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Research on coordinated optimization of unit maintenance plan and economic dispatch in the integrated energy system

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Abstract: The medium and long-term operation of the unit is an important part of the operation of the power energy system. With the development of IES, the coupling of various energy forms such as electricity, heat and natural gas has been continuously strengthened. When a CHP unit or a gas unit is shut down, its impact will involve a variety of energy systems. Therefore, It is of great significance to formulate a reasonable annual unit combination plan and a coordinated optimization plan for the maintenance plan. First of all, starting from the coupling mechanism of the power supply, heating and gas supply of the unit, consider the relationship between each system and equipment. On this basis, taking into account the system operation constraints, unit maintenance constraints and unit operation constraints, a combined dispatch model of IES unit combination and maintenance plan including power-to-gas (P2G) and electric boiler equipment are proposed. The accuracy and effectiveness of the proposed model are verified through simulation analysis of a numerical example. The calculation example results show that the overall arrangement of the unit maintenance plan and the unit combination plan in the integrated energy system can improve the operating economy of the system; the introduction of coupling equipment such as P2G and electric boilers can effectively improve the new energy consumption rate and reduce the system operating cost.

1. Introduction

Energy is an important material basis for the survival and development of human society. With the popularization and application of multi-generation equipment, the electric power system, thermal system and natural gas system that originally operated in isolation have been developed into an integrated energy system(IES) with multiple energy interconnections. The IES can greatly improve the utilization efficiency of energy, increase the consumption of new energy, and reduce the cost of the system. Therefore, the traditional medium and long-term analysis and optimization methods for single energy sources are no longer applicable, and a medium and long-term operation optimization method for IES needs to be proposed.

In IES, electricity, heat, and gas are interconnected through co-generation units and coupling equipment. When a unit or equipment is overhauled, its impact will involve multiple energy systems. In the current research on generating unit power generation plans, the unit maintenance plan and the unit combination plan are essential to forming a safe, stable and economic system. At present, the unit maintenance plan and the unit combination plan are often formulated separately, that is, the unit combination plan is formulated on the basis of the unit maintenance plan. Thus resulting unit maintenance plan may cause the future unit combination to be difficult to meet the constraints of system operation. At this time, it is necessary to manually revise the unit maintenance plan, which reduces the scientificity and efficiency of the system power structure optimization decision. Reference [5] only considers the system safety, and does not consider the economic cost of the system, and plans the unit maintenance period arrangement; reference [6] fully considers the problem of insufficient spare capacity that may be caused by equipment maintenance, so as to wait for the principle of spare and The principle of minimum power shortage determines the objective function to ensure the safe operation of the system; reference [7] fully considers the constraints of system operation and sets N-1 fault constraints to prevent unnecessary power outages; the contribution of reference [8] is mainly based on the in-depth analysis of the correlation mechanism between the maintenance decision and the operation decision, and optimize the minimum cost. Aiming at the objective, the reference proposed a Benders decomposition method for joint decision-making of unit maintenance and unit combination. Most current researches aim to minimize the total cost of the system, while reliability is generally embedded in the model as a constraint, or added to the economic model by converting it into a corresponding cost.

In general, the research in the existing reference mostly focuses on the maintenance plan or the unit combination plan of a single power system, and rarely conducts research on IES. Against this background, this paper fully considers the coupling of electricity, heat and gas, and proposes a collaborative optimization model of the unit maintenance plan and unit combination plan in IES. Under the premise of ensuring system safety and unit maintenance requirements, the model reduces the cost of system operation and improves the wind power consumption rate. In order to realize the coordinated optimization of generator scheduling and unit maintenance, the model introduces the constraints related to unit maintenance and unit maintenance costs, and introduces the constraints of unit combination. In order to increase the consumption of wind, the paper introduced P2G and an electric boiler. Finally, mixed integer linear programming is used to solve the model, and the validity of the proposed model is verified by an example.

