Scheduling of electric-thermal integrated energy system considering environmental cost

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Abstract. Coordinated scheduling of electric heating comprehensive energy system is an effective measure to promote wind power consumption and solve environmental problems fundamentally. In the existing coordinated scheduling of electric heating, the optimization goal usually only considers the minimum of abandoned wind or the minimum of overall coal consumption of the system, and does not directly take pollutant emission as the optimization index. In the actual operation, the target of minimum total coal consumption or light rejection rate of abandoned air is likely to be inconsistent with the target of minimum pollutant emission. Therefore, this paper proposes a coordinated scheduling model of electric heating comprehensive energy system considering environmental cost, selects the appropriate expression form of environmental cost, unifies the economic cost and environmental cost, and takes its weighted sum value as the optimization goal, so as to achieve the lowest comprehensive economic cost and environmental cost on the basis of maximizing the consumption of wind power. Finally, the comparison between the traditional optimization model and the model proposed in this paper is carried out by the way of example simulation. The results show that the new optimization model is helpful to reduce the environmental expenditure, and the cost of considering the environmental cost is 5.2% lower than not considering the environmental cost.

1. Introduction

In recent years, renewable energy power generation in Liaoning Province is developing continuously. By the end of 2018, the installed capacity of new energy power in the whole region was 18.0953 million kilowatts, accounting for 34.85% of the total installed capacity of the whole region; among them, the installed capacity of wind power generation was 7.6074 million kilowatts, and the installed capacity of photovoltaic power generation was 3.20201 million kilowatts¹. With the rapid development of renewable energy, there is also a serious problem of wind and light abandonment. Due to the uncontrollable, random fluctuation and difficulty in accurate prediction of wind and solar power, the demand for flexibility of the system is increased significantly. The lack of flexibility of the system
has become an important reason for wind and light abandonment. Especially in northern areas such as Liaoning, the large-scale application of CHP has significantly reduced the flexibility of the system.

In view of this problem, in recent years, a solution to the comprehensive regulation of electric heating is proposed\cite{2}, which makes use of the characteristics of the comprehensive energy system of electric heating and the regulation capacity of the thermal system to decouple the electricity and heat, so as to liberate the regulation capacity of the heating unit. At present, there are a lot of relevant researches in this field. Literature \cite{3} uses heat storage to improve the flexibility of the power system, realizes the coordination of the on grid revenue and penalty cost, and proposes the scheduling strategy of the joint operation of wind farm and cogeneration unit; literature \cite{4} proposes the coordinated scheduling model of wind energy consumption based on cogeneration unit and electric boiler to improve the regulation capacity of the power system; In reference \cite{5}, the constraints of the system operation are analysed, and the economic optimization is selected as the objective function, and the mixed integer linear programming method is used to solve the simulation example; in reference \cite{6}, the collaborative optimization model of the electric comprehensive energy system considering the uncertainty of new energy output is established; in reference \cite{7} Aiming at the maximum economic benefit of wind storage unit and the minimum cost of wind fire storage system, an optimal scheduling model of wind fire storage based on the chance constrained programming of credibility theory is constructed; In reference \cite{8}, aiming at the influence of network transmission loss on the balance of supply and demand in the electric heating comprehensive energy system, a multi-objective optimal scheduling strategy is proposed to minimize the economic environment scheduling objectives of the system, and to achieve the coordination and optimization between electric heating energy.

There are two kinds of objective functions in the scheduling of the existing electric heating comprehensive energy system, the minimum wind and light rejection rate or the minimum total coal consumption of the system, and less consideration of pollutant emission. For example, the objective function in document \cite{9-10} is the maximum wind power consumption and the minimum total coal consumption of the system, the objective function in document \cite{11} is the minimum user power purchase cost and the maximum wind power consumption, and the objective function in document \cite{12} is the wind abandonment penalty In reference \cite{13}, the objective function is the minimum economic cost. The fundamental goal of developing renewable energy is to reduce fossil energy consumption and pollutant emission, and reduce environmental pollution. Therefore, in addition to increasing the proportion of clean power supply in power supply structure, pollutant emission should also be considered in the operation of power grid. However, if we simply take the lowest economic cost as the objective of optimization, that is, the minimum wind and light rejection rate or the minimum total coal consumption of the system, environmental pollution may increase instead. Therefore, the environmental cost should be taken into account when dispatching the power grid.

