V_{gh}^{max}\le V_{gh,t}-V_{gh,t-1}\le\Delta V_{gh}^{max} \quad (11)$$

2.3 Characteristic curve of equipment

In this paper, the characteristic curves of the boiler efficiency and the turbine power were set up in the MINLP model. Eq. (11) is the general formula for the quadratic fitting curve for the boiler. The quadratic fitting curve between the power and the inlet steam in the turbine has showed in Eq. (12).

$$\eta_{b,t}=a\times d_{b,s,t}^2+b\times d_{b,s,t}+c \quad (12)$$

$$\mathrm{P_{st,t}=p\times\left(D_{st,t}^{in}-D_{st,t}^{exh}\right)^2+q\times\left(D_{st,t}^{in}-D_{st,t}^{exh}\right)+l} \quad (13)$$

3. CASE STUDY

A case carried out in this study is based on the reality data in an iron and steel plant in Chinese northern city. The plant consists of two blast furnaces (BF) with two blast furnace gas (BFG) gasholders, four coke ovens (CO) with a coke oven gas (COG) gasholder. The EMS have two types of four boilers (B1-B2), one type of two turbines (T1), two Coke Dry Quenching with two waste heat boilers (CDQ) with corresponding turbines (T2), two CHP units (CHP) with corresponding turbines (T3), as shown in Fig. 1. The quadratic fitting function between the heat efficiency and steam generation for the boilers, and the power generation and inlet steam for the turbines are shown in Table 1 of Appendix B.

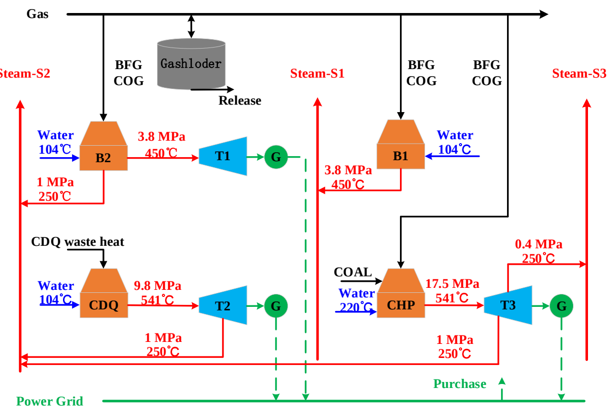

Fig. 1. A schematic view of byproduct gases, steam and power distribution network

There are four kinds of steam differentiated by steam pressure, which are super high-pressure steam S0 with the highest pressure of 9.8MPa, high pressure steam S1 with the high pressure of 3.8MPa, medium pressure steam S2 with a medium pressure of 1.3MPa, and low-pressure steam S3 with a pressure of 0.8MPa. Three types of byproduct gases, BFG, COG and LDCG have different heat values, there are 3652, 17000 and 7500 kJ/Nm^3, respectively. Besides, the boilers in this case study only use BFG, COG and coal as the energy consumption.

This model is established by Pyomo and solved by ipopt on a Lenovo XiaoXinPro16 of R7-5800h at 3.2Ghz and 16GB RAM running on Windows 10.

4. RESULTS

The dataset of the example collected in a steel industry in northern China is from 14-Mar-2018 in 30-min interval. The period spans over 8 hours. The optimal solution is obtained within 1 min. Table 2 lists comparative results from the optimal model and the actual operation. From table 2, the total cost after optimization decreased approximately 3.2% compared to the actual result. Compared to the increase of GUC, the decrease of power sale cost could reduce more cost, which could bring more benefits to companies. The increase of GUC could complain through Fig. 3 that more gas was consumed to generate power and steam. The decrease of SUC is that the reasonable distribution of steam.

Table 2 Cost results comparison

Item (CY)	Actual	Optimal	Change (%)
GUC	657502	687862.7	4.6
CUC	437250	421335.8	-3.6
SUC	269160.2	243969.3	-9.3
Power purchase cost	4148.2	2123.5	-48.8
Power sale cost	-220504	-244361	10.8
GPC	0	0	
Total cost	1147557	1110930	-3.2

Fig.2 shows the comparison of electricity generation after optimization with the actual operation. It could be found that the electricity generation is higher than the actual operation under the TOU power price. That because the optimal goal of this MINLP model is economic cost, and it is benefits to more electricity generation. With the steady operation of electricity generated equipment, their efficiency is improved and could generate more power, as showed in Fig. 2 and Fig. 5.