2. Integrated energy system and coupled equipment model

The input and output of electricity, heat, gas and the conversion of energy are important components of IES. Multiple energy sources are mutually converted and coordinated within the system. While meeting the different load demands of users, it can improve energy supply efficiency, reduce environmental pollution, and increase the flexibility and stability of the energy supply. The schematic diagram of IES is shown in Figure 1.

The coupling equipment of IES is mainly P2G and electric boiler equipment. The electric boiler equipment realizes electric-heat conversion by consuming electric energy and heating the water in the boiler; P2G is a new technology that converts electrical energy into natural gas. First, the excess electrical energy is used to electrolyze water to produce hydrogen, and then hydrogen and carbon dioxide are synthesized to produce methane. The two-stage chemical reaction equation of P2G technology is as follows:

$$2H_2O \xrightarrow{\text{electrolyze}} 2H_2 + O_2 \tag{1}$$

$$CO_2 + 4H_2 \longrightarrow CH_4 + 2H_2O \tag{2}$$

The consumption characteristic of P2G is shown in Equation (3):

$$V_{P2G} = \frac{P_{P2G} \times \eta_{P2G}}{H_G} \tag{3}$$

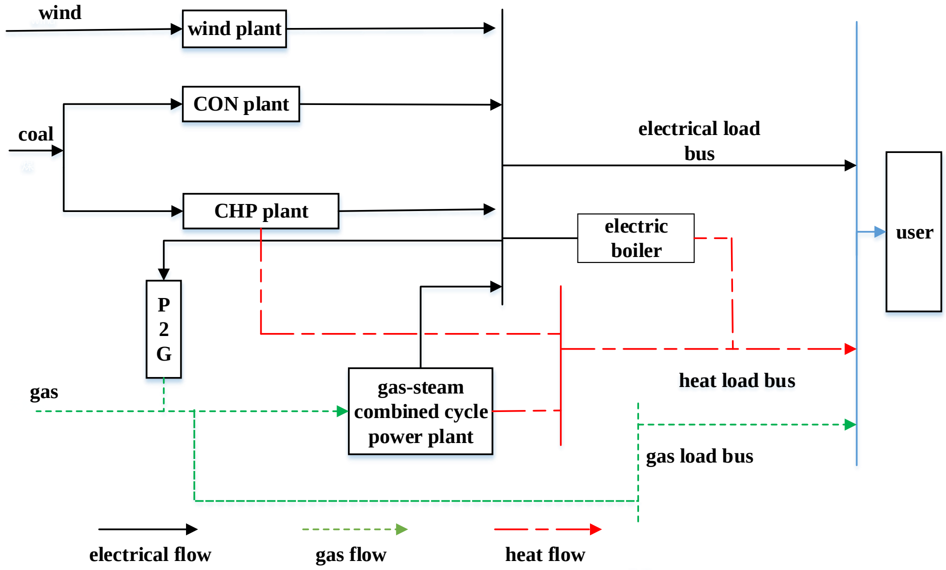

Figure 1. System structure diagram of IES.

The investment of P2G and an electric boiler can couple the electricity, heat, and gas, greatly reducing the rate of wind curtailment in the system. For example, when the electric load is low and the wind power output is large, it will cause difficulty in wind power consumption. If the electric boiler or P2G is activated at this time, the excess wind power can be converted into heat energy and natural gas, which not only saves costs but also has the effect of increasing wind consumption. Taking P2G as an example, the diagram of P2G to consume wind is shown in Figure 2. The equivalent electrical load is the electrical load minus the predicted output of wind power. If the equivalent electrical load is less than the forced output of the unit, wind abandonment will occur. When the P2G is installed, P2G can be put into operation during the wind abandonment period, which is equivalent to increasing the equivalent electrical load and reducing the wind abandonment rate of the system.

In order to avoid the loss caused by unnecessary energy conversion, the P2G and electric boilers in the system adopt abandoned wind start-stop strategy. The judgment criterion is shown in Equation (4).

$$flag=\begin{cases} 1, & P_{gas}^{forced}+P_w+P_{CON}^{forced}+P_{CHP}^{forced}>P_{load} \\ 0, & P_{gas}^{forced}+P_w+P_{CON}^{forced}+P_{CHP}^{forced}<P_{load} \end{cases} \tag{4}$$

In this formula, P_{gas}^{forced} is the sum of the forced output for all gas units; P_{CON}^{forced} is the sum of the forced output for all CON units; P_{CHP}^{forced} is the sum of the forced output for all CHP units; P_w is wind power forecast output.