There is no uniform standard to define environmental cost. The international Intergovernmental Working Group on accounting and reporting standards (ISAR), established by the economic and Social Council of the United Nations (ECOSOC), defines environmental cost as: Based on the principle of responsibility for the ecological environment, environmental cost includes the price paid for environmental damage in the production process of enterprises, as well as the expenses incurred to achieve the goal of environmental protection\cite{14}. In this paper, the definition of environmental cost is to adopt the above definition method, and adopt two definitions for different types of components respectively.

According to the definition of environmental cost standard formulated by international economic organization, this paper takes the northern region of China as the research object, selects the appropriate expression form of environmental cost, unifies the economic cost and environmental cost, and takes its weighted sum value as the optimization goal, so that the optimal scheduling can be carried out on the basis of maximizing the consumption of wind power and making the economic cost and environmental cost lowest. Because there are both economic cost and environmental cost in the optimization objective, the final optimization result is that the comprehensive cost of the system is the lowest, which can not only maximize the consumption of renewable energy, but also reduce the
emission of pollutants as much as possible, and at the same time, the expenditure for purification of emissions is the least. In this way, fossil energy can be saved to the greatest extent and environmental pollution can be reduced.

2. Objective function considering environmental cost
According to the composition of power supply and heat source of power system and thermal system in northern China, in this paper, the power supply includes thermal power and wind power, thermal power includes pure condensing unit and heating unit, and the heat source includes heating unit and coal-fired boiler. At the same time, heat storage device is also considered in the thermal system to increase the regulation capacity of the system. There are pure condensing unit, heating unit and coal-fired boiler which consume fossil fuel in the system. These three kinds of components are mainly considered in the objective function.

2.1 Composition of objective function
In the optimization of scheduling, the traditional optimization is generally based on the optimal economic cost. Furthermore, on this basis, various other optimization objectives are added and multiplied by the weight value to achieve the desired optimization results.

If we want to consider the optimization of economic cost and environmental cost comprehensively, on the one hand, we need to unify the units of these two kinds of costs, so as to add them directly in the objective function; on the other hand, we need to find the appropriate weight to measure the ratio of economic cost and environmental cost caused by coal consumption per ton.

Therefore, the objective function of this paper consists of the following two parts. One part is the coal consumption of traditional thermal power units and coal-fired boilers, the other part is the environmental cost in the process of system operation. In the objective function, the environmental cost is multiplied by the reciprocal of standard coal price as the weight. On the one hand, the dimension of economic cost and environmental cost is unified, and on the other hand, the difference between the economic cost and environmental cost corresponding to unit coal consumption is balanced.

2.2 Environmental protection tax
The environmental protection tax is a kind of tax that has been implemented since January 1, 2018. Its calculation method is the equivalent number of taxable pollutants multiplied by the coefficient. The pollution equivalent number of taxable air pollutants is calculated by dividing the emission amount of the pollutant by the pollution equivalent value of the pollutant [15]. Since the environmental tax only collects the top three pollutants, only sulfur dioxide, nitrogen oxides and soot are considered. According to the table of taxable pollutants and equivalent values, the pollution equivalent value of sulfur dioxide and nitrogen oxide is 0.95kg, the pollution equivalent value of smoke and dust is 2.18kg, and the tax amount of air pollutants is 1.2 yuan per time.

This kind of tax is a kind of punitive expense for the emission enterprises after the pollutants have been discharged, so it is more suitable as the first quantitative form of environmental cost.

2.3 Coal consumption and environmental cost
In this paper, the economic cost and environmental cost are selected as the best, so the coal consumption of the system is selected as the economic cost, the operation cost of the desulfurization, denitrification and dust removal device of the thermal power unit is selected as the environmental cost of the thermal power unit, the environmental protection tax that should be collected is selected as the environmental cost of the coal-fired boiler, the environmental cost divided by the standard coal price is taken as the weight coefficient, and the sum of the above costs is taken as the objective function. The cost of wind power generation is relatively small compared with thermal power, so the short-term heat loss of thermal storage device is ignored.