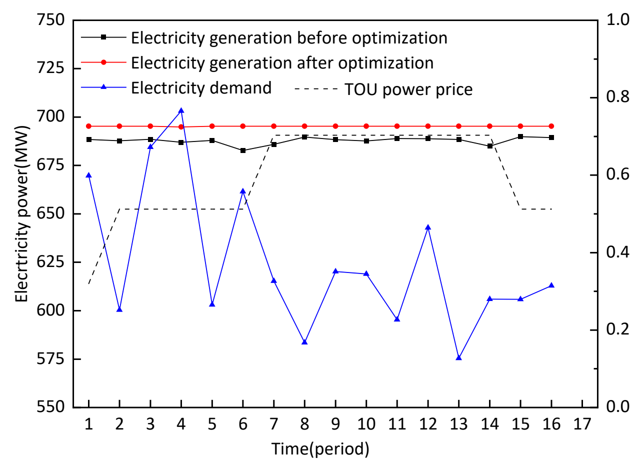

Fig. 2. Optimal electricity generation

The fluctuation curve of the gasholder level is shown in Fig. 3 and Fig.4. As figures showed, the gasholder

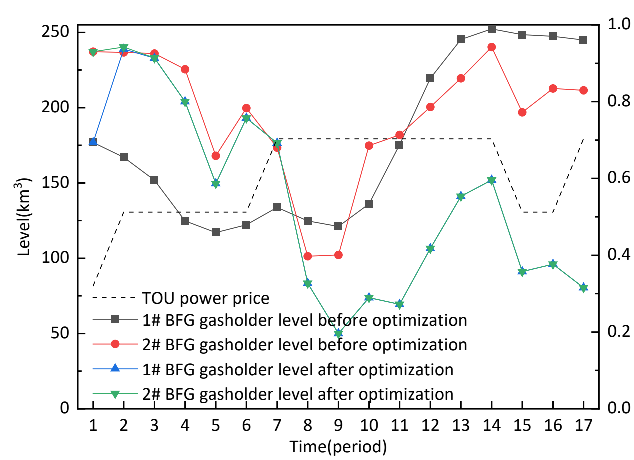

Fig. 3. Optimal level of BFG gasholder

deviation has the same trend compared to the actual level of gasholder. After optimization, the level of BFG gasholders is lower compared to the actual level. Considering to the steady operation of equipment and the TOU power price, it is wise to use more byproduct gases to generate power, especially at Time = 7 to 14. Due to the amount consumption of BFG, the level of COG gasholder drops rapidly at Time = 4 to 9, and reach the minimum limit and rises immediately at Time = 12.

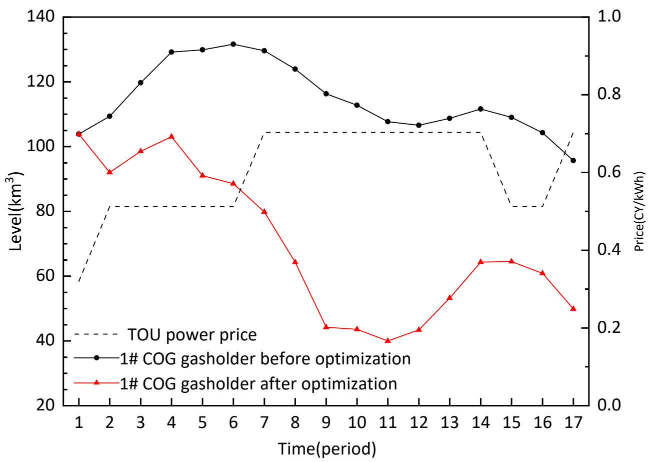

Fig. 4. Optimal level of COG gasholder

Fig. 5 showed the efficiency of boilers before and after optimization. The boilers after optimization have the higher average efficiency, and has more stability operation conditions to generate more power, that increase the power sale to grid.

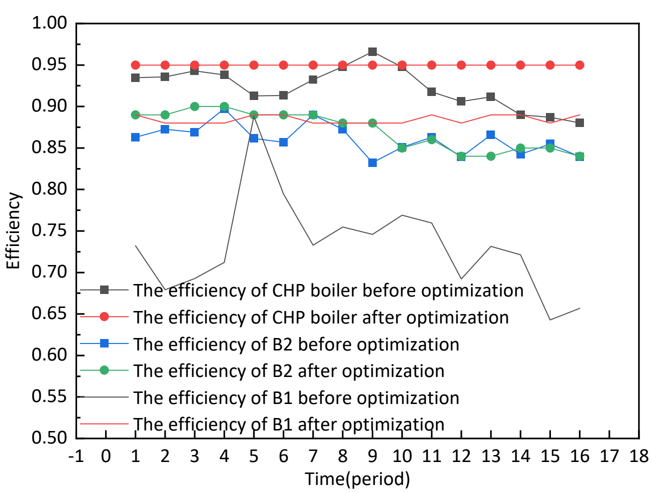

Fig. 5. Optimal efficiency of boilers

5. CONCLUSIONS

In this paper, a MINLP model of the EMS has been proposed by considering the TOU power price and releasing some limit of gasholder. Research based on the mass balance and energy balance, do simultaneous optimization of the distribution of byproduct gases, steam, and power between some types of boilers. Furthermore, the quadratic function curve of the boiler and turbine are fitted to close the actual working conditions. The optimization results are summarized as follows.