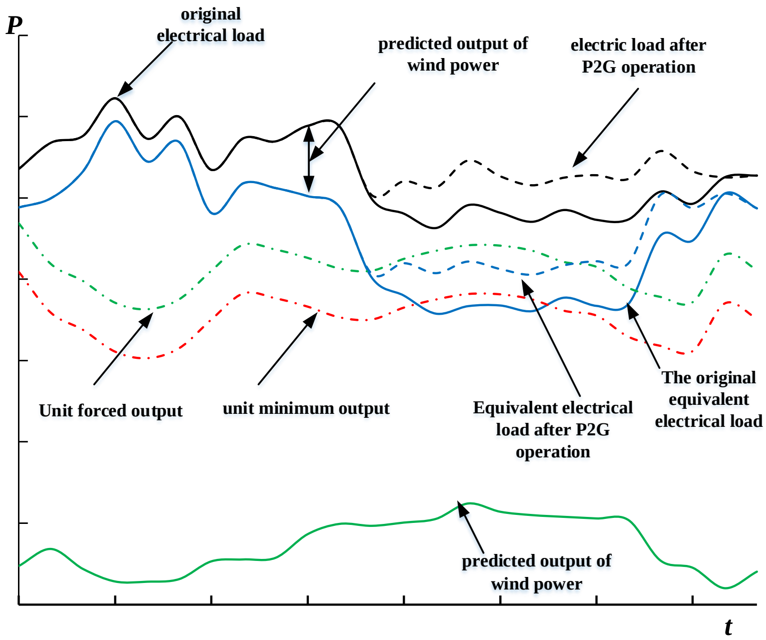

Figure 2. The diagram of P2G to consume wind.

3. Unit maintenance plan and unit combination collaborative optimization model of IES

3.1. Objective function

The unit maintenance plan and unit combination are both important components of the optimization of the power supply operation structure of the power system. The large-scale access to new energy sources such as wind power and the promotion of smart grid dispatching have put forward new requirements for the operational structure of the power system power supply. In the previous planning mode, the unit maintenance plan is usually first formulated, and then, under the premise of the unit maintenance plan, the start-up and shutdown plan of the unit is optimized and decided. If the security constraints of the power grid are considered in this operation mode, the unit combination model may not find a solution. At the same time, with the large-scale access to new energy sources such as wind power in recent years, it is urgent to plan the start-up and shutdown of units in a longer time scale, reduce the wind abandonment rate, and improve the energy saving and emission reduction benefits of the power grid.

The model in this paper mainly takes economy as the optimization objective. That is, the optimization goal is to minimize the maintenance cost and system operation costs. When arranging the unit maintenance plan, it is necessary to ensure that the IES can achieve a balance between supply and demand in each maintenance cycle. Suppose there is one wind farm; K CON units; A gas-steam combined cycle plant, R gas-steam combined cycle units in the plant; I thermal power plants, J CHP units in the plants, each heating power plant is equipped with 1 electric boiler; H and P2G are installed in the system; There are M units in the system that need to declare maintenance plans; The objective function is specifically expressed as follows:

$$\begin{cases} \min F = F_I + F_{II} \\ \begin{cases} F_I = \sum_{m=1}^{M}\sum_{t=1}^{T} X_{m,t} w_m + \sum_{m=1}^{M} \Delta w_m \\ F_{II} = C_1 \sum_{t=1}^{T} V_{buy}^{t} + C_2 (\sum_{t=1}^{T}\sum_{i=1}^{I}\sum_{j=1}^{J} U_{i,j,t} F_{CHP}^{t,i,j} + \sum_{t=1}^{T}\sum_{k=1}^{K} U_{k,t} F_{CON}^{t,k}) + \sum_{t=1}^{T}\sum_{g=1}^{I+J} S_{g,t} U_{g,t} (1-U_{g,t-1}) \end{cases} \end{cases} \tag{5}$$