For a pure condensing thermal power unit, the coal consumption \( C_e \) can be expressed as:
\[ C_e = a_i (P_{ei})^2 + b_i P_{ei} + c_i \] (1)

Among them, \( a_i \), \( b_i \) and \( c_i \) are the coal consumption coefficient of the ith unit, and \( P_{ei} \) is the electrical output of the ith unit.

The heat supply unit mainly considers the air extraction type heat supply unit. The power \( P_{ei} \) and heat supply power \( P_{hi} \) are equivalent to the electric output under the pure condensing condition:

\[ P_{ec} = P_{ei} + c_i P_{hi} \] (2)

When (2) is introduced into (1), the expression of coal consumption \( C_{eh} \) of air extraction heating unit can be obtained [16]:

\[ C_{eh} = a_i (P_{eci})^2 + b_i P_{eci} + c_i = A_i (P_{ei})^2 + B_i P_{ei} + C_i P_{ei} P_{hi} + D_i (P_{hi})^2 + E_i P_{hi} + F_i \] (3)

The relationship between environmental cost and coal consumption of the unit is a primary function, so the expression is as follows:

\[ C_{evG} = k_i C_e + J \] (4)

\[ (C_{evG} = k_i C_{eh} + J) \]

Among them, \( k_i \) is the cost of pollutant treatment per unit coal consumption, and \( J \) is the maintenance cost of environmental protection device.

The coal consumption of coal-fired boiler \( C_{B} \) is the ratio of the thermal work output of coal-fired boiler to the thermal value of coal:

\[ C_B = \frac{p_{bh} \Delta t}{\delta \Delta h} \] (5)

Where \( P_{bh} \) is the thermal power of coal-fired boiler, \( \delta \) is the efficiency of coal-fired boiler, and \( \Delta h \) is the thermal value of coal.

The environmental protection tax \( H \) payable for each unit of coal consumption is related to the sulfur dioxide, nitrogen oxides and smoke and dust produced by each unit of coal consumption as follows:

\[ H = (\frac{N_s}{0.95} + \frac{N_N}{0.95} + \frac{N_{pm}}{2.18}) \times 1.2 \] (6)

Among them, \( N_s \), \( N_N \), \( N_{pm} \) are sulfur dioxide, nitrogen oxide and smoke and dust produced by combustion of each ton of coal.

The environmental cost of coal-fired boiler, \( C_{evB} \) is the environmental tax payable, and the calculation formula is as follows:

\[ C_{evB} = C_B H \] (7)

According to the definition of environmental cost in this paper, the above two kinds of environmental costs are obtained by selecting the appropriate items of capital expenditure, but the unit is ‘Yuan’, which is different from the unit ‘ton’ of economic cost, and cannot be added directly. Therefore, in the application of the objective function, the environmental cost is divided by the standard coal price (unit: ‘yuan per ton’) to make it equivalent to coal consumption, so that the unit is unified and can be directly added and optimized as the objective function.

3. Scheduling model of electric heating comprehensive energy system considering environmental cost

3.1 Objective function

Combining all the above formulas, we can get the objective function considering the economic cost and environmental cost comprehensively:

\[ C = \sum C_{ei} + \sum C_{eh} + \sum C_B + (\sum C_{evG} + \sum C_{evB})/M \] (8)

Where \( M \) is the standard coal price.

3.2 Constraint condition

3.2.1 Power balance constraint

Power balance constraints:

\[ \sum P_{ei} + P_{w} = P_{L} \] (9)
Where, $P_w$ is the wind power output and $P_L$ is the load demand.

Thermal balance constraints:
$$\sum P_{hi} + P_s + P_{bh} = P_{nl} \quad (10)$$

Among them, $P_s$ is the thermal output of the heat storage device. When the value is positive, the heat storage device is in the exothermic state, when the value is negative, the heat storage device is in the heat storage state; $P_{nl}$ is the heat load demand.