1) The total cost decreased 3.2% in 8 h operation, and the power sale cost drop down by 10.8% compared to the actual operation.
2) The efficiency of the boilers and turbines has been fitted by quadratic function to close the actual operations. Furthermore, the efficiency is more stability and higher after optimization.

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Appendix A

NONMENCLATURE

Abbreviations	
TOU	Time-of-use
EMS	Energy management system
MILP	Mixed-integer linear program
MINLP	Mixed-integer nonlinear program
CHP	Combined heat and power
GUC	Byproduct gases usage cost
SUC	Steam usage cost
EPC	Electricity purchase cost
CUC	Coal usage cost
BFG	Blast furnace gas
COG	Coke oven gas
Super/subscript	
B	Index of boilers
G	Index of byproduct gases
S	Index of steams
ST	Index of steam turbines
flare	flare of gasholder
t	Index of time period
Symbols	
C_g	Byproduct gas usage price
$f_{b,g,t}$	The flow rate of the *g* type of byproduct gases from boiler *b*
C_s^{sp}	The price of *s* type of steam from boilers
C_s^{se}	The price of *s* type of steam from turbines
$D_{b,s,t}^{sp}$	The demand of *s* type steam from boilers
$D_{st,s,t}^{se}$	The demand of *s* type steam from turbines
$E_{d,t}$	The demand electricity power
$E_{g,t}$	The generated electricity power
$C_{p,t}$	The power purchase price per kWh
$C_{s,t}$	The power sale price per kWh
$C_{g,flare}$	The flaring penalty price
$f_{g,flare,t}$	The volume amount of *g* type of flaring gas
$D_{b,s,t}$	The steam flow of steam from boilers
$D_{b,s}^{min}$	Minimum steam flow of boilers
$D_{b,s}^{max}$	Maximum steam flow of boilers
$f_{b,g,t}$	The flow rate of byproduct gases of boiler
$f_{b,g}^{\min}$	Minimum feed flow of byproduct gases of boilers
$f_{b,g}^{\max}$	Maximum feed flow of byproduct gases of boilers
H_g	The heating value of byproduct gases
H_b^{min}	Minimum heating value required in boiler *b*
H_b^{max}	Maximum heating value required in boiler *b*
$\eta_{b,t}$	Thermal efficiency for boiler *b*
$H_{b,s,t}$	Enthalpy of the *s* level of steam
$Water_{b,t}$	Water flowing into boiler *b*
$H_{b,Water,t}$	Enthalpy of boiler feed water
$P_{st,t}$	Power generation rate from turbine
HC^P	Energy content of electricity
$\eta_{st,t}$	The electricity efficiency of turbine
$D_{st,t}^{in}$	The inlet steam in turbine *st*
$D_{st,s,t}^{out}$	The outlet of the *s* level of steam in turbine *st*
$D_{st,s,t}^{exh}$	The exhaust steam streaming from turbine *st*
$D_{st,in}^{min}$	The lower limit of the inlet steam flow rate of turbine *st*
$D_{st,in}^{max}$	The upper limit of the inlet steam flow rate of turbine *st*
$D_{st,out}^{min}$	The lower limit of the outlet steam flow rate of turbine *st*
$D_{st,out}^{max}$	The upper limit of the outlet steam flow rate of turbine *st*
P_{st}^{min}	Minimum electricity generation rate from turbine *st*
P_{st}^{max}	Maximum electricity generation rate from turbine *st*
$GV_{gh,min}$	Minimum storage capacity of the gasholder *gh*
$GV_{gh,max}$	Maximum storage capacity of the gasholder *gh*
$V_{gh,t}$	The storage level of gasholder *gh*
$\eta_{b,t}$	Efficiency of boiler *b*
a, *b*, and *c*	Coefficients of the quadratic function of boiler *b*
$d_{b,s,t}$	The steam flow generated by boiler *b*
p, *q*, and *l*	Coefficients of the quadratic function of turbine *st*

Appendix B

Table 1 The Curve of Equipment Characteristic

Equipment	Efficiency/The curve of power generation
B1	$\eta=0.7555\times(D_{b,s}/35)^2+1.4468\times(D_{b,s}/35)+0.1966$
B2	$\eta=-1.461\times(D_{b,s}/130)^2+3.2126\times(D_{b,s}/130)-0.8305$
CHP	$\eta=-0.093\times(D_{b,s}/1025)^2+0.225\times(D_{b,s}/1025)+0.828$
T1	$P=-6.288\times(D_{st,in}-D_{st,ex})^2+1191\times(D_{st,in}-D_{st,ex})-33610$
T2	$P=2\times(D_{st,in}-D_{st,ex})^2-248.1\times(D_{st,in}-D_{st,ex})+27590.4$
T3	$P=-0.3574\times(D_{st,in}-D_{st,ex})^2+807.9\times(D_{st,in}-D_{st,ex})-82380$