In this formula, F is the total cost of co-optimization scheduling; F_I is the maintenance cost; F_{II}

is the power generation cost; T is the period of optimizing the total scheduling; w_m is the ideal overhaul time for unit m; Δw_m is additional cost due to adjustment of the maintenance plan; V_{buy} is purchase volume of natural gas; $F_{CHP}^{t,i,j}$ is the coal consumption of the j CHP unit of the i CHP plant in t period; $F_{CON}^{t,k}$ is the coal consumption of the k CON unit in t period; $S_{g,t}$ is g unit startup cost in t period; $U_{g,t}$ is the operation state of unit g in t period; if $U_{g,t}$ is 1, it means the unit is running; if $U_{g,t}$ is 0, it means unit has shut down; C_1、C_2 is the price of natural gas and coal.

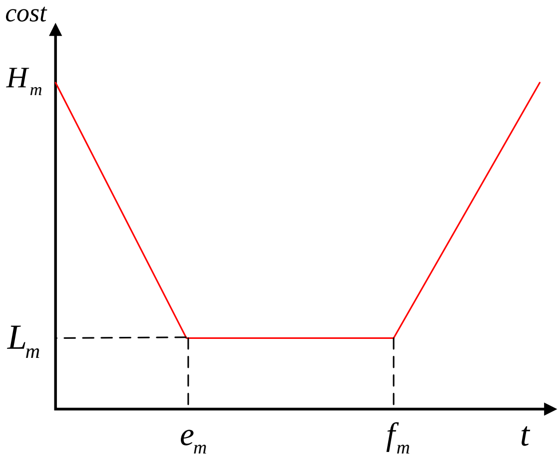

Figure 3. Unit maintenance cost

The maintenance cost of the unit is shown in Figure 3, [e_m, f_m] is the ideal maintenance period for unit five submitted by the power plant to the dispatch department, L_m and H_m is the minimum and maximum maintenance cost for unit m.

3.2. Maintenance-related constraints

3.2.1.Maintenance time constraints

$$\sum_{t=t_{m,\min}}^{t=t_{m,\max}} X_{m,t} = 1 \tag{6}$$

3.2.2.Maintenance status constraints

$$Y_{m,t} = \sum_{t_1=t-T_m+1}^{t} X_{m,t_1} \tag{7}$$

3.2.3.Simultaneous maintenance constraints

$$\sum_{t=1}^{T} (X_{m_i,t} - X_{m_j,t}) = 0 \tag{8}$$

3.2.4.Mutually exclusive maintenance constraints

$$\sum_{t=1}^{T} (Y_{m_i,t} \times Y_{m_j,t}) = 0 \tag{9}$$

3.2.5.Continuous maintenance constraints

$$\sum_{t_1=t-T_m+1}^{t} Y_{m,t} = 0 \tag{10}$$

3.2.6, Relational constraints between the start-stop status and the maintenance status

$$U_{m,t} \le 1 - Y_{m,t} \tag{11}$$

3.2.7.Integer constraints on unit states

$$U_{m,t}、Y_{m,t}、X_{m,t} \in \{0,1\} \tag{12}$$

3.2.8.System Spare Capacity Constraints

$$\sum_{i=1}^{N} U_{i,t} P_{i,t} \ge D_{t,\max}(1+r_+) \tag{13}$$

In the above formula, $X_{m,t}$ is the sign of unit m start maintenance, and if $X_{m,t}$ is 1, it means the unit will start overhaul; $Y_{m,t}$ is the sign of unit m Maintenance status, and if $Y_{m,t}$ is 1, it means the unit is under maintenance; $t_{m,\min}$ and $t_{m,\max}$ are the earliest and latest maintenance time of unit m; T_m is continuous maintenance time of unit m; D_t is the electrical load in t period; r_+ is System reserve factor.