3.2.2 Unit output constraint

the upper and lower limits of the unit power output are restricted[16]:
$$\begin{cases}
P_{el} \geq \max \{C_{mi}P_{hi} + K_i, P_{e,i,min} - C_{vi}P_{hi}\} \\
P_{el} \leq P_{e,i,max} - C_{vi}P_{hi}
\end{cases} \quad (11)$$

When $C_m = 0$, $C_v = 0$, the unit is a pure condensing unit.

Upper and lower limits of unit thermal output:
$$0 \leq P_{hi} \leq P_{hi,max} \quad (12)$$

Where, $P_{hi,max}$ is the upper limit of the thermal output of the $i$th heating unit.

Unit climbing constraint:
$$P_{el} - P_{el,c} \leq P_{up,i}$$
$$P_{el,c} - P_{el} \leq P_{down,i} \quad (13)$$

Among them, $P_{el,c}$ is the electrical output of each unit at the current time, $P_{up,i}$ is the maximum upward climbing rate of each unit, and $P_{down,i}$ is the maximum downward climbing rate of each unit.

Wind power output constraint:
$$P_w \leq P_{w,max} \quad (14)$$

Where, $P_{w,max}$ is the maximum output power of wind power.

3.2.3 Restriction of heat storage device and coal-fired boiler

Restriction of heat storage and release capacity of heat storage device:
$$\begin{cases}
|P_s| \leq P_{s,c,max}P_s \leq 0 \\
|P_s| \leq P_{s,f,max}P_s \geq 0
\end{cases} \quad (15)$$

Among them, $P_{s,c,max}$, $P_{s,f,max}$ are the maximum rate of heat storage and heat release.

Thermal storage capacity constraints:
$$\begin{cases}
Q_s + |P_s|\Delta t \leq Q_{s,max}P_s \leq 0 \\
|P_s|\Delta t \leq Q_sP_s \geq 0
\end{cases} \quad (16)$$

$Q_s$ is the energy stored in the heat storage device at the current time, and $Q_{s,max}$ is the maximum energy stored in the heat storage device.

Thermal output restriction of coal-fired boiler:
$$0 \leq P_{bh} \leq P_{bh,max} \quad (17)$$

Among them, $P_{bh,max}$ is the maximum thermal output of coal-fired boiler.

4. Example analysis

4.1 Basic data

The calculation example adopted in this paper is the simplification of the actual power supply structure proportion in the "Three North" area of China. The basic data is from literature [18]. The installed structure of the power grid is shown in Table 1, and the unit parameters are shown in Table 2. The cost parameters of pollutant treatment required for unit coal consumption are shown in Table 3. Among them, units 1-6 are heating units, all of which are large-scale extraction units. Units 1-3 belong to thermal power plant A, which supplies heat to urban area 1. Units 4-6 belong to thermal power plant B, which supplies heat to urban area 2. Each thermal power plant has a heat storage device with a heat storage capacity of 1000MW·h, and the maximum heat storage and release rate is 100MW. Units 7
and 8 are large pure condensing units. Each urban area also has a centralized heating boiler, with a thermal efficiency of 80% and a maximum thermal power of 300MW. All wind farms in the system are equivalent to one wind farm.

| Table 1. Installed capacity of power grid |
|------------------------------------------|
| Unit type                  | Installed capacity / MW | Proportion /% |
|---------------------------|-------------------------|---------------|
| Pure condensing unit     | 700                     | 25            |
| Heating unit              | 1800                    | 64.3          |
| Wind power                | 300                     | 10.7          |