3.3. System-related constraints

3.3.1.Electric power balance constraint

$$\sum_{i=1}^{I}\sum_{j=1}^{J} U_{i,j,t} P_{CHP}^{t,i,j} + \sum_{k=1}^{K} U_{k,t} P_{CON}^{t,k} + \sum_{r=1}^{R} U_{r,t} P_{GAS}^{t,r} + P_{wind}^{t} = \sum_{d=1}^{D} P_{load}^{t,d} + \sum_{h=1}^{H} P_{P2G}^{t,h} + \sum_{i=1}^{I} P_e^{t,i} + \sum_{r=1}^{R} P_e^{t,r} \tag{14}$$

In the formula, $P_{CHP}^{t,i,j}$ is the average electric power of the j CHP unit of the i CHP plant in t period; $P_{CON}^{t,k}$ is the average electric power of k CON unit in t period; $P_{GAS}^{t,r}$ is the average electric power of r gas-steam combined cycle unit in t period; P_{wind}^{t} is average wind power output in t period; $P_{load}^{t,d}$ is the average electrical load in t period; $P_{P2G}^{t,h}$ is the average electric power of h P2G in t period; $P_e^{t,i}$ is the average electric power of i electric boiler of the i CHP plant in t period.

3.3.2.Heat balance constraint

$$\sum_{j=1}^{J} U_{i,j,t} Q_{CHP}^{t,i,j} + Q_e^{t,i} = Q_{load}^{t,i},\ i = 1, 2 \cdots I \tag{15}$$

$$\sum_{r=1}^{R} U_{r,t} Q_{GAS}^{t,r} + Q_e^{t,GAS} = Q_{load}^{t,GAS} \tag{16}$$

In the formula, $Q_{CHP}^{t,i,j}$ is the average heat power of the j CHP unit of the i CHP plant in t period; $Q_{GAS}^{t,r}$ is the average heat power of r gas-steam combined cycle unit in t period; $Q_e^{t,i}$ is the average heat power of i electric boiler of the i CHP plant in t period; $Q_e^{t,GAS}$ is the average heat power of electric boiler of gas-steam combined cycle plant in t period; $Q_{load}^{t,i}$ is the average heat load of i CHP plant in t period; $Q_{load}^{t,GAS}$ is the average heat load of gas-steam combined cycle plant in t period.

3.3.3.Gas balance constraint

$$V_{buy}^{t}+V_{P2G}^{t,h}=U_{r,t}V_{GAS}^{t,r}+V_{load}^{t} \tag{17}$$

In the formula, $V_{GAS}^{t,r}$ is gas consumption of r gas-steam combined cycle unit in t period; V_{load}^{t} is gas load demand in t period; V_{buy}^{t} is gas purchase volume in t period; $V_{P2G}^{t,h}$ is gas production of h P2G in t period.

3.4. Unit-related constraints

3.4.1.CON unit output

$$U_{k,t}P_{CON.\min}^{k}\le P_{CON}^{t,k}\le U_{k,t}P_{CON.\max}^{k} \tag{18}$$

In the formula, $P_{CON.\min}^{k}$ and $P_{CON.\max}^{k}$ are electric output upper and lower limit of unit k.

3.4.2.CHP unit output

$$\begin{cases}U_{i,j,t}(P_{CHP.\min}^{i,j}+b_L D^{t,i,j})\le P_{CHP}^{t,i,j}\le U_{i,j,t}(P_{CHP.\max}^{i,j}-b_H D^{t,i,j})\\ U_{i,j,t}D_{CHP.\min}^{i,j}\le D^{t,i,j}\le U_{i,j,t}D_{CHP.\max}^{i,j}\end{cases} \tag{19}$$

In the formula, $P_{CHP.\min}^{i,j}$ and $P_{CHP.\max}^{i,j}$ are electric output upper and lower limit of j CHP unit of i CHP plant; $D_{CHP.\min}^{i,j}$ and $D_{CHP.\max}^{i,j}$ are pumping rate upper and lower limit of j CHP unit of i CHP plant.

3.4.3.Gas-steam combined cycle unit output

$$\begin{cases}U_{r,t}P_{GAS1.\min}^{r}\le P_{GAS1}^{t,r}\le U_{r,t}P_{GAS1.\max}^{r}\\ U_{r,t}P_{GAS2.\min}^{r}\le P_{GAS2}^{t,r}\le U_{r,t}P_{GAS2.\max}^{r}\\ U_{r,t}Q_{GAS2.\min}^{r}\le Q_{GAS2}^{t,r}\le U_{r,t}Q_{GAS2.\max}^{r}\end{cases} \tag{20}$$

In the formula, $P_{GAS1.\min}^{r}$ and $P_{GAS1.\max}^{r}$ are electric output upper and lower limit of gas unit r; $P_{GAS2.\min}^{r}$ and $P_{GAS2.\max}^{r}$ are electric output upper and lower limit of steam unit r; $Q_{GAS2.\min}^{r}$ and $Q_{GAS2.\max}^{r}$ are heat output upper and lower limit of steam unit r.

4. Case analysis

4.1. Case system

The case system consists of 1 CON plant (configured with 6 CON units, number #7-#13), 2 CHP plants (with CHP plant 1 and CHP plant 2 respectively equipped with 3 CHP units, number #1-#6), 1 wind farm (installed wind power capacity of 300MW), 1 steam-gas combined cycle power plant (configured with 1 steam-gas combined cycle unit, number #7), 3 electric boilers (number #14-#16), 1 P2G(number #17). The study period is 1 year, divided into 52 weeks. Some units and load data are presented [2][3], and Table 1 shows unit maintenance information.

Table 1 Expected time for maintenance of the unit

	#3	#7	#8	#14
expected time	30	25	15	35

4.2. Analysis of optimized results

In order to verify the effectiveness of the model proposed in this paper, the following four cases are analyzed:

Case 1: The unit combination plan is formulated separately, and the maintenance plan is not considered;

Case 2: The unit maintenance plan and the unit combination plan are formulated at the same time, but the maintenance cost is the same for the entire period.

Case 3: Each power plant submits the intended maintenance time to the dispatch department (the maintenance cost is the lowest at this time), and the dispatch department formulates the unit combination plan according to the maintenance plan;

Case 4: Each power plant submits the intended maintenance time to the dispatching department, and the dispatching department revises the maintenance plan submitted by each power plant to realize the coordinated optimization of maintenance and power generation.

The scheduling schemes of the 4 cases are shown below, in which black means the unit is in a maintenance state, white means the unit is in a shutdown state caused by unit combination, and gray means the unit is in a running state.