| Table 2. Unit parameters |
|--------------------------|
| Unit | Maximum generating power/MW | Minimum generating power/MW | Maximum heating power/MW | \( a_i/(t \cdot MW^{-2} \cdot h^{-1}) \) | \( b_i/(t \cdot (MW \cdot h)^{-1}) \) | \( c_i/(t \cdot h^{-1}) \) | \( c_{v1} \) | \( c_{v2} \) | \( c_m \) | \( K_i \) | Rate of climb up (MW/h) | Rate of climb down (MW/h) |
| 1   | 200  | 100  | 250  | 0.000171 | 0.2705 | 11.537 | 0.15 | 0.15 | 0.75 | 0 | 50 | 50 |
| 2   | 350  | 175  | 450  | 0.000072 | 0.2292 | 14.618 | 0.15 | 0.15 | 0.75 | 0 | 70 | 70 |
| 3   | 350  | 175  | 450  | 0.000072 | 0.2292 | 14.618 | 0.15 | 0.15 | 0.75 | 0 | 70 | 70 |
| 4   | 300  | 150  | 400  | 0.000076 | 0.2716 | 18.822 | 0.15 | 0.15 | 0.75 | 0 | 80 | 80 |
| 5   | 300  | 150  | 400  | 0.000076 | 0.2716 | 18.822 | 0.15 | 0.15 | 0.75 | 0 | 80 | 80 |
| 6   | 300  | 150  | 400  | 0.000076 | 0.2716 | 18.822 | 0.15 | 0.15 | 0.75 | 0 | 80 | 80 |
| 7   | 200  | 80   | 0    | 0.000171 | 0.2705 | 11.537 | 0   | 0   | 0   | 0 | 50 | 50 |
| 8   | 500  | 200  | 0    | 0.000138 | 0.2716 | 37.645 | 0   | 0   | 0   | 0 | 130 | 130 |

| Table 3. Power load and wind power prediction value |
|-----------------------------------------------|
| Time       | Electrical load /MW | Wind power /MW | Time       | Electrical load /MW | Wind power /MW |
|------------|---------------------|----------------|------------|---------------------|----------------|
| 09:00      | 2130                | 255            | 21:00      | 1915                | 268            |
| 10:00      | 2208                | 233            | 22:00      | 1860                | 270            |
| 11:00      | 2296                | 194            | 23:00      | 1800                | 269            |
| 12:00      | 2254                | 186            | 24:00      | 1782                | 250            |
| 13:00      | 2112                | 202            | 01:00      | 1702                | 241            |
| 14:00      | 2140                | 190            | 02:00      | 1696                | 258            |
| 15:00      | 2262                | 181            | 03:00      | 1694                | 268            |
| 16:00      | 2400                | 217            | 04:00      | 1716                | 278            |
| 17:00      | 2350                | 223            | 05:00      | 1770                | 288            |
| 18:00      | 2182                | 235            | 06:00      | 1792                | 300            |
| 19:00      | 2098                | 255            | 07:00      | 1864                | 280            |
| 20:00      | 2038                | 260            | 08:00      | 1946                | 262            |

| Table 4. Cost parameters of pollutants to be treated per unit coal consumption |
|-----------------------------------------------|
| Unit | Cost of pollutant treatment \( k_i \) (yuan/t) | Cost of maintenance \( J \) (yuan/t) | Cost of pollutant treatment \( k_i \) (yuan/t) | Cost of maintenance \( J \) (yuan/t) |
| 1    | 20                      | 500                      | 5    | 20                      | 500                      |
| 2    | 25                      | 500                      | 6    | 90                      | 500                      |
| 3    | 85                      | 500                      | 7    | 30                      | 500                      |
| 4    | 30                      | 500                      | 8    | 20                      | 500                      |

In the calculation example, the predicted values of the electric load and the maximum generating power of the wind farm from 9:00 to 9:00 of the next day are shown in Table 3, and the data after 24:00 is the data of the next day. It is assumed that the heat load of both urban areas is 900MW and does not change.
Assuming that the local standard coal price is 300 yuan / ton, 15 kg of sulfur dioxide, 1.7 kg of nitrogen oxide and 270 kg of smoke and dust will be generated per ton of coal after combustion. Table 4 shows the cost parameters of pollutant treatment required by unit coal consumption of each unit.

In this calculation example, two calculation methods are adopted to compare environmental cost and environmental cost. The scheduling cycle is 1 day and the scheduling step is 1 hour. Matlab program is used for simulation calculation.