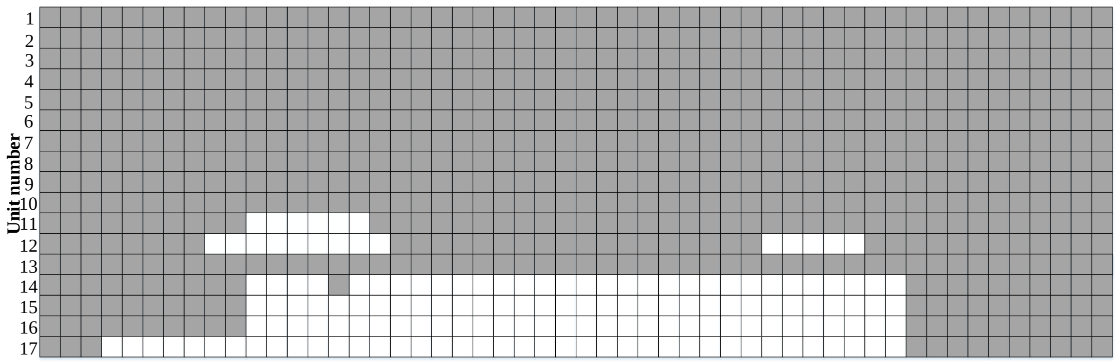

Figure 4. Case 1 scheduling scheme

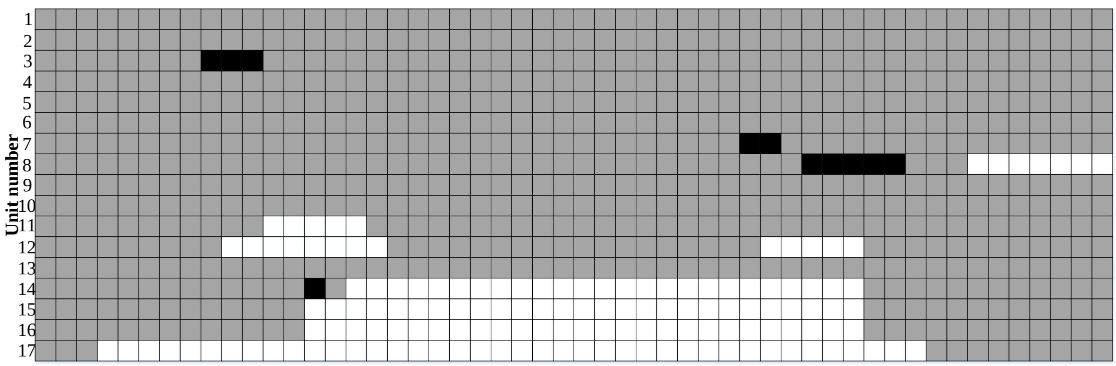

Figure 5. Case 2 scheduling scheme

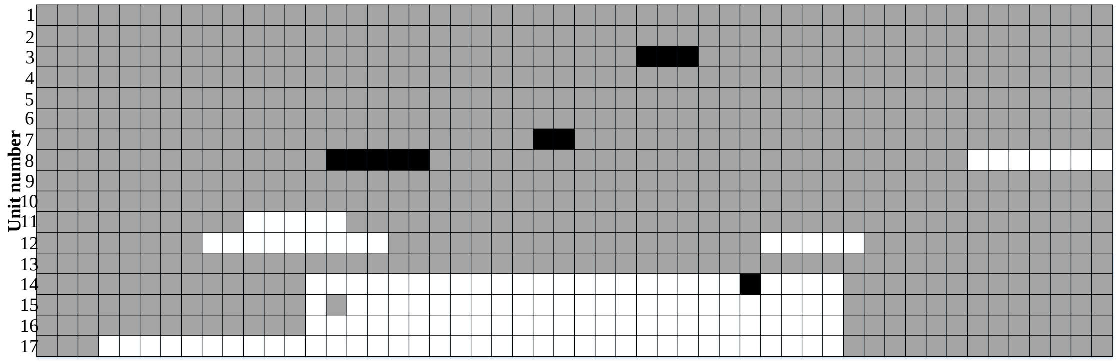

Figure 6. Case 3 scheduling scheme

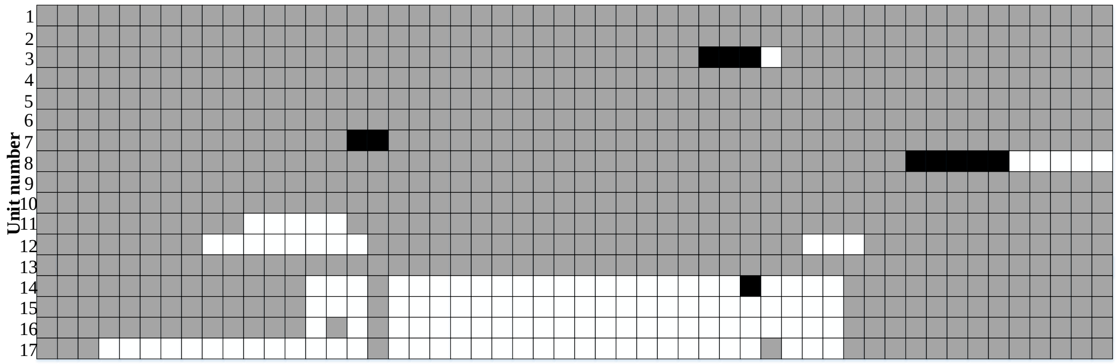

Figure 7. Case 4 scheduling scheme

The maintenance plan under case 2-case 4 is shown in Table 2:

Table 2 maintenance plan under case2-case4

Maintenance equipment	Maintenance start time		
	case2	case3	case4
#3	9	30	33
#7	35	25	16
#8	38	15	43
#14	14	35	35

The calculation results of coal consumption, gas purchase volume and wind curtailment rate before and after the installation of P2G and electric boilers in the system are shown in Table 3 (case 4), and the wind power is shown in Figure 8.

Table 3 coal consumption, gas purchase volume and wind curtailment rate

	coal consumption(t)	gas purchase(m^3)	wind curtailment rate %
Install P2G and electric boilers	30827.10	431161.56	7.596
No P2G and electric boilers	30914.98	436766.8548	0.556

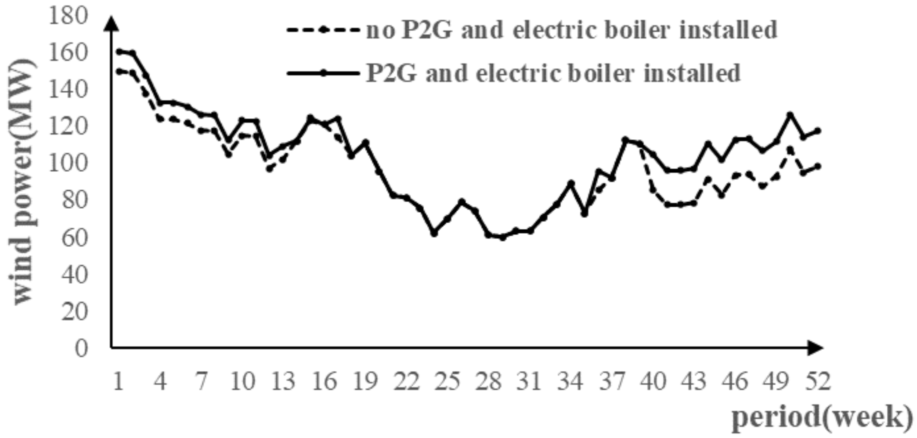

Figure 8. Wind power on the grid

The cost comparison under case1-case4 is shown in Table 4:

Table 4 Total cost under case1-case4

	Case1	Case2	Case3	Case4
total cost(RMB)	22161738.26	22316433.36	22375454.4	22344053.37

It can be seen from Table2 that under case4 (unit maintenance and unit combination collaborative optimization), the maintenance plans of #3, #7, #8, and #14 are all adjusted on the basis of the ideal maintenance period. The CHP unit 3 is scheduled for maintenance during the period of low heat load, the CON unit 9 is scheduled for maintenance during the period with low electrical load, and the electric boiler is scheduled for maintenance during the period when both heat and the electrical load are low.

It can be seen from Table3 and Figure8 that in the period of low load and large wind power output, wind power can't be completely consumed, resulting in the phenomenon of wind curtailment. After the P2G and electric boiler are installed in the system, the effect of "filling the valley" is realized, the system consumes more wind energy, effectively reduces the wind curtailment rate, and reduces the coal consumption, and gas purchase volume of the system.

As can be seen from Table4, comparing case1 and case2, arranging the unit maintenance plan will affect the original unit combination plan, resulting in an increase in the total cost; comparing case3 and case4, it can be seen that compared with the independent formulation of the maintenance plan and the unit combination plan, the cost of the collaborative optimization plan is greatly reduced, which verifies the effectiveness of the collaborative optimization model in IES.

5. Conclusions

Based on the IES, this paper proposes a collaborative optimization model of a unit maintenance plan and unit combination plan. At the same time, in order to improve wind power consumption, P2G and electric boiler equipment are introduced in the model. The simulation case proves that the collaborative optimization model can reasonably arrange the unit maintenance time and reduce the system cost; the installation of P2G equipment and electric boilers can greatly reduce the system wind curtailment rate.

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