4.2 Result analysis

4.2.1 Output of each type of generator set

The calculation results of the calculation example are shown in the figure. Figure 1 and Figure 2 are the output diagrams of each unit without considering the environmental cost and the environmental cost respectively.

It can be seen from the figure that the output of the second unit is the same due to the same parameters of unit 2 and unit 3; the output of unit 4-6 is the same. Because each unit adopts different types of desulfurization, denigrations and dust removal devices, it will tend to make the unit with lower environmental cost have higher output when scheduling, so as to reduce the overall environmental cost of the system.

The thermal output of unit 4-6 and coal-fired boiler in urban area 2 are shown in Figure 3. It can be seen from the figure that the output of coal-fired boiler is 0 before 24:00, then increases, and then decreases to 0 at 9:00. This is because the economic cost and environmental cost of coal-fired boiler are high, so the coal-fired boiler will not operate when the grid itself can absorb wind power. During
the day, the electric load is high and the thermal load is also high. When the coal-fired boiler is closed and only the thermal power unit is started, the thermal load can be satisfied and the wind power can be consumed completely. At night, when the power load is reduced, the wind power is increased and the heat load is increased, the thermal power unit must be reduced to absorb the wind power to the maximum extent, while the heat output can only be guaranteed by increasing the coal-fired boiler. If there is no coal-fired boiler, the actual output and predicted maximum output of the wind power are shown in Figure 4.

In addition, although the cost of coal-fired boiler is very high, the optimization results show that in order to maximize the wind power consumption, the operation of coal-fired boiler is basically unaffected regardless of environmental factors, and it is closed in the daytime and opened at night.

4.2.2 Total environmental cost analysis

In this example, when the environmental cost is not considered in the optimization, the calculation method in the objective function can be used to calculate the actual environmental cost of unit 1-8 is 73468 yuan; after the environmental cost is considered in the optimization, the actual environmental cost of unit 1-8 is 69647 yuan, saving 3821 yuan in total, accounting for 5.2% of the environmental cost. The system is a small-scale system, so the cost saving is less; if the scale of the system is expanded, and the technical level of each node using the purification device is different, the environmental cost generated by unit coal consumption is quite different, the node with higher environmental cost will be reduced during scheduling, so that more environmental cost can be reduced.

Under the two calculation methods, the actual output of the coal-fired boiler does not change, because the economic cost of the coal-fired boiler itself is already very high, and it will not be used unless the wind power is completely consumed. Therefore, although the environmental cost is very high, the operation of the coal-fired boiler has not been affected because the premise is that the wind power is completely consumed. If we do not take the complete consumption of wind power as the premise, but take the abandoned wind itself as a cost to participate in the optimization, we may call the coal-fired boiler when we do not consider the environmental cost, and when we consider the environmental cost, the new environmental cost exceeds the cost of the abandoned wind, so instead of calling the coal-fired boiler, we choose the abandoned wind to reduce the comprehensive cost.

5. Conclusion

This paper selects the appropriate definition of environmental cost, and selects the appropriate expression form of environmental cost according to the definition, unifies the economic cost and environmental cost, and takes the weighted sum as the objective function for optimization, so that the optimal scheduling can be carried out with the lowest comprehensive economic cost and environmental cost on the basis of maximizing the consumption of wind power. The main contents are as follows:

The definition of environmental cost selected in this paper is: Based on the principle of being responsible for the ecological environment, environmental cost includes the cost of environmental damage in the production process of the enterprise, as well as the expense formed to achieve the goal of environmental protection. These two kinds of environmental costs correspond to the environmental protection tax levied on coal-fired boilers due to emissions, and the operation costs of reducing pollution emissions through desulfurization, denitrification and dust removal devices of thermal power units.

Taking the above environmental cost plus economic cost as the objective function to optimize, through the simulation experiment, the final optimization result is compared with the optimization result without considering the environmental cost, and it is concluded that considering the environmental cost in the optimal scheduling reduces the expenditure caused by environmental protection by 5.2%, and also affects the output of each unit in different periods. Therefore, from the perspective of environmental protection, it is effective to bring environmental cost into the objective function for optimal scheduling.
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